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Experimental investigation on the effects of waste plastics in bituminous binders

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Abstract

This thesis has been developed within the framework of the PRIN SWITCH project. The initiative addresses one of the most pressing challenges of modern society: the increasing production of non-biodegradable plastics and their inadequate disposal, which often leads to significant environmental concerns. The road infrastructure sector, especially road engineering, emerges as a promising area for exploring new applications, all while keeping sustainability at the forefront.

This research focuses on the characterization and modification of standard bitumen by incorporating recycled polymers to enhance binder performance. The mixtures were assessed using both **traditional empirical classification** and **performance-based methods** to evaluate how they behave under various conditions. The experimental campaign is designed to assess the influence of different recycled plastics, selected for their availability and interesting compatibility with bituminous binders.

Different types of recycled plastics were employed to modify the binder, each characterized by specific compositions. To evaluate their impact, the investigation combined empirical tests—carried out on all binders in their original state—with performance-based analyses. Rheological properties were studied through the Dynamic Shear Rheometer (DSR) under different ageing conditions, while the Bending Beam Rheometer (BBR) was applied to PAV-aged binders to assess low-temperature performance. This integrated approach allowed for a comprehensive understanding of the materials' behavior, from their initial condition to advanced ageing scenarios.

The results showed that plastics with higher polyolefin content ensured better compatibility with bitumen, facilitating blending. On the other hand, plastics composed of different polymers (e.g. polypropylene) provide more significant benefits in terms of performance, particularly with improvements in the complex modules. Overall, the study confirms the feasibility of using post-consumer plastics as sustainable modifiers to enhance the properties of bituminous binders.

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1. Introduction

Plastics have become an essential material in modern society, yet the increasing demand for these non-biodegradable polymers has led to a global production growth of approximately 10% compared to 1950 [1].

However, plastic waste represents one of the major environmental concerns, as it is composed of numerous potentially hazardous substances which, if not properly managed, may contaminate soil, air, and water. The large volume of discarded plastics highlights the urgent need to develop safe recycling and reuse protocols, especially considering that many of these substances can infiltrate the food chain [2]. Moreover, uncontrolled disposal may result in the formation of landfills and, consequently, in the contamination of groundwater. At present, the largest share of plastics (around 41%) is directed to incineration, while approximately 30% is recycled [3].

In this context, several eco-friendly approaches have been developed to promote the recovery and reuse of plastic waste. One of the most promising fields is the construction sector, particularly road infrastructure, where the incorporation of recycled plastics into asphalt mixtures offers interesting opportunities both from an environmental and a technical perspective.

Among the most widely used materials in pavement construction are asphalt mixtures, mainly employed in surface and base courses; hydraulically bound mixtures, primarily used in base and subbase layers; and unbound mixtures, typically applied in the subbase, capping, and subgrade [4]. In particular, surface or wearing courses form the outermost layer of the pavement: they must withstand the direct action of traffic, ensure safety through adequate skid resistance, provide comfort to road users, and protect the underlying layers [5]. It is precisely within this framework that the present study is introduced, developed as part of the **PRIN SMASHit** project, which aims to evaluate the use of recycled plastics as bitumen modifiers, in a perspective of sustainability and technological innovation. Recent literature indeed highlights a growing interest in the adoption of innovative and sustainable materials, such as recycled plastics and alternative binders, with the aim of combining technical performance with environmental sustainability.

2. Literary review

2.1. Overview of recycled plastics

There are numerous types of plastics, each characterized by specific compositions and engineering properties. Depending on their intended applications, plastics can be found in a wide variety of forms, with distinct chemical and mechanical properties, and they can also undergo different recycling processes.

Due to their versatility and widespread use, plastics are found in abundance across numerous sectors and everyday products. To standardize their identification and facilitate proper recycling, plastics are categorized into seven distinct groups, each defined by specific chemical and mechanical traits, as it is shown in **Figure 1**. In particular, the groups are:

- **PET (Polyethylene terephthalate):** a polyester-based thermoplastic, partly crystalline and more biodegradable than many other plastics. It is widely used for bottles and food packaging because of its transparency, light weight, and mechanical strength [2].
- **HDPE (High-Density Polyethylene):** a highly crystalline polymer with excellent resistance to impact, abrasion, and chemicals. It is commonly applied in containers, piping, and films [2].
- **PVC (Vinyl or Polyvinyl chloride):** a non-biodegradable material, odorless and resistant to weathering. It has good chemical resistance and can be produced in both rigid and flexible forms. Typical applications include pipes, window frames, and medical devices [2].
- **LDPE (Low-Density polyethylene):** a lightweight and flexible polymer, with low crystallinity. It remains elastic even at low temperatures and shows resistance to corrosion. It is widely used for bags, films, and protective coatings [2].
- **PP (Polypropylene):** a polyolefin with higher thermal and mechanical resistance compared to polyethylene. It is lightweight and chemically resistant, used in automotive parts, textiles, and packaging [2].

- **PS (Polystyrene):** a rigid and brittle polymer obtained from styrene polymerization. In solid form it is transparent and robust, suitable for containers and disposable products [2].
- **Category 7 (Other plastics):** this group includes polymers not covered by the previous categories. It often contains blends or engineering plastics such as polycarbonate, nylon, or thermosetting resins. They are used in advanced fields such as electronics and medical technology [6,7].

Each group is represented by a recycling symbol: an equilateral triangle enclosing a number from 1 to 7, which denotes the corresponding resin type.

Identification Number	Polymer Description	Properties	Melting temperatures (°C)
	PET	• Excellent thermal characteristics • Solvent resistant • Shatterproof and impact-resistant • Gas permeability is low.	• 230 – 250 [76]
	HDPE	• In comparison to other polyethylene resins, it has a higher tensile strength. • Resilient to most of the solvents • Low-temperature tolerance • Rigid material	• 120 – 150 [76,77]
	PVC or Vinyl (V)	• Excellent insulating qualities • High-quality durability • Flame-resistant • Inorganic chemical resistance	• 280 – 298 [76]
	LDPE	• Chemically resistant to acids • The absorption of water is low. • At low temperatures, high-impact strength • It resembles a thin film-like material.	• 110 – 135 [76]
	PP	• Resistance to crack • Mechanical and electrical properties that are strong • Excellent optical characteristics • Stiffer than polyethylene	• 300 – 320 [77]
	PS	• Exceptional insulating properties • Compressive strength is high. • Salt and alkali resistance • Anti-aging properties	• 180 – 240 [76,77]
	Category 7 polycaprolactone and acrylonitrile butadiene styrene (ABS) are examples of plastics. Polycarbonates (PC) and nylon (PA6), among others	• Chemical and mechanical characteristics are highly variable.	-

Figure 1 – Classification of plastic materials [2]

Among the various types of plastic waste, PET, HDPE, LDPE and PP are the most recycled, accounting for approximately 85% of the total amount of plastic reprocessed globally [3]. One of the key reasons behind their widespread recyclability lies in their low density, which is lower than that of water. This physical property allows for an efficient separation process during recycling, where these plastics are isolate from heavier polymers through flotation in water baths.

As a material family, they exhibit significant differences in terms of chemical composition, physical behavior and engineering performance, which need to be taken into account. When considering their use in modified bituminous binders, thermal

behavior becomes a critical factor, particularly the melting point. This is because plastics must be fully or at least sufficiently softened to be homogeneously blended with bitumen and to ensure proper dispersion within the matrix.

However, most bitumen mixtures are typically produced at temperatures not exceeding 180 °C, which limits the range of compatible plastic types. For instance, PVC (Polyvinyl chloride) has a melting point significantly higher than 180 °C, making it unsuitable for direct blending with hot bitumen. Consequently, in order to identify suitable plastic waste materials for bitumen modification, it is essential to consider not only their melting temperature and compatibility with hot bitumen, but also the specific recycling process they undergo.

The recycling process of plastic materials can be categorized into four main types:

- **Primary recycling** involves clean and homogeneous plastic waste that is reprocessed to obtain the same original product. [8]
- **Secondary recycling** refers to the mechanical processing of plastic waste, which is then reused for purposes different from its original function. [8]
- **Tertiary recycling** includes chemical depolymerization of the plastic material to break it down into its basic chemical constituents. [8]
- **Quaternary recycling** recovers energy from plastic waste through incineration or use as alternative fuel. [8]

In this study, the plastics used are mainly derived from post-consumer waste, which is predominantly processed through secondary (mechanical) recycling, and occasionally through tertiary (chemical) methods. As a result, the plastic feedstock is typically non-homogeneous, exhibiting variations in rheological behavior, thermal stability and compatibility.

Such variability can significantly affect the performance of bituminous mixtures, especially in terms of adhesion between the plastic-modified binder and the mineral aggregates, as well as the blending efficiency of the plastic within the bitumen phase. In many cases, bituminous mixtures modified with plastic waste tend to show reduced mechanical performance, and in some instances, even visible phase separation between the components.

2.2. Polymer incorporation techniques

There are two main methods for modifying asphalt mixtures using waste polymers: the dry process (mechanical) and the wet process (chemical). In the dry process, waste polymers are directly added to the asphalt mixture during production. In contrast, the wet process involves an initial step in which the binder is modified by blending it with the polymer; the modified binder is then incorporated into the final asphalt mix. [2,3,9].

In the dry method, plastics are first incorporated into the mix together with the hot aggregates, followed by the addition of the hot bituminous binder. This technique is primarily used for rigid and hard plastics with high melting points, such as PET, whose thermal properties allow them to be integrated into the mixture without melting, acting as fillers or even aggregate replacements [9]. Polymers with lower melting points can be also introduced through the dry method; however, it is hypothesized that these plastics melt upon contact with the hot aggregates, forming a thin coating film around the particles. For this reasons, the dry method is often referred to as an aggregate modification, mixture modification or even bitumen replacement approach [2].

In the wet method, waste polymers are added directly into the hot bitumen, acting as modifiers. This technique is particularly suitable for waste plastics with low melting points, such as LDPE and PP [3]. These polymers are finely grounded or pulverized before being mixed with the hot binder at a sufficiently high mixing speed. This procedure ensures that the resulting blend is adequately homogenous, which is essential to guarantee thermal stability at high temperatures, particularly during the storage phases of laboratory-produced mixtures [9].

The process of the two techniques is well represented in **Figure 2**.

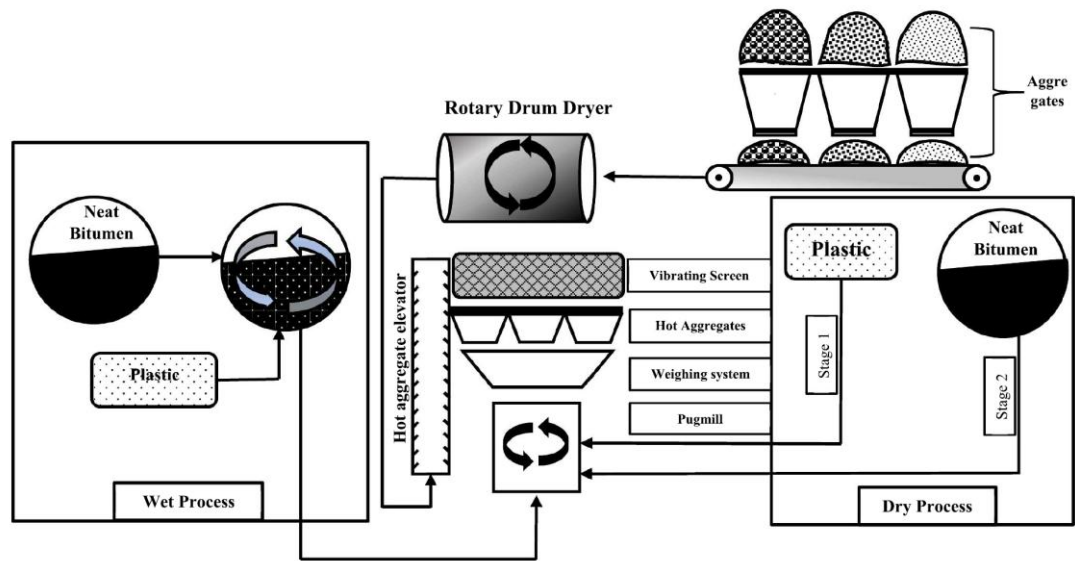


Figure 2 - Schematic representation of the wet and dry methods [2]

It is important to highlight that the dry method does not require any specialized equipment, and the direct addition of polymers into the aggregates makes it a simpler and more straightforward process. In contrast, the wet method requires dedicated machinery and is more demanding in terms of time and energy, making it somehow more complex to implement in practice [3].

Furthermore, **Figure 3** provides a summary of the different methods used for incorporating recycled plastics as asphalt modifiers, including examples of materials and techniques aimed at enhancing compatibility and performance with the bituminous binder.

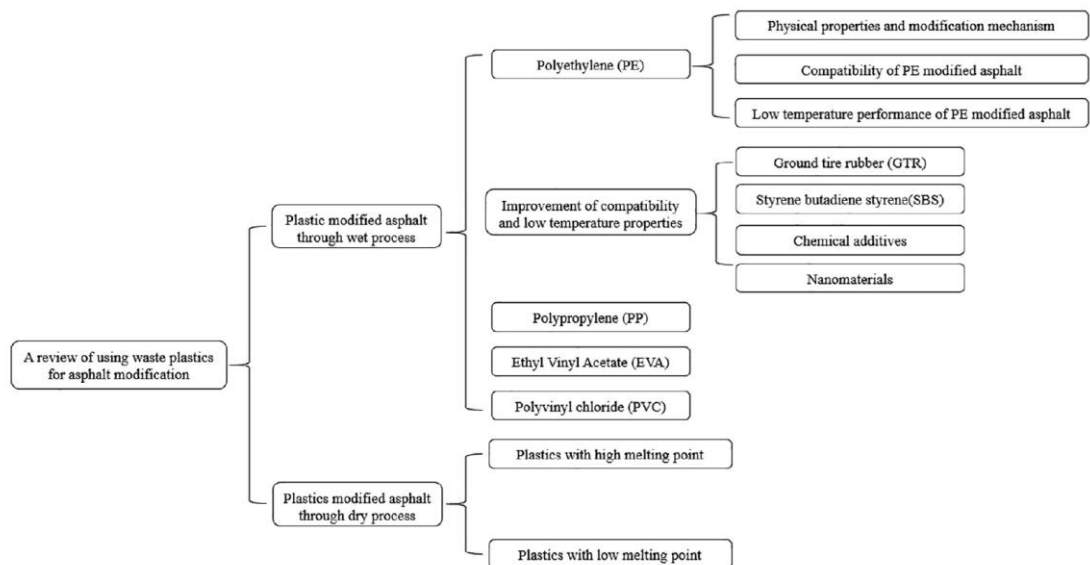


Figure 3 - Flow chart [10]

2.3. Performance of polymer-modified bituminous binder

2.3.1. Polyethylene terephthalate (PET): features and binder modification

In recent years, polyethylene terephthalate (PET) has gained increasing attention as a recycled material, with a growing number of products being manufactured from it.

PET is a thermoplastic polymer belonging to the polyester family and is one of the most widely used non-biodegradable materials. It is known for its mechanical strength, chemical resistance and thermal stability. Its chemical formula is $C_{10}H_8O_4$, with the structure shown in **Figure 4**.

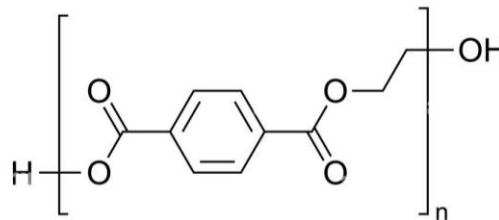


Figure 4 – Chemical structure of PET [11]

Among the studies reviewed, the polymers employed were primarily derived from mechanically recycled plastic bottles, which represent one of the most abundant sources of post-consumer PET waste [12–14].

Once recycled, PET bottles can be used as modifying agents in the form of granules or fibers, typically ranging in size from 1.18 to 2.36 mm, which can be incorporated into bituminous mixtures through “dry process”, due to the high melting point [3]. The typical physical properties of the recycled PET used in the studies are summarized in **Table 1**.

Specific gravity	1.32	-
Tensile strength	300 – 350	Mpa
Modulus of elasticity	13	GPa
Elongation	7.5	%
Softening point	180	°C

Table 1 – PET physical properties [3]

In general, the presence of PET in the mixture tends to increase the stiffness of the material and enhance resistance to rutting and fatigue. However, the literature also

reports some limitations, such as the reduced thermal cracking resistance and increased moisture susceptibility.

Among the critical variables identified, the optimal dosage of plastic stands, as this significantly affects the overall performance of the modified binder. For this reason, the analyzed studies have investigated different contents in order to identify the most effective proportion.

In this context, the study by Mashaan et al. (2021) evaluated PET contents of 0%, 4%, 6% and 8% by weight of the binder [14]; PET was used as 15% by weight of the binder according to Aldagari et al. (2021) [12]; Nizamuddin et al. (2021) in their review confirmed that PET contents typically range between 2% and 12% in the literature, with optimal performance generally observe around 6-8% [13].

In the three studies reviewed PET was used as bitumen modifier in varying proportions. Notably, the mixing methods adopted varied: two studies — Mashaan et al. (2021) and Aldagari et al. (2021) — used the wet process, while Nizamuddin et al. (2021) predominantly reported the use of the dry process.

To assess the performance of the modified binder, the authors from Mashaan et al. (2021) [14] compared the virgin and PET-modified bitumen using rheological tests conducted with the Dynamic Shear Rheometer (DSR), focusing on viscoelastic behavior and resistance to rutting and fatigue. The tests were performed at different temperatures – 50, 58, 60, 64, 70 and 76 °C – in accordance with the AASHTO M332 specification, aiming to evaluate the binder's response over a wide thermal range.

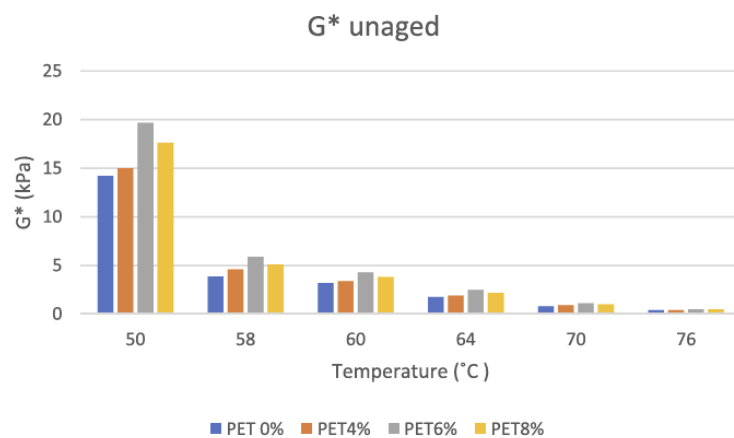


Figure 5 - Complex modulus of PET-modified bitumen [14]

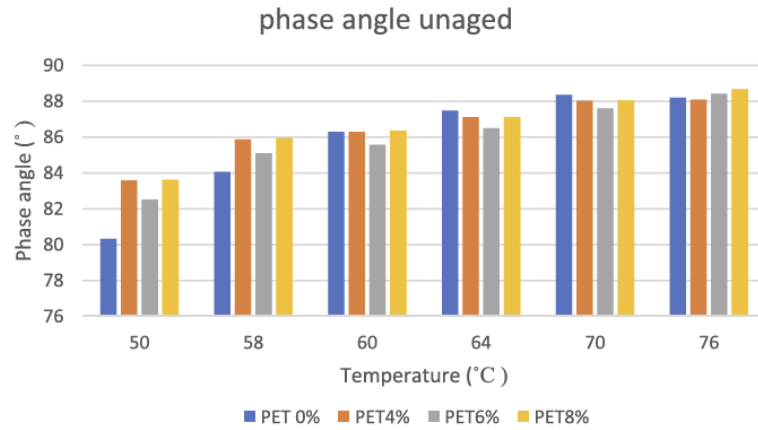


Figure 6 - Phase angle of PET-modified bitumen [14]

The analysis of the complex modulus (G^*) and the phase angle (δ) provides a clear understanding of how PET affects the rheological behavior. As shown in **Figure 5** and **Figure 6**, there is an increase in G^* across all PET-modified binders, indicating improved stiffness. However, a noticeable decrease in δ is observed only for the binder with 6% PET, suggesting a more elastic and less viscous behavior in this specific case. For the other PET contents, the phase angle tends to remain stable or even slightly increase [14]. These findings are further supported by Nizamuddin et al. (2021), who reported that a 4% PET content enhanced the complex shear modulus while significantly reducing the phase angle [13].

Moreover, the study conducted by Mahsaan et al. (2021) shows that at all temperatures, PET-modified bitumen showed improved rutting resistance compared to the unmodified binder [**Figure 7**]. The $G^*/\sin \delta$ values were consistently higher, particularly at 50 °C, highlighting reduced susceptibility to permanent deformation. Although the rutting factor decreased with temperature, it remained higher in the PET samples, confirming their greater stiffness and structural stability under repeated loads [14]. This is also supported by Nizamuddin et al. (2021), who reviewed from other studies that the MSCR characteristic (%R and J_{nr}) are improved as the PET content increases [13].

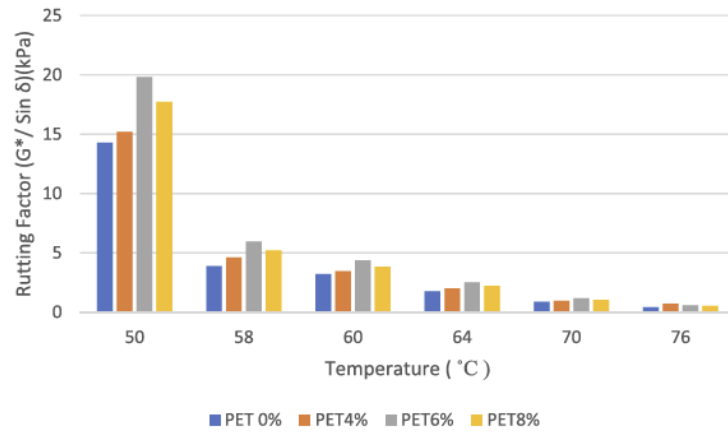


Figure 7 - Rutting factor of PET-modified bitumen

In terms of ageing behavior, both studies from Mashaan et al. (2021) and Aldagari et al. (2021) confirm that PET modification has a positive effect on the performance of bitumen. Mashaan et al (2021) observed a marked increase in complex shear modulus (G^*) across the temperature range of 50 – 70 °C following RTFOT, indicating enhanced stiffness and durability. Additionally, the phase angle (δ) decreased for binders containing 6-8% PET, suggesting improved elasticity. This results in a higher rutting factor and a 55% improvement in rutting resistance compared to the unaged binder. Consequently, PET-modified binders are less prone to deformation and cracking after the ageing phenomenon [14].

Similarly, Aldagari et al. (2021) evaluated the effects of both short-term and long-term ageing. Their results showed that at high temperatures and low frequencies, the PET-modified bitumen had higher stiffness than the neat binder, which is beneficial for rutting. They showed less variation in stiffness, indicating a lower sensitivity to temperature-related ageing compared to the neat bitumen [12].

Eventually, in the three studies analyzed, PET was used as bitumen modified in different proportions and using different methodologies. Mashaan et al. (2021) have found the most notable improvements with 6-8% contents; Aldagari et al. (2021) focused on a single PET content of 15%, considering both non-treated PET and oil-treated PET and the significant improvements were due to the treatment, more than the amount of PET used; Nizamuddin et al. (2021) show that the optimal performance is typically observed between 6-8%, in which range it is possible to see a good balance of stiffness, elasticity and workability.

2.3.2. Polyethylene (HDPE - LDPE): features and binder modification

Among the most widely used plastics globally, a key role is played by thermoplastic polymers from the polyolefin family, known for their versatility and wide industrial applications.

Its technical properties are not fixed but vary considerably depending on key structural factors such as molecular weight, molecular weight distribution and degree of crystallinity. The latter refers to the extent to which polymer chains are arranged within the material. In polymers, both crystalline regions – where chains are tightly and regularly packed – and amorphous regions – characterized by a more random and disordered configuration – can coexist. The balance between these two structural domains has a direct impact on the overall performance of the polymer, influencing essential characteristics such as stiffness, mechanical strength, flexibility and thermal stability [15].

Polyethylene is commonly produced in three main forms:

- Low-density polyethylene (LDPE): $< 0.930 \text{ g/cm}^3$.
- Linear low-density polyethylene (LLDPE): $0.915 - 0.940 \text{ g/cm}^3$.
- High-density polyethylene (HDPE): $0.940 - 0.965 \text{ g/cm}^3$. [3]

In particular, HDPE is characterized by a linear molecular structure with very few side branches. This configuration allows the polymer chains to pack closely together, resulting in higher density and increased rigidity. Consequently, HDPE exhibits superior mechanical strength, making it particularly suitable for applications requiring high structural performance. Its chemical formula is $(C_2H_4)_n$ [Figure 8]. [15]

On the other hand, LDPE has a highly branched molecular structure, which prevents the polymer chains from aligning compactly. This results in greater thermal flexibility, especially under variable temperature conditions, but also leads to reduced stiffness and lower mechanical strength compared to HDPE. Due to these properties, it has attracted considerable interest as a modifier for bituminous binders, thanks to its ability to better accommodate thermal and mechanical stresses, typically experienced by road pavements. Its chemical formula is $(CH_2 - CH_2)_n$ [Figure 8]. [13]



Figure 8 - Chemical structure of HDPE and LDPE [9]

Each typology presents specific operational challenges:

- HDPE: storage stability is one of the main issues, often evidenced by phase separation. To prevent this, the use of high-speed stirrers is essential to ensure a uniform dispersion of the polymer.
- LDPE: some parameters necessity of attention such as the type of material, the dosage in the mixture and the mixing process, as the interaction between the polymer and bitumen is primarily physical, with no significant chemical bonding.

Several studies have investigated the addition of polyolefins as bitumen modifiers. Among the most relevant ones, the ones conducted by Sarkar et al. (2019) [16], Ghani et al. (2022) [17] and Mashaan et al. (2022) [18] are particularly noteworthy. In all these studies, the polymers have been added through the “wet process”, using different percentages in order to find the optimal one.

Moreover, the type of material used differs slightly across the three studies. In the first study, HDPE and LDPE are derived from municipal solid waste, tested for dosages from 1% to 4% [16]. In the second study, waste polymers were used too, but in a shredded form passing through a No. 4 sieve, with dosage ranging from 2% to 6% [17]. In the third study, polymers were sourced from local waste and ground to a particle size of 0.245 mm, with concentrations ranging from 2% to 8% [18].

The studies conducted by Mashaan et al. (2022) [18] and Sarkar (2019) [16] highlight that the addition of HDPE and LDPE to bitumen leads to an increase in binder stiffness, resulting in lower penetration values. Both works report a decrease in penetration as the polymer content increases, particularly within the range of 1% to 4%. However, only the study by Mashaan et al. (2022) explored higher dosages (ranging from 6% to 8%), where a reversal of the trend was observed, with penetration values starting to rise again. This behavior may be attributed to reduced compatibility between the polymer and the bitumen beyond a certain concentration threshold.

Furthermore, as expected, HDPE induces a more pronounced increase in binder stiffness compared to LDPE.

The two studies conducted by Mashaan et al. (2022) [18] and Ghani et al. (2022) [17] provide a complementary view of the behavior of polymer-modified bitumen. On one hand, it is possible to find graphs that show that the addition of HDPE and LDPE significantly increases $G^*/\sin\delta$, indicating improved rutting resistance, especially at high temperatures and with HDPE. On the other hand, the complex shear modulus (G^*) graphs show minor variations between modified samples. This discrepancy suggests that the effectiveness of the polymers lies more in enhancing the elastic component of the binder ($\sin\delta$) than in increasing its overall stiffness [Figure 9].

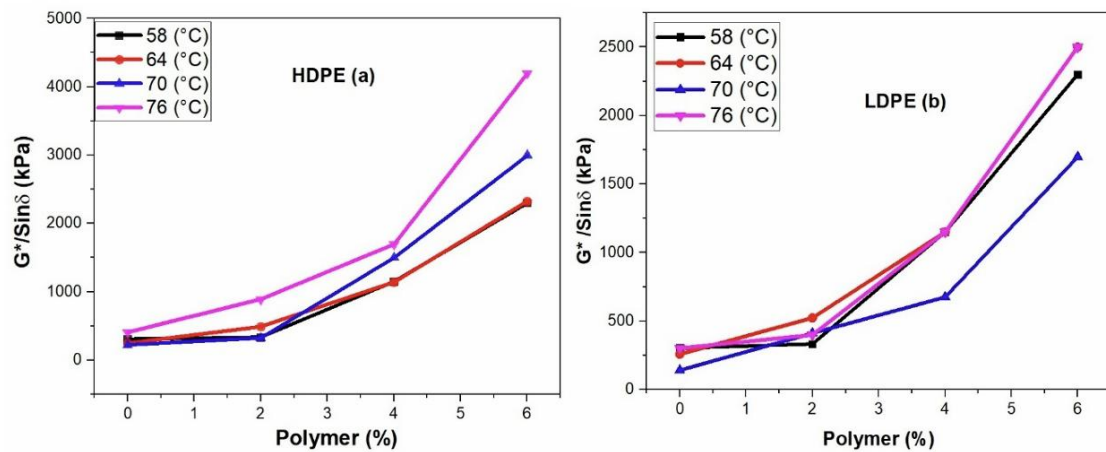


Figure 9 - HDPE and LDPE viscoelastic behavior

Furthermore, the studies conducted by Sarkar (2019) [16] and Ghani et al. (2022) [17] have analyzed the behavior of viscosity in the polymer-modified samples. It is possible to highlight that the viscosity is strongly influenced both by temperature and polymer content. On one hand it has been carried out the test at high temperatures (135 – 136 °C), where HDPE increases viscosity up to 2%, after which it declines, while LDPE reaches its maximum effect at 4%. This suggests that higher dosages do not improve workability and may even worsen it. [17] This trend is also visible on results reported by Sarkar (2019), in which the viscosity is plotted against polymer percentage at 135 °C. The curve related to HDPE shows a steep and continuous increase, whereas LDPE displays a more moderate and linear rise. On the other hand, it has been carried out the viscosity test at 60 °C, which shows that both polymers allow a progressive increase, with HDPE yielding significantly higher values. This

indicates that at lower temperatures, higher polymer content can be beneficial in enhancing binder stiffness and rutting resistance [16].

To sum up, both HDPE and LDPE can improve the stiffness and rutting resistance of bituminous binder, but their effectiveness strongly depends on the dosage and the temperature range considered. HDPE shows a stronger stiffening effect, making it suitable for improving resistance to permanent deformation. However, excessive amount may compromise workability. Conversely, LDPE offers more flexibility and better processing behavior, particularly at moderate dosages. Therefore, a careful balance between performance and workability must be considered when selecting polymer type and dosage.

2.3.3. Polypropylene (PP): features and binder modification

Polypropylene (PP) accounts for approximately 21% of global plastic production and is commonly found in automotive parts, microwave containers and food packaging [13]. It is a thermoplastic polymer composed of a linear hydrocarbon chain with a medium level of crystallinity compared to HDPE and LDPE. It is a lightweight material with a specific gravity of approximately 0.91, which, added to the bituminous matrix, tends to reduce the overall density of the mixture. Its chemical formula is $[C_3H_6]_n$.

In general, literature agrees on the effects of adding this polymer to bituminous mixtures. In fact, it enhances rutting and fatigue resistance, while also improving the overall stability of the asphalt mixtures.

The studies reviewed in this work focused on the use of recycled polypropylene (rPP). Specifically, the study by Xia et al. (2020) [19] employed three types of rPP, differentiated by their source and recycling method: rPP1 (from lunch boxes), rPP2 (from woven bags) and rPP3 (from ton bags). The second study, conducted by Xu et al. (2022) [20], used rPP obtained from disposable tableware collected from local supermarkets. Finally, the review by Nizamuddin et al. (2021) [13] confirmed that the optimal percentage of PP ranges between 3% and 5%, as a review of several studies.

The reviewed studies assessed the viscoelastic properties of bitumen modified with recycled polypropylene (rPP) through DSR testing, focusing on the behavior of the complex modulus $|G^*|$ and phase angle δ . In particular, Xia et al. (2020) [19] reported a general increase in the stiffness [**Figure 10**] of the modified binder compared to the

unmodified one, with significant variations depending on the type of rPP used. Among the three types analyzed, rPP3 stood out for its greater thermal stability, displaying a more balanced performance. Although rPP2 exhibited higher $|G^*|$ values under certain conditions, its phase angle [Figure 11] remained relatively high, indicating lower elasticity. Conversely, rPP3 showed a significant reduction in δ even at 60 °C, suggesting a more elastic and structurally efficient response.

The study by Xu et al. (2022) [20], although lacking a reference sample of virgin bitumen, confirms a similar trend: the consistent evolution of the rheological parameters suggests a stable behavior of the modified binder. Overall, the use of rPP can enhance the performance of bituminous binders, provided that a compatible material is selected, as the polymer's origin and treatment have a substantial impact on the final properties.

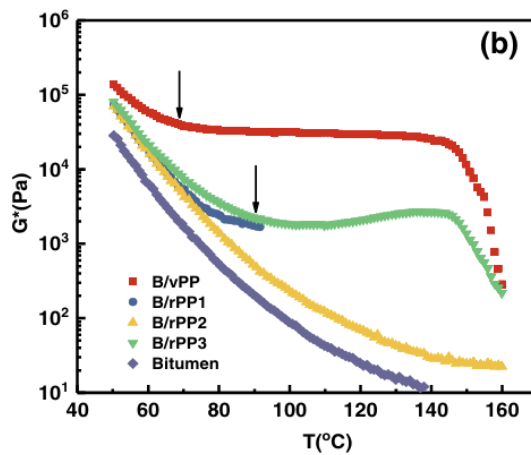


Figure 10 - G^* for PP-modified bitumen [19]

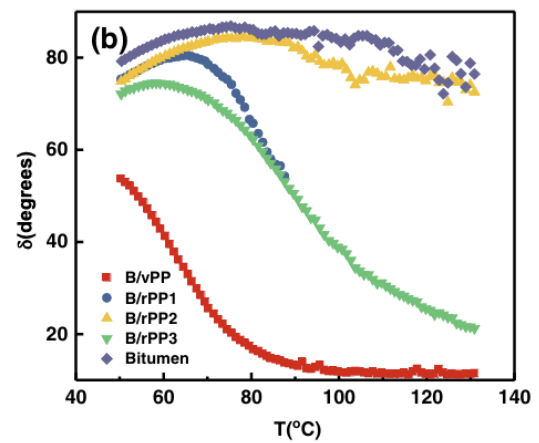


Figure 11 - δ for PP-modified bitumen [19]

Moreover, the study conducted by Xu et al. (2022) [20] provides complementary results of rheological testing, particularly focusing on the rutting factor. It clearly shows that the value of $G^* \sin \delta$ gradually decreases as the temperature increases, as expected. Nevertheless, the value remains high over a wide temperature range, indicating greater stiffness and stability of the bitumen. This is further confirmed by the study of Nizamuddin et al. (2021) [13], which, after a thorough review of additional research, concludes that PP-modified bitumen exhibits improved rutting resistance, especially at high temperatures.

In conclusion, the addition of polypropylene (PP) to bitumen has shown consistent results across the three studies analyzed, improving the rheological properties of the binder at high temperature, especially enhancing its resistance to permanent deformation. However, some critical issues have emerged, mainly related to the poor

compatibility between bitumen and polymer. This incompatibility has led to phase separation, as observed through optical microscopy and to a reduced performance at low temperatures [19]. To address these issues, the study by Xu et al. (2022) [20] proposed a thermomechanical treatment of PP, which allowed for a more homogenous dispersion of the polymer within the bituminous matrix, although it did not fully eliminate segregation phenomenon.

2.3.4. PVC, PS and Category 7 polymers: features and binder modification

Other plastics such as PVC, polystyrene (PS) and polymers categorized under group 7 (as shown in **Figure 1**) have been investigated as bitumen modifiers, although they have attracted less interest due to less favorable properties.

Focusing on polyvinyl chloride (PVC), it accounts for approximately 10.1% of plastic production in Europe and is often referred to as a “poisonous plastic” due to the presence of various toxic compounds that are released upon heating, despite the absence of open flames. Notably, hydrochloric acid (HCl) is emitted in large quantities at high temperatures. [13]

For this reason, the literature recommends the use of PVC only after partial dichlorination via chemical treatments.

Review studies by Nizamuddin et al. (2022) [13], Xu et al. (2021) [7] and Brasileiro et al. (2019) [21], report that PVC recycling and handling practices remain inadequate, particularly in developing countries. However, PVC is primarily recovered from industrial profile, window frames and garden hoses, and has been tested in some studies as bitumen modifier [13,21]. The outcomes, however, have not always been optimal due to PVC’s high melting point (approximately 298 °C), which complicates direct blending with the binder. To address this issue, PVC was crushed into particles ranging from 0.075 to 2 mm and added at an optimal dosage of 5% by weight of bitumen [13,21]. Rheological tests showed an increase in the complex modulus and a reduction in the phase angle, resulting in enhanced rutting resistance at high temperatures. Additionally, a marked reduction in penetration, a significant rise in softening point and an increase in viscosity were observed [7,13,21].

Polystyrene (PS) has been investigated as bitumen modifier, particularly through the dry process, due to its high melting temperature (210 – 249 °C) [7]. The addition of

PS has been shown to increase the stiffness of the binder, raising the softening point, viscosity and improving the rutting resistance at high temperatures [13]. Rheological tests have confirmed that increasing the PS dosage (up to 15%) results in enhanced thermal stability, accompanied by a reduction in penetration values and enhancement of flash point and fire point [13].

Despite all these benefits, the use of PS has several limitations that restrict its range of application. It has the lowest elastic behavior, compared to other polymers, which results in poor flexibility and reduced low-temperature performance, which increases the risk of thermal cracking [7]. Moreover, the compatibility between bitumen and PS is very poor, due to the non-polar nature of the polymer, which leads to a phase separation [13].

Furthermore, PS can release toxic substances when heated above 70 °C, which is a risk not only to melt it, but also in the phase of production and laying asphalt [7]. Another limit is the sensitivity to UV degradation, which leads to surface cracking over time, reducing the long-term durability of PS-modified binders [13].

As it is shown in **Figure 12** a particularly relevant analysis is that of the rutting factor ($G^*/\sin\delta$) as a function of temperature, which also serves as a basis for comparison among the different polymers examined. All materials show a typical viscoelastic behavior, with a progressive decrease in the parameter as the temperature increases – an expected trend in viscoelastic materials. Among the polymers considered, polypropylene (PP) shows the highest values across almost the entire temperature range, showing superior thermal stiffness. In contrast, polyethylene (PE) and polyethylene terephthalate (PET) display a more moderate behavior. Focusing on PVC and PS, marked differences can be observed: PVC demonstrates good thermal stability, maintaining high rutting factor values up to and beyond 85 °C, with a smoother curve and a more gradual decline compared to the other polymers. This behavior indicates greater viscoelastic stability at elevated temperatures, likely due to the chemical structure of PVC, which contains polar groups capable of forming strong intermolecular interactions. On the other hand, PS shows a sharper decline in the rutting factor even at lower temperatures, highlighting its pronounced sensitivity to heat and reduced mechanical performance as temperature increases.

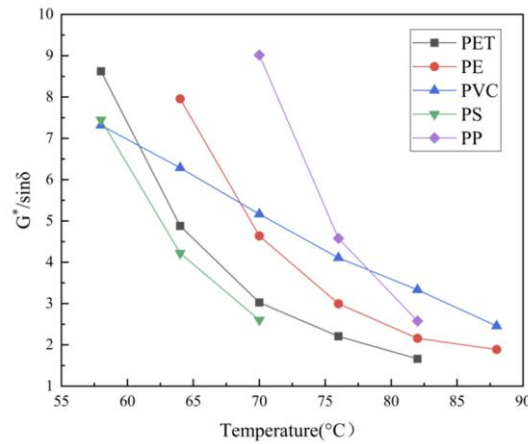


Figure 12 - Rutting factor behavior for different plastic types [7]

Eventually, attention should be given to the group 7 polymers, which include a wide and heterogeneous range of synthetic materials that do not fall into the first six categories. This classification encompasses several high-performance plastics, commonly used in industrial, automotive and electronic applications. Among the most promising for recent experimental studies on bitumen modification are Acrylonitrile Butadiene Styrene (ABS) and Polycarbonate (PC), but the latter is not a recycled polymer. Although widely adopted in other sectors, their application in bitumen modification remains relatively underexplored, presenting a valuable opportunity for the sustainable reuse of technical plastics.

Focusing specifically on ABS the study conducted by Singh et al. (2020) [6] involved the use of waste derived from e-plastics, for instance plastics used in the manufacturing of electronic devices. In this research, ABS was used in powdered form and added to the bitumen in percentage from 1% to 5% by weight. The results demonstrated significant improvements in the rheological and mechanical performance of the modified binder. The optimal effect was observed at a 4% dosage, which led to:

- A 59.71% reduction in penetration compared to the virgin bitumen [6].
- A 56.07% increase of the softening point [6].
- A reduction of viscosity ad temperature increases [6].

Furthermore, the rutting factor also increased at 4%, suggesting enhanced resistance to permanent deformation. Beyond this percentage, however, an inversion in the trend of the curve was noted, as it is shown in **Figure 13**.

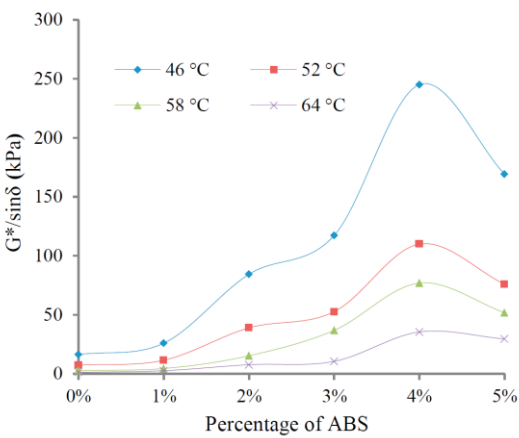


Figure 13 - Effects of ABS on $G^*/\sin\delta$ [6]

2.4. Performance of polymer-modified asphalt mixtures

After analyzing the influence of recycled plastics on the rheological and chemical properties of the bituminous binder, it is essential to extend the investigation to the behavior of the asphalt mixture as a whole. The addition of polymers, in fact, affects not only the binder matrix, but also significantly impacts the mechanical and functional performance of the final mix, such as stability, resistance to deformation, and durability.

Numerous studies have assessed the performance of asphalt mixtures modified with different types of plastics, evaluating their effectiveness in both the short and long term. This section provides a general overview of the behavior of polymer-modified asphalt mixtures, highlighting the main benefits, limitations, and potential challenges identified in the scientific literature.

2.4.1. Modified asphalt mixtures with PET

Polyethylene terephthalate (PET), as discussed in Chapter 2.3, is a highly promising polymer and a focus of several studies on bitumen modification for asphalt mixtures. Due to its high melting point, PET cannot be introduced through the wet process, making the dry process mandatory. Numerous studies have examined the behavior of asphalt mixtures modified with PET via this method, including those by Modarres and Hamed (2014) [22] and Mashaan et al. (2021) [23].

These two studies offer complementary insights: the former focused on the evaluation of the resilient modulus (MR) and fatigue resistance, while the latter investigated the Marshall properties. The indirect tensile strength (ITS) was assessed at two temperatures, 5 °C and 20 °C, highlighting the crucial role of temperature on the mechanical performance of asphalt mixtures. As expected, higher ITS values were recorded at 5 °C due to the increased stiffness of the binder at lower temperatures [Figure 14]. The addition of 2% PET resulted in an increase in ITS at both temperatures, suggesting improved internal cohesion and enhanced adhesion between bitumen and aggregates [22].

However, PET contents above 2% led to a decrease in tensile strength, likely due to excessive binder absorption by PET particles, which reduces the thickness of the bitumen film coating the aggregates and may compromise the mixture's moisture resistance. Nonetheless, all values remained within the acceptable limits [22].

Similarly, the resilient modulus results confirmed the trend observed in the ITS tests: stiffness improved with PET up to 2%, then declined with higher contents [Figure 15]. The study also evaluated the thermal sensitivity of the mixture by analyzing MR variation as a function of temperature. In this context, a 6% PET dosage provided the best thermal stability and was therefore identified as the optimum dosage.

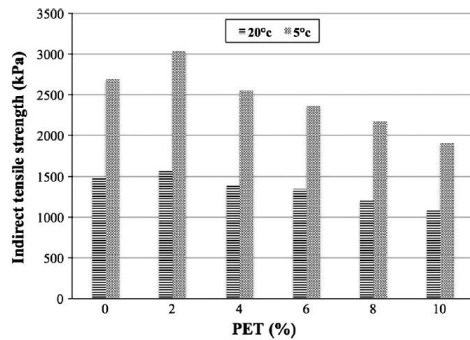


Figure 14 - ITS for PET-modified bituminous mixture [22]

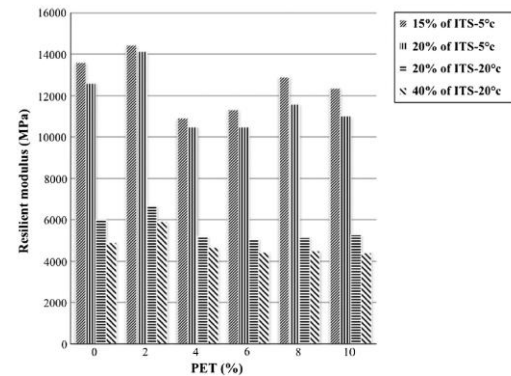


Figure 15 - Resilient Modulus for PET-modified bituminous mixture [22]

The Marshall tests were conducted to evaluate the mechanical performance of asphalt mixture modified with PET, focusing in particular on their resistance to vertical loads and ability to deform without failure. The results reported in the study of Mashaan et al. (2021) [23], show that the addition of PET has a positive effect on Marshall Stability, which increases with higher plastic content. This suggests that the mixtures become more resistant to deformation and cracking under static loads, likely due to the increased stiffness of the bituminous matrix induced by PET.

At the same time, a reduction in Marshall Flow values is observed, indicating less permanent deformation and a stiffer mixture overall. The Marshall Quotient, defined as the ratio between stability and flow, serves as a key indicator of rutting resistance. The highest values were recorded with 6% and 8% PET content [23].

Both studies therefore confirm that the addition of PET enhances the stiffness of the mixture. However, it is essential to adopt a balanced design approach, based on the specific performance objectives, in order to determine the optimal dosage of recycled plastic to be used.

2.4.2. Modified asphalt mixtures with HDPE-LDPE

As discussed in Chapter 2.3.2, polyolefins have a lower melting point and a lower density compared to other types of plastics. These properties make them particularly suitable for use in the wet process, where they are melted and blended directly into

the bitumen to form a homogeneous modified matrix. However, recent studies have also highlighted the potential of polyolefins when used through the dry process. In particular, the works by Rhasbudin Shah et al. (2018) [24] and Heydari et al. (2021) [1] examined the effects of adding these polymers to asphalt mixtures, evaluating their impact on the mechanical properties and durability of the mix.

The study conducted by Rhasbudin Shah et al. (2018) [24] involved heating the aggregates to a temperature between 150 °C and 180 °C, followed by the dry addition of HDPE and LDPE polymers. This process resulted in the formation of a thin film around the aggregate surfaces. Marshall tests were performed to assess stability, flow and volumetric properties, in order to evaluate the performance of the modified mixture.

The results indicated that the most significant improvement in Marshall Stability occurred with the addition of 2% polymer and 5% bitumen, both percentages based on the weight of the aggregates. However, exceeding this bitumen content led to a reduction in stability, due to the mixture becoming softer and less structurally sound [24].

The study by Heydra et al. (2021) [1], on the other hand, carried out similar tests, focusing on the performance of individual polymers. The best results were obtained with higher polymer contents, up to 10% by weight. Among the materials tested, HDPE demonstrated superior performance compared to LDPE, which showed a less consistent trend, likely due to its lower stiffness. Furthermore, the study compared the outcomes of the same tests using both the wet and dry process. The first one proved to be more effective at lower dosages, while the dry one offered greater long-term stability, making it more suitable for applications requiring higher reliability over time [Figure 16]. The trend of the stability value of LDPE is shown in Figure 17. Although the individual polymers improved the mixture performance, the results were inferior to those obtained with the HDPE-LDPE blend [Figure 18]. This suggests a synergistic compatibility between the two materials, combining rigidity and flexibility in a balanced manner that helps optimize the mechanical properties of the asphalt mixtures [1].

Regarding the flow behavior, the study by Rhasbudin Shah et al. (2018) [24] observed a general increase in flow with higher polymer content, reaching optimal values with

a 2% addition of polyolefins and 5% bitumen, both by weight of the aggregates. These results are consistent with the findings of Heydari et al. (2021) for LDPE, where a significant increase in flow number was reported with increasing plastic content, particularly at dosages between 4% and 6% [1].

On the other hand, mixtures containing only HDPE showed more stable flow values, typically ranging between 2.5 and 3.5 mm, suggesting greater resistance to deformation. In this context as well, the use of an HDPE-LDPE blend emerges as the most effective option, offering balanced solution that enhances the ductility of the asphalt mixture without compromising its structural resistance.

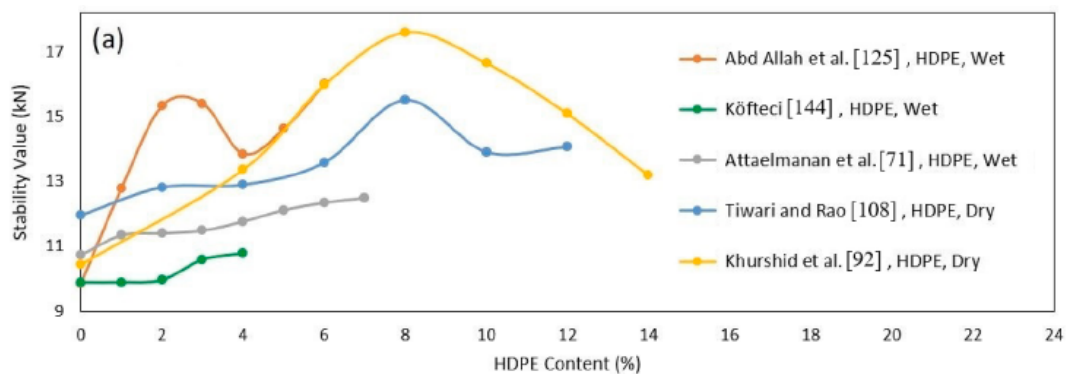


Figure 16 - Stability value for HDPE modified mixtures [1]

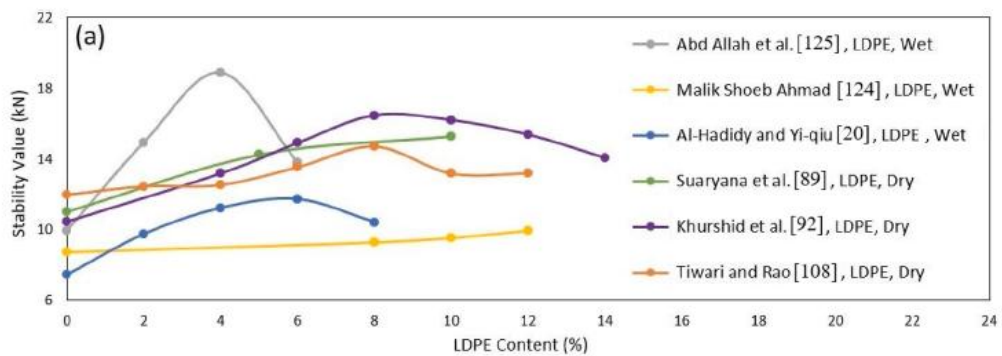


Figure 17 - Stability value for LDPE modified mixtures [1]

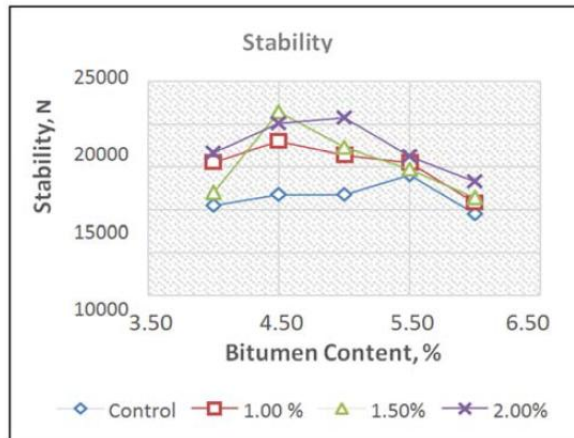


Figure 18 - Stability value for HDPE+LDPE modified mixtures [24]

It is therefore evident, from the literature, that the addition of these polymers improves the overall quality of the asphalt mixtures, particularly when a blend of polyolefins is used. Moreover, their inclusion allows for a reduction in the required amount of bitumen, leading to lower material costs for pavement construction.

This is because the polymers melt when mixed with hot aggregates, and instead of acting as fillers, they tend to interact with and modify the bitumen, effectively enhancing its properties while reducing the total binder demand.

2.4.3. Modified asphalt mixtures with PP

After reviewing the main characteristics of polypropylene (PP) and its effects on bituminous binders, it is also possible to analyze its impact on asphalt mixtures. Several studies have found this type of polymer particularly interesting due to its thermal stability and resistance at high temperatures.

The studies conducted by Otuoze and Shuaibu (2017) [25] and Abdulkhabeer et al. (2021) [26] both employed the wet method to incorporate waste polypropylene (WPP) into the mixtures. The results showed in the second paper, demonstrate that the modified mixtures exhibited higher stability values compared to the control mix, especially when WPP content ranged between 3% and 5%, accompanied by a general increase in the viscosity of the modified binder [Figure 19] [26].

These are also supported by the findings of Otuoze and Shuaibu (2017) [25], who reported improved stability at an optimal HDPP content of 2%, combined with a bitumen content of 5.5% [Figure 20]. Exceeding this value, however, led to a shift in the binder behavior from viscoelastic to overly plastic.

As for flow analysis, the first study [26] reported a sharp decrease in flow with increasing WPP content, dropping from 5.0 mm to 1.2 mm at 5% WPP, indicating a stiffer mix with reduced susceptibility to viscous deformation [Figure 19]. This behavior, closely linked to the increased binder viscosity, could be desirable to resist rutting, although excessively low flow values might also imply brittleness at low temperatures, as observed in the study.

Conversely, the findings by Otuoze and Shuaibu (2017) [25] revealed an increasing trend in flow with higher HDPP percentages, presenting smoother and more regular curves compared to the previous study [Figure 21]. In this case, the mixtures showed balanced flow values, suggesting a more effective compromise between stiffness and ductility.

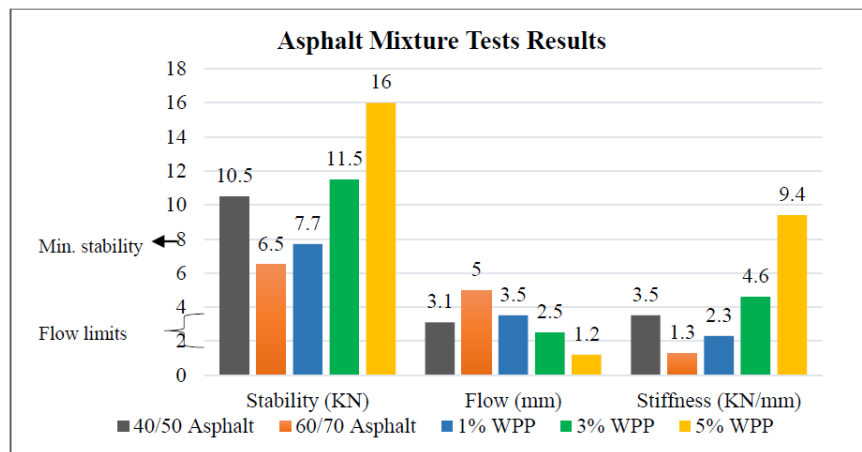


Figure 19 - Asphalt Mixture with WPP Tests Results [26]

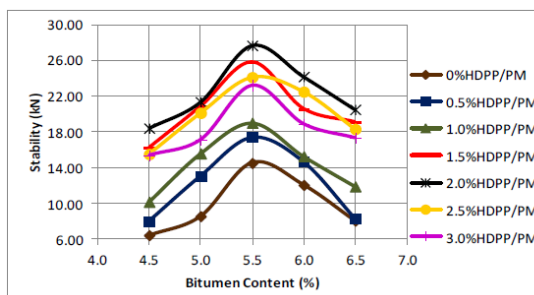


Figure 20 - Stability for HDPP modified mixtures [25]

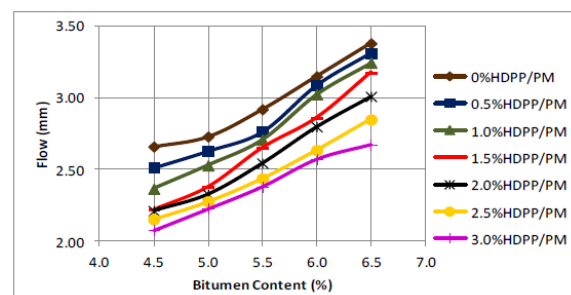


Figure 21 - Flow values for HDPP modified mixtures [25]

2.4.4. Modified asphalt mixtures with PVC, PS and category 7 polymers

Due to their hazardous characteristics, plastics such as PVC, PS and those classified under group 7 (Other) are not commonly used in asphalt mixture modification. This is mainly attributed to the potential release of toxins at high temperatures and the challenges associated with their recycling.

Nevertheless, as with binder modification, some studies have investigated the effect of incorporating these plastics directly into bituminous mixtures. For instance, the study by Rasel et al. (2011) [27] demonstrated that PVC can be evenly dispersed within the mix; however, when used in excessive amounts, it tends to segregate from the bituminous matrix. This behavior is reflected in the Marshall Stability results, which show an increase up to a 10% PVC content, followed by a decline, likely due to the separation of the polymer from the binder phase.

Regarding Marshall Flow, a progressive increase was observed with higher polymer dosages, indicating that the mixture becomes more ductile, but also more prone to permanent deformation. The corresponding results have been summarized and presented in **Table 2**.

Properties	Fresh bituminous mix (5.4% OBC)	% of PVC content							
		2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0
Unit weight (Kg/m ³)	2335	2390	2430	2460	2465	2450	2400	2340	2310
% of air voids	3.99	3.58	3.44	3.21	3.10	4.10	4.70	5.50	7.80
Stability (kN)	13.22	14.50	14.90	15.60	15.90	14	12	10	8
Flow value (0.25mm)	18	19	20.30	22.70	24.50	28	31	35	39
%VMA	18.25	14.88	14.04	13.66	13.32	14.18	15.76	16.21	19
%VFB	71.12	77.34	82.77	85.46	87.96	81.79	72.25	70.01	58.48
Marshall stiffness (kN/mm)	2.94	3.05	2.94	2.75	2.60	2	1.55	1.14	0.82

Table 2 - Properties of bituminous mixes for various percentage of waste PVC [27]

This trend is also reflected in the Marshall Stiffness results, which remain above the minimum required value of 2.10 kN/mm only up to a 10% PVC content. Beyond this point, a marked decline in mechanical performance is observed.

As for Polystyrene (PS), the study conducted by Mei Lim et al. (2024) [28] highlighted its significant impact on the Marshall properties of the mixture. Specifically, stability peaked at dosages between 7.5% and 10%, while higher amount led to reduced performance and polymer segregation. Simultaneously, Marshall Flow increased with higher PS content, indicating that the mixture became more deformable. The study also reported a reduction in air void content up to 10% PS dosage, which is beneficial for the durability of the pavement, as it helps limit the ingress of air and moisture. Overall, the optimal performance was observed at polymer contents ranging between 5% and 10%. The related diagrams are shown in **Figure 22**.

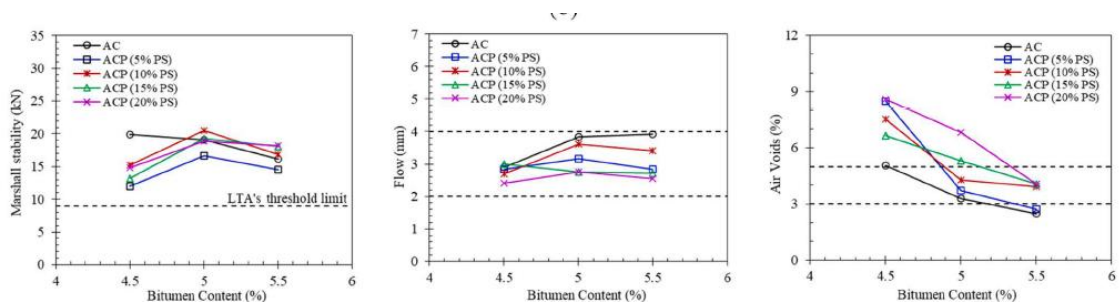


Figure 22 - Marshall Stability, Flow and Air Void value of asphalt concrete mixtures [28]

With regard to the final plastic type from group 7, the selected material was polycarbonate (PC), as investigated in the study by Ovyedepo Olugbenga et al. (2024) [29]. The study used recycled polycarbonate sourced from electronic waste components, with the main objective being the identification of the optimal polymer dosage. To this end, several concentrations were tested, and the optimal content was determined to be 0.5% by weight of the aggregates.

By partially replacing the aggregates, the average Marshall Stability reached 8.25 kN, exceeding the minimum threshold for pavements subjected to heavy traffic (6.672 kN, according to the Asphalt Institute, 1997). The flow value recorded was 3.33 mm, which falls within acceptable limits and indicates good deformability under load. The resulting Marshall Quotient, calculated as the ratio of stability to flow, was 2.47 kN/mm, suggesting a strong balance between stiffness and ductility.

Overall, the results confirm that the addition of polycarbonate yields high-performance mixtures, suitable for roads with high traffic volumes. However, as observed with other polymers, increasing the dosage beyond the optimal point led to

a gradual deterioration in mechanical properties, likely due to segregation of the plastic particles within the mixture.

3. Classification system

3.1. Empirical classification

The characterization of bituminous binders can be carried out through two main approaches: the **traditional method** and the **performance-based** one. The traditional procedure relies on simple empirical tests, which are inexpensive and quick to carry out, while the performance-based approach is grounded on rheological parameters obtained from specific laboratory measurements. Although the traditional method is still widely adopted, it shows clear limitations:

- The testing procedures do not accurately reproduce real service conditions, thus providing only qualitative insights;
- It is not suitable for assessing modified or innovative binders.

The most common empirical tests included in the traditional approach are:

- Penetration test;
- Softening point test;
- Fraass breaking point test;
- Ductility test.

3.1.1. Penetration test

The penetration test evaluates the depth reached by a standard needle when it penetrates a bitumen specimen kept at **25 °C**, under a load of **100 g** applied for **5 seconds**. The outcome provides useful information on the binder's hardness at service temperature: lower penetration values are typical of stiffer binders (minimum reference class 20/30), while higher values identify softer binders (maximum reference class 180/220).

The experimental procedure was performed in compliance with **BS EN 1426:2024** [30]. The device adopted, the penetrometer, is designed with a needle holder moving vertically with negligible friction, ensuring accurate depth measurements with a maximum error tolerance of 0.1 mm. A schematic illustration of the apparatus is reported in **Figure 23**.

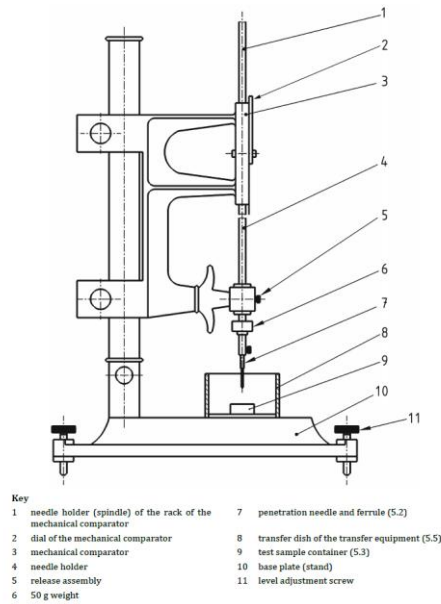


Figure 23 – Schematic representation of a standard penetrometer [30]

Before testing, the combined weight of the needle, ferrule and holder must be checked and kept within 100.00 ± 0.10 g. The penetrometer should also be positioned on a stable, vibration-free surface to guarantee reliable results. Moreover, the geometry of the needle must comply with the specifications set by the standard, which vary depending on the expected penetration range:

- For penetration up to 330×0.1 mm, the needle length should be 50 ± 5 mm;
- For penetration between 330×0.1 m and 500×0.1 mm, the needle must be 42.5 ± 2.5 mm, with the option of extending it further to avoid contact with the specimen during testing.

To improve reliability, the test was repeated three times on the same specimen, and the results were expressed in decimillimetres (dmm).

3.1.2. Ring and Ball Test

The ring-and-ball test, also known as the softening point test, is one of the most adopted methods to characterize bituminous binders at high service temperatures. The procedure is described in the standard **BS EN 1427:2015** [31].

The test involves the preparation of two bitumen discs, each placed within a metallic guiding ring and loaded with a small steel ball. The assemblies are positioned on a metallic support and immersed in a thermostatic bath filled with a heating medium: **water**, when the expected softening point lies between 28°C and 80°C , or **glycerine**

for values above 80 °C. the bath is then heated at a controlled rate of **approximately 5 °C per minute**, causing a gradual decrease in binder consistency until softening occurs.

Two specimens are tested simultaneously, providing independent measurements that are then averaged. The softening point is defined as the temperature at which each specimen undergoes a vertical displacement of **25.4 mm**.

Although it does not represent an intrinsic property of bitumen, this parameter serves as a practical index for binder classification. It is particularly relevant for assessing the suitability of a material to withstand high-temperature conditions, such as those encountered in warm climates or under heavy traffic loads, where excessive softening could compromise pavement performance. A schematic representation of the test is shown in **Figure 25**.

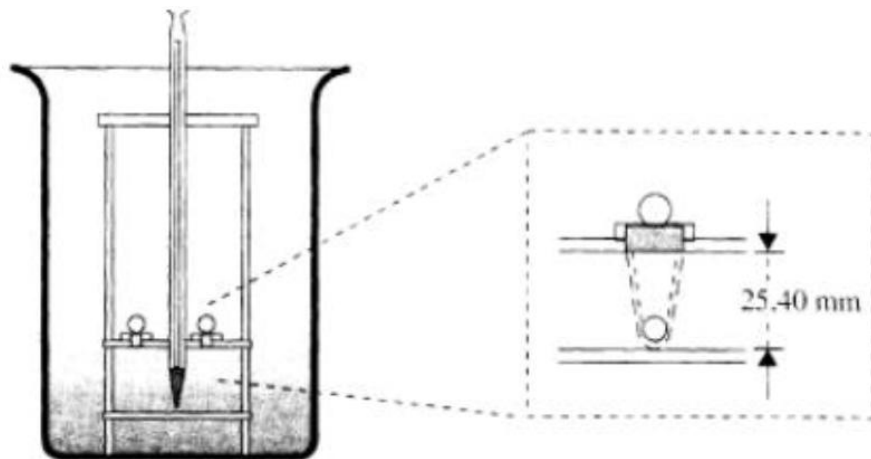


Figure 24 - Ring and Ball Test scheme representation¹

3.1.3. Fraass Breaking Point Test

The Fraass Breaking Point Test is a standard method traditionally used to assess the low-temperature behavior of bituminous binders, particularly their brittleness. The procedure is specified in **UNI EN 12593** [32].

The test employs a device containing a rectangular metal plate, fixed at both ends on which a thin bitumen film of approximately **0.5 mm** is applied. The plate is gradually bent by means of a hand-crank system, while the initial temperature of 10 °C is reduced at a constant rate of about **1 °C per minute** through the use of suitable cooling

¹ Slides from the course *Construction of Transportation Infrastructures* (Master's Degree in Civil Engineering, Politecnico di Torino).

agents. The temperature at which a visible crack appears on the specimen corresponds to the Fraass breaking point temperature, expressed in degrees Celsius.

Although widely used, this test has notable limitations. Its strongly empirical nature leads to low accuracy and repeatability of the results, and the Fraass temperature often shows weak correlation with the actual field performance of asphalt mixtures at low temperatures. Consequently, this parameter is usually regarded as a qualitative indicator of binder fragility rather than a reliable performance-related property. The schematic representation and the apparatus and of the tests are respectively shown in **Figure 25** and **Figure 26**.

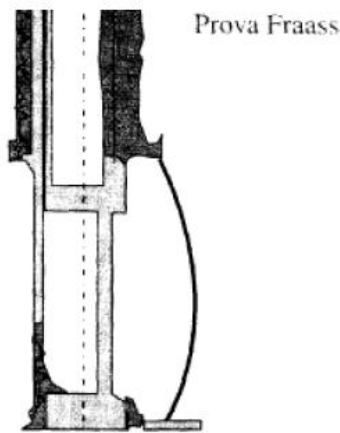


Figure 25 – Schematic representation of the Fraass breaking point test¹



Figure 26 – Apparatus used for the Fraass breaking point test¹

3.1.4. Ductility Test

The ductility test is used to evaluate the tensile behavior of bituminous binders, providing an indication of their ability to undergo plastic deformation before failure. The procedure is standardized by **UNI EN 13589** [33].

The apparatus, known as a ductilometer, consists of a thermostatic water bath maintained at a temperature of **25 °C**, which serves as the reference testing condition. Inside the bath, three binder specimens are prepared in the characteristic “dog-bone” shape [**Figure 27**] and fixed at both ends to two plates: one fixed and one movable. By means of the movable plate, the specimens are elongated at a constant rate of **50 mm/min** until rupture occurs.

The main parameter measured is the maximum elongation, expressed in centimeters, recorded at the point of failure. If rupture does not occur and the movable plate reaches the end of the bath, the result is reported as “over 100 cm”.

Although empirical in nature, this test provides useful insights into the binder's cohesion and tensile strength at intermediate temperatures, properties that are relevant for mitigating cracking phenomena and ensuring pavement durability.

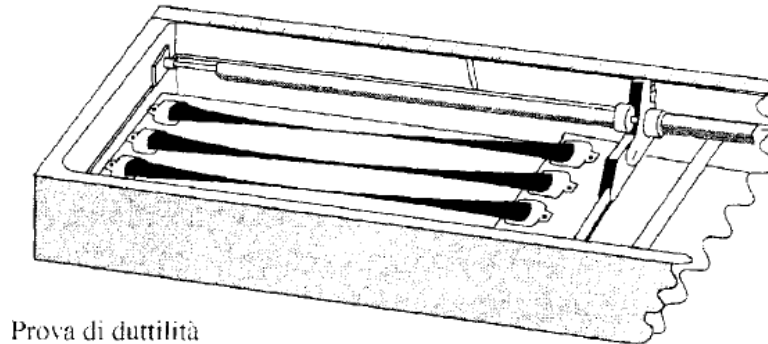


Figure 27 – Schematic representation of the Ductility Test¹

3.1.5. Empirical Parameters Correlation

Individual empirical tests, such as penetration and softening point, provide only limited information, since they describe the binder's behavior under specific and isolated conditions. To achieve a more comprehensive evaluation, it is necessary to introduce derived indices obtained by combining the outcomes of different empirical tests.

A notable example is **thermal susceptibility**, which expresses the variation in binder consistency as a function of temperature. In practice, by plotting the logarithm of penetration against temperature (°C) on a Cartesian diagram [Figure 28], a nearly linear trend is typically observed, which can be expressed as:

$$\log(\text{pen}(T)) = \alpha T + K$$

where α is the slope of the line, representing the thermal susceptibility index, and K is a constant related to the binder. Using penetration values measured at standard temperatures (e.g., 25 °C with a conventional value of 800 dmm), the line can be defined, allowing the binder's behavior with temperature variations to be characterized.

From these correlations, the **Penetration Index (PI)** can be derived, by combining penetration data with the softening point value. This index provides a concise representation of thermal susceptibility: values close to zero denote binders with a

“normal” response, while negative values indicate greater stiffness at low temperatures and positive values highlight increased sensitivity at high temperatures.

The use of PI therefore helps to overcome the limitations of individual empirical tests, offering a valuable comparative criterion for both the traditional classification of binders and the assessment of their suitability under different climatic conditions.

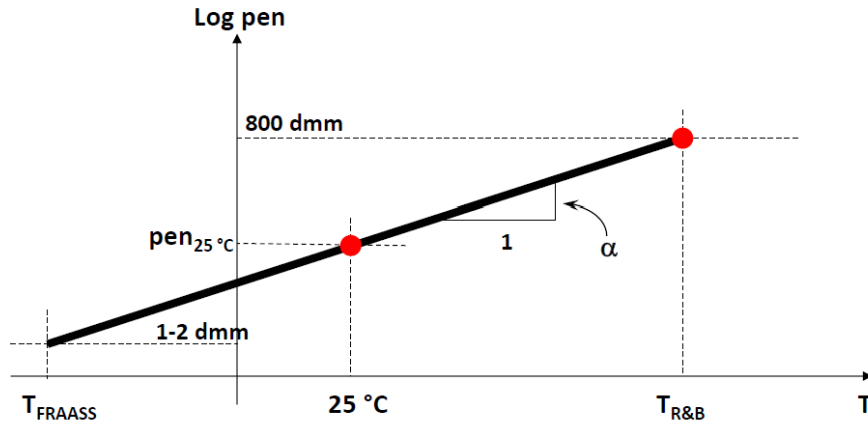


Figure 28 - Linear relationship between $\log(\text{pen})$ and T for evaluating bitumen thermal susceptibility¹

Moreover, the slope is calculated as:

$$\alpha = \frac{\log(800) - \log(\text{pen } 25^\circ\text{C})}{T_{PA} - 25^\circ\text{C}}$$

From which the penetration index can be derived as:

$$IP = \frac{20 - 500 \alpha}{50 \alpha + 1}$$

3.2. Rheology of Bituminous Binders

Since the **performance-based classification system** of binders relies on rheological evaluation, it is essential to fully understand the meaning of rheology and its role in the study of bituminous materials.

Bituminous binders exhibit a particularly complex behavior, which depends on both temperature and loading rate. They are classified as **viscoelastic materials**, as their response changes with conditions: at low temperatures they act predominantly as elastic solids, at high temperatures they behave similarly to a Newtonian viscous fluid, while at intermediate temperatures they simultaneously display both elastic and viscous properties.

The rheological analysis of bituminous binders is grounded in the theory of **viscoelasticity**, which accounts for this dual nature. The theory assumes that bitumen can be treated as a continuous, homogeneous, and isotropic medium, allowing its behavior to be represented through mathematical and analogical models. This framework enables a more accurate description of the binder's performance under varying service conditions, thus overcoming the limitations of purely empirical characterization.

3.2.1. Analogical Models of Viscoelastic Behavior

When analyzing the two limiting cases that serve as fundamental references in rheological studies, it is possible to distinguish between the model of the ideal elastic solid and that of the ideal viscous fluid.

In the first case, the material's behavior can be represented by a spring [**Figure 29**], which follows **Hooke's law**. According to this model, the applied stress is proportional to the resulting strain, with proportionality constants given by the elastic moduli: Young's modulus (E) for longitudinal deformations and the shear modulus (G) for shear deformations. A distinctive feature of the ideal elastic solid is that, once the stress is removed, the strain vanishes instantaneously and the material immediately returns to its original state, without any permanent deformation.



Figure 29 – Analogical model of an ideal elastic solid¹

The second extreme case is that of the ideal viscous fluid, represented by a Newtonian dashpot [Figure 30]. In this model, shear stress is proportional to the strain rate, with viscosity (η) acting as the proportionality factor. A fluid with these characteristics is defined as a Newtonian fluid, whose constitutive relationship is linear. However, viscosity is not a fixed parameter: it changes with temperature, following an exponential trend described by the **Arrhenius equation**. According to this relationship, as temperature increases, viscosity decreases, thereby reducing the fluid's resistance to flow.

Unlike the ideal elastic solid, the Newtonian fluid does not exhibit an immediate recovery of strain under loading. Instead, the deformation increases progressively with time and is proportional to the duration of the applied stress. When the load is removed, the material does not return to its initial configuration but retains a permanent, irreversible deformation.

These two models therefore represent the theoretical extremes of material behavior. In reality, bitumen and, more generally, bituminous binders exhibit an intermediate viscoelastic response, combining features of both elastic solids and viscous fluids.

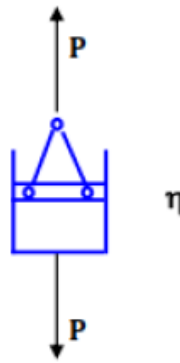


Figure 30 – Analogical model of Newtonian viscous dashpot¹

3.2.2. Viscoelastic Models

The two ideal conditions of an elastic solid and a viscous fluid can be combined to develop simplified models that describe the behavior of viscoelastic materials, such as bituminous binders. Although these are idealized representations, they play a crucial role in interpreting the mechanical response of the material, by combining springs (elastic component) with dashpots (viscous component).

Among the most widely known elementary models is the **Maxwell model**, which consists of a spring and a dashpot arranged in series [Figure 31]. This model is particularly suitable for describing **stress relaxation phenomena**: when a material is subjected to a constant load, the strain increases indefinitely over time, reflecting the permanent component associated with viscosity. At the same time, the elastic element accounts for the partial recovery of deformation once the stress is removed.

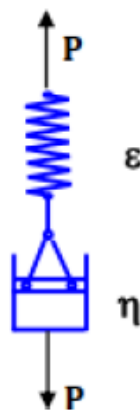


Figure 31 – Maxwell model¹

The **Kelvin-Voigt model** consists of a spring and a dashpot connected in parallel [Figure 32]. This configuration is used to describe the **phenomenon of creep**, namely the progressive deformation that occurs under a constant load. In this case, the strain does not appear instantly but increases gradually over time, while once the stress is removed, the material tends to return to its original configuration, exhibiting a gradual recovery.

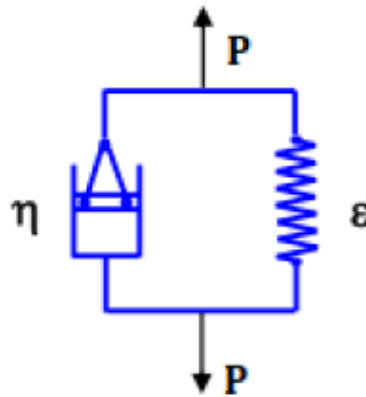


Figure 32 - Kelvin-Voigt Model¹

Beyond the elementary models, more advanced schemes have been developed to better capture the actual behavior of viscoelastic materials. One example is the **Burgers model**¹, obtained by combining the Kelvin-Voigt and Maxwell configurations. This approach makes it possible to represent both the immediate response of the material underload and its long-term behavior, providing a particularly effective tool for describing the viscoelastic properties of bituminous binders.

3.2.3. Rheological Tests

The determination of rheological parameters is carried out through rheometry, which represents the practical application of rheology to material testing. Two main types of tests are commonly employed:

- Tests in continuous regime;
- Tests in oscillatory regime.

Tests in continuous regime allow the evaluation of fundamental quantities by subjecting the material to a **constant load** over time at a given temperature. They mainly include creep tests and stress relaxation tests: in creep, a constant stress (normal or shear) is applied and the resulting strain is measured as it evolves over

time; in relaxation, a constant strain is imposed and the corresponding stress response is recorded.

Oscillatory tests, on the other hand, involve the application of a **sinusoidal or harmonic load**, a condition that realistically simulates the cyclic action induced by traffic on pavements. The material's response is also sinusoidal, but with a phase shift (δ) between stress and strain occurs:

- $\delta = 0^\circ$ corresponds to a purely elastic behavior;
- $\delta = 90^\circ$ corresponds to a purely viscous behavior.

To capture both aspects of the response, the complex modulus is introduced:

$$G^* = G' + G''$$

where G' is the storage modulus (elastic part) and G'' is the loss modulus (viscous part).

Experimental results are often interpreted using graphical tools such as **Black diagrams** and **master curves**. Black diagrams show the relationship between the phase angle and the complex modulus, while master curves are constructed by applying the time–temperature superposition principle, which extends the experimental data to a wide range of reduced frequencies. These tools make it possible to compare different binders and to provide a more complete description of the evolution of their viscoelastic properties.

For a more accurate interpretation and modeling of master curves, mathematical models are often applied. Among them, the **CAM model** (Christensen–Anderson–Marasteanu)¹ is one of the most widely used. It allows experimental data to be fitted into a continuous analytical function, accurately representing the variation of the complex modulus with reduced frequency. Moreover, it enables the extraction of significant parameters that describe the stiffness and the viscoelastic transition of the binder.

The CAM model is particularly suitable for the study of modified bitumen, as it provides a better representation of their performance compared to other models. In this formulation, the complex modulus is expressed as:

$$G^*(w) = G_g \left(1 + \left(\frac{w_0}{w} \right)^{\frac{\log 2}{R}} \right)^{-\left(\frac{mR}{\log 2} \right)}$$

And the phase angle is given by:

$$\delta = \frac{90}{\left(1 + \frac{w_0}{w}\right)^{\frac{\log 2}{R}}}$$

3.3. Performance-based classification system (SUPERPAVE)

The empirical classification system, presented in Chapter 3.1 shows significant limitations that hinder the establishment of a clear link between the physical properties of the binder and its actual field performance. Empirical tests are only reliable when operational conditions are reproduced consistently from one pavement to another and, most importantly, they do not account for the viscoelastic nature of bitumen, whose response depends on both temperature and loading rate.

To overcome these shortcomings, the performance-based classification system was introduced, relying on rheological parameters shown in Chapter 3.2. A decisive step in this direction was provided by the **SHRP** (Strategic Highway Research Program), which led to the development of the **SUPERPAVE** (Superior Performing Asphalt Pavements) **system**. This approach was conceived with the aim of designing asphalt mixtures capable of meeting performance requirements under diverse local climatic and traffic conditions, through advanced design criteria and the use of rheological binder parameters.

Within this framework, binders are categorized according to the **Performance Grade** (PG) system, which defines a temperature range between a maximum value (XX) and a minimum value (-YY), within which the binder must ensure adequate performance. The maximum classification temperature is set above the pavement design maximum temperature, which is calculated as a 7-day moving average measured at a depth of 20 mm below the pavement surface. Conversely, the minimum classification temperature is lower than the pavement design minimum temperature, defined as the average of annual minimum values and measured at the pavement surface.

It should be emphasized that both temperatures refer to the pavement temperatures rather than air temperatures, and are calculated as follows:

$$T_{min,p} = -1.56 + 0.72 T_{min,a} - 0.004 \cdot LAT^2 + 6.26 \cdot \log(H + 25) - z \\ \cdot (4.4 + 0.52 \sigma_{min,a}^2)^{0.5}$$

$$T_{max,p} = 54.32 + 0.78 \cdot T_{max,a} - 0.0025 LAT^2 - 15.14 \cdot \log(H + 25) + z \cdot (9 + 0.61 \sigma_{max,a}^2)^{0.5}$$

Dove:

- $T_{min,a}$ = minimum air temperature;
- $T_{max,a}$ = maximum air temperature;
- LAT = study latitude;
- H = depth at which the temperature is calculated;
- z = reliability coefficient;
- $\sigma_{max,a}$ = standard deviation of maximum air temperatures;
- $\sigma_{min,a}$ = standard deviation of minimum air temperatures.

To determine the Performance Grade (PG), reference is made to the **AASHTO M320** [34] specification, which includes a table divided into four sections. Each section corresponds to a specific temperature range, as illustrated in **Figure 33**.

Performance Grade	PG 46			PG 52							PG 58					PG 64					
	34	40	46	10	16	22	28	34	40	46	16	22	28	34	40	10	16	22	28	34	40
Average 7-day max pavement design temp, °C ^a	<46			<52							<58					<64					
Min pavement design temperature, °C ^a	≥ 34	≥ 40	≥ 46	≥ 10	≥ 16	≥ 22	≥ 28	≥ 34	≥ 40	≥ 46	≥ 16	≥ 22	≥ 28	≥ 34	≥ 40	≥ 10	≥ 16	≥ 22	≥ 28	≥ 34	≥ 40
Original Binder																					
Flash point temp, T 48, min °C	230																				
Viscosity, T 316: ^b max 3 Pa·s, test temp, °C	135																				
Dynamic shear, T 315: ^c G*/sinδ, ^d min 1.00 kPa test temp @ 10 rad/s, °C	46			52							58					64					
Rolling Thin-Film Oven Residue (T 240)																					
Mass change, ^e max, percent	1.00																				
Dynamic shear, T 315: ^c G*/sinδ, ^d min 2.20 kPa test temp @ 10 rad/s, °C	46			52							58					64					
Pressurized Aging Vessel Residue (R 28)																					
PAV aging temperature, °C ^f	90			90							100					100					
Dynamic shear, T 315: ^c G* sinδ, ^d max 5000 kPa test temp @ 10 rad/s, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13	31	28	25	22	19	16
Creep stiffness, T 313: ^g S, max 300 MPa m-value, min 0.300 test temp @ 60 s, °C																					
Direct tension, T 314: ^h Failure strain, min 1.0% test temp @ 1.0 mm/min, °C																					

- ^a Pavement temperatures are estimated from air temperatures using an algorithm contained in the LTPP Bind program, may be provided by the specifying agency, or by following the procedures as outlined in M 323 and R 35.
- ^b This requirement may be waived at the discretion of the specifying agency if the supplier warrants that the asphalt binder can be adequately pumped and mixed at temperatures that meet all applicable safety standards.
- ^c For quality control of unmodified asphalt binder production, measurement of the viscosity of the original asphalt binder may be used to supplement dynamic shear measurements of G*/sinδ at test temperatures where the asphalt is a Newtonian fluid.
- ^d G*/sinδ = high temperature stiffness and G* sinδ = intermediate temperature stiffness.
- ^e The mass change shall be less than 1.00 percent for either a positive (mass gain) or a negative (mass loss) change.
- ^f The PAV aging temperature is based on simulated climatic conditions and is one of three temperatures, 90°C, 100°C, or 110°C. Normally the PAV aging temperature is 100°C for PG 58-xx and above. However, in desert climates, the PAV aging temperature for PG 70-xx and above may be specified as 110°C.
- ^g If the creep stiffness is below 300 MPa, the direct tension test is not required. If the creep stiffness is between 300 and 600 MPa, the direct tension failure strain requirement can be used in lieu of the creep stiffness requirement. The m-value requirement must be satisfied in both cases.

Figure 33 - Performance-Graded Asphalt Binder Specification [34]

Temperature intervals are established using a constant step of 6 °C. The classification table is divided into four sections, each serving a distinct purpose: the first specifies the performance grade PG (XX-YY), while the others address safety requirements and the evaluation of binder durability under different aging conditions, namely in its

original state, after short-term aging, and after long-term aging. Non-performance-related tests are performed only on the unaged binder, focusing on essential safety and workability requirements, such as a flash point above 230 °C and a viscosity of at least 3 Pa·s at 135 °C [34].

3.3.1. Dynamic Shear Rheometer (DSR)

The **Dynamic Shear Rheometer (DSR)** is a high-precision instrument used to characterize the rheological properties of asphalt binders. It applies torsional stresses to cylindrical specimens, allowing the evaluation of both the elastic and viscous behavior of the material over a wide range of temperatures and loading frequencies.

Sample preparation follows standardized procedures established by current regulations, depending on the type of test to be performed. The device consists of two opposing plates: a fixed lower plate and a movable upper plate connected to a mechanical arm that can be adjusted with great accuracy. The testing cell is enclosed in a thermostatic chamber, which isolates the specimen from external conditions and ensures stable testing temperatures. To extend the range of analysis, the DSR is coupled with an external cryostat, enabling measurements at temperatures far below or above ambient levels.

Depending on the experimental setup, two main geometries can be employed: the **parallel plate system** [Figure 34], with two flat opposing plates, and the **cone–plate system** [Figure 35], which combines a flat lower plate with an upper conical plate, ensuring uniform specimen thickness during testing.

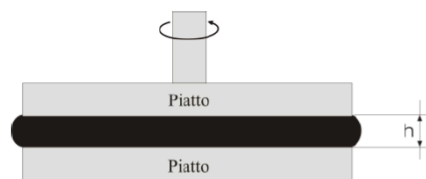


Figure 34 – Parallel plate configuration¹

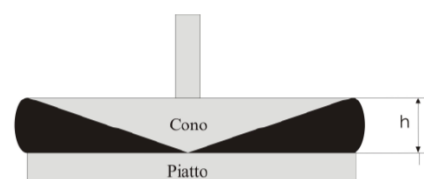


Figure 35 - Cone-Plate configuration¹

The diameter of the DSR plates can vary, with four standard options available: 4 mm, 8 mm, 25 mm, and 50 mm. The choice of diameter depends on the test conditions and the temperature of analysis: at higher temperatures, when the binder becomes more fluid, larger plates are typically used, whereas at lower temperatures, where the binder is stiffer, smaller plates are preferred.

In the parallel plate configuration, the test is conducted under **continuous shear**, and the main parameters are calculated as follows:

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

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

where T is the applied torque, r the plate radius, h the specimen thickness, and φ the rotation angle.

For the cone–plate configuration, the governing equations are expressed as:

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

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

with θ representing the cone angle. This setup provides a uniform shear strain across the entire specimen surface, making it particularly suitable for high-precision rheological measurements.

3.3.2. Multiple Stress Creep Recovery (MSCR)

In this study, aimed at the rheological characterization of asphalt binder, the Dynamic Shear Rheometer (DSR) was used to perform the **Multiple Stress Creep Recovery (MSCR)** test, in accordance with **AASHTO T350 – 19 (2023)**¹ [35] and **ASTM D7405-24** [36]. Prior to testing, the binder sample was subjected to short-term aging using the RTFOT procedure to simulate service conditions.

The main purpose of the MSCR test is to assess the elastic response of the binder, namely its ability to deform under shear stress and to partially recover once the load is removed. The testing setup consists of two parallel plates with a diameter of **25 mm** and a gap of **1 mm**.

The complete procedure includes 20 load-recovery cycles: the first ten performed under an applied stress of 0.1 kPa, followed by ten cycles at 3.2 kPa. Each cycle comprises a 1-second loading phase and a 9-second recovery phase. The typical material response is illustrated through stress–strain curves, as shown in **Figure 36**.

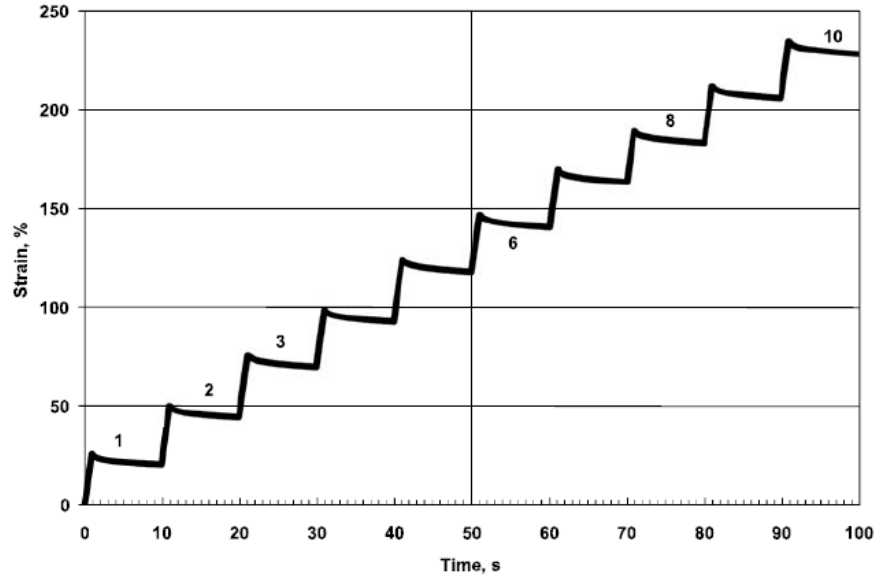


Figure 36 - Test Data Plot showing typical 10 cycles of creep and recovery [35]

The parameters evaluated for each cycle are the following:

- ϵ_0 = initial strain;
- ϵ_c = strain at the end of the creep portion (1 s);
- $\epsilon_1 = \epsilon_c - \epsilon_0$ = adjusted strain value at the end of the creep portion (1 s);
- ϵ_r = strain value at the end of the recovery portion (10 s);
- $\epsilon_{10} = \epsilon_r - \epsilon_0$ = adjusted strain value at the end of the recovery portion (after 10 s);
- $\epsilon_r (0.1;N) = \frac{(\epsilon_1 - \epsilon_{10}) * 100}{\epsilon_1}$ = percent recovery (tension 0.1 kPa);
- $\epsilon_r (3.2;N) = \frac{(\epsilon_1 - \epsilon_{10}) * 100}{\epsilon_1}$ = percent recovery (tension 3.2 kPa).

With N as number of cycles (for N = 1 to 10).

Based on the above-mentioned quantities, it is possible to derive additional parameters namely:

- $R_{0.1} = \frac{SUM[(\epsilon_r(0.1;N))]}{10}$ = calculating average percent recovery at 0.1 kPa;
- $R_{3.2} = \frac{SUM[(\epsilon_r(3.2;N))]}{10}$ = calculating average percent recovery at 3.2 kPa;
- $J_{nr} (0.1; N) = \frac{\epsilon_{10}}{0.1}$ = Nonrecoverable creep compliance for the last 10 cycles at 0.1 kPa;
- $J_{nr} (3.2; N) = \frac{\epsilon_{10}}{3.2}$ = Nonrecoverable creep compliance at 3.2 kPa;

- $J_{nr0.1} = \frac{SUM[J_{nr}(0.1;N)]}{10}$ = average nonrecoverable creep compliance at 0.1 kPa;
- $J_{nr3.2} = \frac{SUM[J_{nr}(3.2;N)]}{10}$ = average nonrecoverable creep compliance at 3.2 kPa;
- $J_{nr diff} = \frac{[J_{nr3.2} - J_{nr0.1}] * 100}{J_{nr0.1}}$ = percent difference in nonrecoverable creep compliance between 0.1 kPa and 3.2 kPa.

Based on the analysis of the $J_{nr3.2}$ parameter, it is possible to determine the so-called **High PG**, namely the highest temperature at which the binder still meets the specified limits. This approach is part of the broader evolution of the Superpave system: the original classification, established by AASHTO M320 [34], relied exclusively on the results of DSR and BBR tests and was suitable for conventional binders. However, the widespread use of modified binders highlighted the need for parameters more sensitive to viscoelastic behavior and elastic recovery.

To address this issue, the **AASHTO M332-23** [37] specification was introduced, incorporating the results of the Multiple Stress Creep Recovery (MSCR) test into performance grading [Figure 37]. Within this framework, the $J_{nr3.2}$ parameter serves as a key indicator of resistance to permanent deformation under repeated loading, with threshold values depending on the expected traffic level (standard, heavy, very heavy, extremely heavy), as reported in **Table 3**:

Traffic							
STANDARD		HEAVY		VERY HEAVY		EXTREMELY HEAVY	
$J_{nr3.2} \text{ max}$ [kPa]	4.5	$J_{nr3.2} \text{ max}$ [kPa]	2.0	$J_{nr3.2} \text{ max}$ [kPa]	1.0	$J_{nr3.2} \text{ max}$ [kPa]	0.5

Table 3 - Limit values of $J_{nr3.2}$

At this point, the High PG can be defined as the highest temperature at which the reference limit is satisfied.

Classification system

Performance Grade:	PG 46			PG 52							PG 58				
	34	40	46	10	16	22	28	34	40	46	16	22	28	34	40
LTPPBind calculated max pavement design temp, °C ^b	<46			<52							<58				
Min pavement design temp, °C ^b	≥34	≥40	≥46	≥10	≥16	≥22	≥28	≥34	≥40	≥46	≥16	≥22	≥28	≥34	≥40
Original Binder															
Flash point temp, T 48, min °C	230														
Viscosity, T 316: ^c max 3 Pa·s, test temp, °C	135														
Dynamic shear, T 315: G*/sinδ, min 1.00 kPa test temp @ 10 rad/s, °C	46			52							58				
Rolling Thin-Film Oven Residue (T 240)															
Mass change, max, percent ^d	1.00														
MSCR, T 350: Standard Traffic “S” J _{nr3.2} , max 4.5 kPa ⁻¹ J _{nr0.05} , max 75% ^e test temp, °C	46			52							58				
MSCR, T 350: Heavy Traffic “H” J _{nr3.2} , max 2.0 kPa ⁻¹ J _{nr0.05} , max 75% ^e test temp, °C	46			52							58				
MSCR, T 350: Very Heavy Traffic “V” J _{nr3.2} , max 1.0 kPa ⁻¹ J _{nr0.05} , max 75% ^e test temp, °C	46			52							58				
MSCR, T 350: Extremely Heavy Traffic “E” J _{nr3.2} , max 0.5 kPa ⁻¹ test temp, °C	46			52							58				
Pressurized Aging Vessel Residue (R 28)															
PAV conditioning temp, °C/ ^f	90			90							100				
Dynamic shear, T 315: “S” G* sin δ, ε max 6000 kPa δ, ε min 42° test temp @ 10 rad/s, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13
Dynamic shear, T 315: “H,” “V,” “E” G* sin δ, max 6000 kPa test temp @ 10 rad/s, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13
Creep stiffness, T 313: ^h S, max 300 MPa m-value, min 0.300 test temp @ 60 s, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30
Direct tension, T 314: ^h Failure strain, min 1.0% test temp @ 1.0 mm/min, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30

Figure 37 - Performance-Graded Asphalt Binder Specification (MSCR) [37]

3.3.3. Bending Beam Rheometer (BBR)

The determination of the low performance grade (**Low PG**) is carried out using the **Bending Beam Rheometer (BBR)**, in accordance with **AASHTO T313-12** [38] and **BS EN 14771-2023** [39]. This test is designed to evaluate the viscoelastic properties of asphalt binders at low temperatures by measuring the mid-span deflection of a bituminous beam supported at both ends and subjected to a constant load applied at the center.

After being prepared according to the standard procedure, the specimen is placed in a temperature-controlled bath and conditioned for about one hour to ensure thermal equilibrium. The test is then performed by applying a center load of 980 ± 50 mN for

240 seconds, while recording the deformation values at 8, 15, 30, 60, 120, and 240 seconds.

The collected data are used to calculate both the flexural stiffness and the relaxation parameter of the binder, which are essential for assessing its resistance to thermal cracking. A schematic representation of the testing device and setup is provided in **Figure 38**.

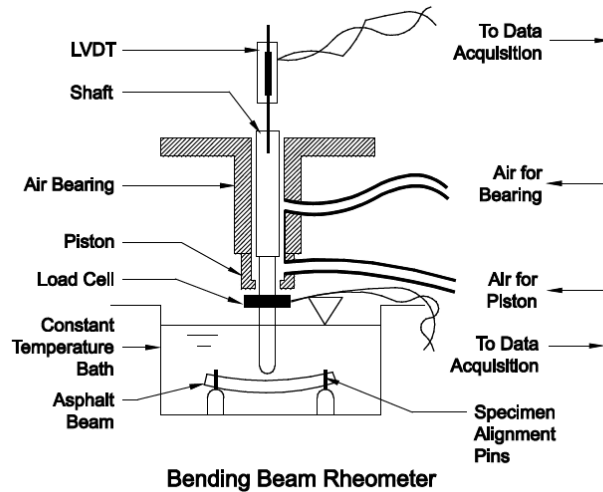


Figure 38 - Bending Beam Rheometer Schematic representation [38]

The Bending Beam Rheometer test also relies on the time–temperature superposition principle. In practice, the long-term behavior of the binder at low temperatures can be simulated in the laboratory over shorter testing times by increasing the test temperature. Therefore, instead of applying a load for 2 hours at the actual minimum design temperature, the test is performed at a temperature 10 °C higher, with the load applied for only 60 seconds. This approach reproduces the same effect that would occur in service conditions, but within a shorter and more manageable laboratory timeframe.

The main outputs of the test are:

- S_{60} : the flexural stiffness of the specimen after 60 seconds of loading;
- m_{60} : the creep rate, representing the rate of change of flexural stiffness over time.

Within the SUPERPAVE classification system, performance limits are imposed on PAV-aged binders: the flexural stiffness must not exceed **30 MPa**, and the m_{60} value must be at least **0.300**. These limits were introduced to control internal stresses during

the cooling process and to ensure that the binder maintains sufficient stress relaxation capacity.

By interpolating the test results at different temperatures, it is possible to determine the critical temperature governing the binder's behavior, which defines the lowest temperature corresponding to the Performance Grade (PG).

3.4. Aging tests

As highlighted in the previous chapter, the **SUPERPAVE system** relies on the evaluation of asphalt binders in different aging conditions, in order to reproduce the changes occurring throughout the material's service life. Asphalt binder aging is indeed one of the main factors contributing to pavement deterioration, together with temperature and loading time. This phenomenon results from the combined effect of traffic loads and environmental conditions, which gradually and irreversibly reduce pavement performance. From a physico-chemical standpoint, aging is associated with changes in the binder driven by temperature and oxygen exposure.

Two main types of aging can be distinguished:

- **Short-term aging**, which occurs during the initial stages of binder life and accounts for the effects of mixing, transport, and paving operations. It is characterized by the high temperatures reached during production and placement.¹
- **Long-term aging**, which develops during the service life of the pavement and is primarily associated with traffic loads and environmental conditions, thus occurring at in-service temperatures.¹

During short-term aging, three main mechanisms are involved:

- **Volatilization**, corresponding to the loss of the lighter fractions of the binder;¹
- **Oxidation**, namely the reaction between oxygen and binder components;¹
- **Polymerization**, leading to the formation of intermolecular bonds and macromolecules.¹

In long-term aging, the volatile components have already been depleted, so the dominant processes are oxidation and polymerization, mainly induced by environmental factors such as solar ultraviolet radiation and in-service temperatures. Consequently, the upper pavement layers, which are more exposed to these agents, age more rapidly than the underlying ones.

Overall, aging produces two major effects on asphalt binders:

- an increase in stiffness;
- a reduction in elasticity.

To quantitatively assess the impact of aging not only on the chemical composition but also on the rheological properties of asphalt binders, an **Aging Index (AI)** is commonly employed, defined as:

$$AI = \frac{I_{inv}}{I_{tq}}$$

where I_{inv} is the property measured after aging and I_{tq} the corresponding value for the unaged binder.

3.4.1. Rolling Thin Film Oven Test (RTFOT)

The **Rolling Thin Film Oven Test (RTFOT)** is a laboratory procedure used to simulate the short-term aging of asphalt binder. The purpose of this test is to reproduce the combined effect of heat and oxygen on a thin film of binder.

In this study, the procedure followed the specification **BS EN 12607-1:2014** [40]. To provide a broader and more consistent methodological framework, the guidelines defined in **AASHTO T240-19** [41] and **ASTM D2872-19** [42] were also consulted.

For the execution of the test, eight cylindrical glass containers were prepared, each filled with 35 ± 0.5 g of asphalt binder. After preliminary preheating of the containers, the binder, once sufficiently fluid, was poured and gently rotated within the glass to coat the inner surface and form a thin film of a few millimeters. Once all containers were filled, the samples underwent a **1-hour conditioning phase**.

At the end of this stage, the containers were placed in the **sample-holding space** of the oven, equipped with dedicated slots [**Figure 39**]. The oven, preheated to **163 °C**, was operated with an air flow of **4000 ± 300 mL/min** and a rotation speed of **15 ± 0.2 r/min**. The combined effect of heat and oxygen on the binder was assessed by measuring either the percentage mass change or the variation in the binder's rheological properties.

After loading the samples, the standard requires the oven temperature to stabilize at **163 ± 1.0 °C** within the first 10 minutes; this interval is not considered as part of the official test duration. The test itself lasts **75 ± 1 minutes**, after which each container is removed and the remaining binder collected, ensuring that at least **90 %** of the material is recovered on average, including both the portion freely draining from the container and that retrieved with dedicated spatulas.

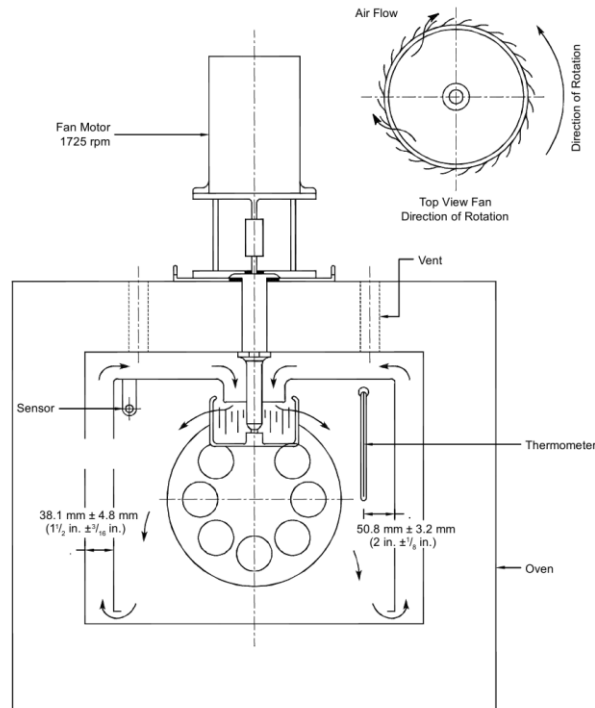


Figure 39 - Rolling Thin Film Oven Scheme [41]

3.4.2. Pressure Aging Vessel (PAV)

The long-term aging of asphalt binder is simulated using the **Pressure Aging Vessel (PAV)**. Although this test does not accurately reproduce the actual aging rates occurring in service, it is designed to replicate the rheological changes that asphalt binder undergoes over the pavement's service life [43].

The procedure was performed in accordance with **BS EN 14769:2023** [44]. To ensure methodological consistency, additional guidance from **AASHTO T240-21** [45] and **ASTM D2872-19** [43] were also considered.

The material used in the PAV test was derived from samples previously conditioned with the RTFOT procedure. Approximately 31.5 g of binder were recovered from each specimen and placed into pans, each with a mass of 50 ± 0.5 g. The pans were positioned within a pan holder [**Figure 41**], which was then placed inside a sealed chamber subjected to pressure and controlled temperature.

The oven was preheated to 100 °C, and once this temperature was reached, the pans were introduced into the chamber. After allowing sufficient time for thermal equilibrium to be restored – compensating for the temperature drop caused by sample

insertion – the chamber was pressurized to 2.1 MPa. Once all parameters were stabilized, the test was automatically started and carried out for a total duration of 20 hours. The representation of the entire instrument is shown in **Figure 40**.

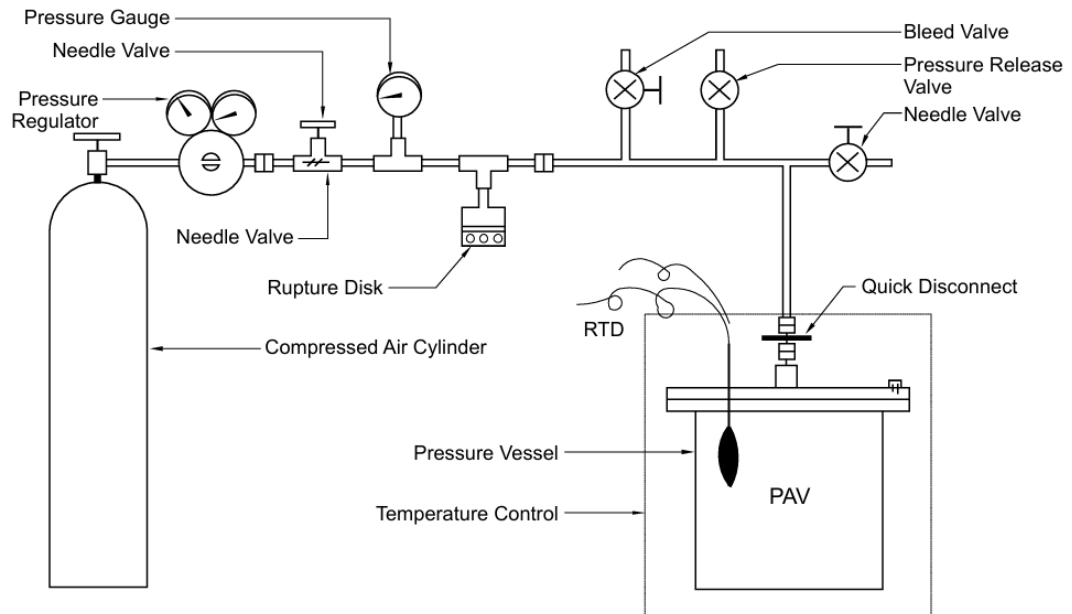


Figure 40 - Schematic of Typical PAV Test System [36]

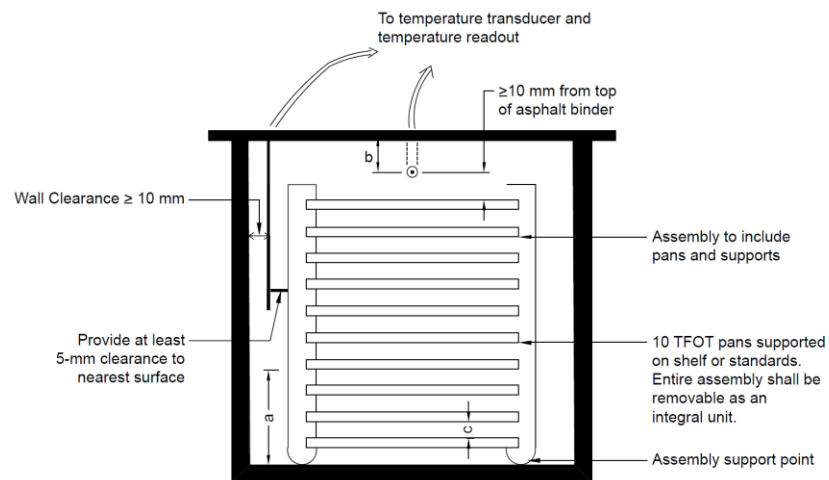


Figure 41 - Schematic showing locations of Pans [45]

3.5. Frequency Sweep Test

After having described the empirical and performance-based classification systems, as well as the simulation methods of asphalt binder aging, it is appropriate to examine those rheological techniques that allow for a more comprehensive characterization of binder behavior. Within this framework, the **Frequency Sweep Test** plays a crucial role. Although it is not included in the standard protocols defined by the SUPERPAVE system, it represents a highly valuable tool in both scientific research and experimental practice.

The procedure adopted in this study follows the **AASHTO T 315-12** [46], standard, which specifies the method for determining the rheological properties of asphalt binders using the Dynamic Shear Rheometer (DSR). According to the standard, the test employs parallel plate geometry [**Figure 42**] and enables the determination of the complex modulus (G^*) and phase angle (δ) within a range between 100 Pa and 10 MPa, typically observed at temperatures between 6 °C and 88 °C with an angular frequency of 10 rad/s [46].

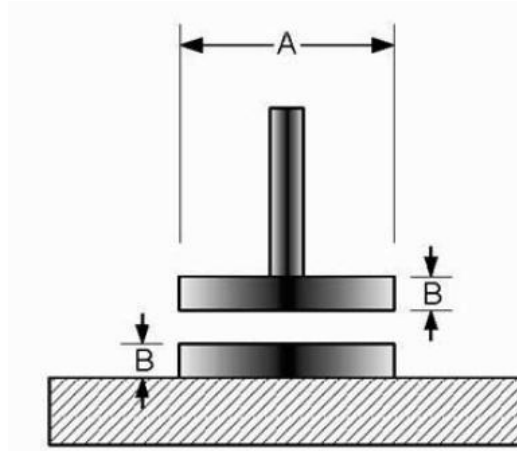


Figure 42 - Parallel Plate configuration for Frequency Sweep Test [46]

The analysis of the results allows distinguishing between the elastic component (storage modulus, G') and the viscous component (loss modulus, G''), thus describing the dual viscoelastic nature of asphalt binders. Furthermore, the standard highlights that the DSR operates within the **linear viscoelastic regime (LVE)**, meaning under conditions in which the binder's response does not depend on the magnitude of the applied stress or strain, thereby ensuring the reliability of the measurements.

The data obtained from the frequency sweep can be reprocessed to construct Black diagrams, which directly relate the complex modulus to the phase angle, and to develop master curves, based on the time–temperature superposition principle. These tools extend the experimental results across a wider frequency spectrum, simulating real traffic conditions characterized by different loading times.

From an applicative perspective, the insights provided by the frequency sweep are particularly relevant for comparing binders with different degrees of aging or modified with additives and rejuvenators, as in the present study. Moreover, the parameters derived from the test provide the basis for the application of rheological models (such as the CAM model or viscoelastic analogical models), which enable a continuous and predictive description of binder behavior.

Therefore, although not part of the normative classification protocols, the frequency sweep test constitutes an essential step for the advanced and in-depth characterization of asphalt binders.

4. Experimental campaign

This chapter presents the experimental program carried out, with the aim of providing a clear and comprehensive overview of the materials employed, the equipment used, and the methodologies adopted during the laboratory tests.

4.1. Materials

4.1.1. Bituminous binder

Bitumen is a complex mixture of paraffinic and aromatic hydrocarbons with high molecular weight, mainly obtained from crude oil refining. Its specific chemical nature provides distinctive properties, such as thermoplastic behavior and adhesive capacity, which enable its use in more than two hundred different applications, approximately 85% of which are related to road pavements¹.

From a molecular perspective, bitumen is sometimes described as a dispersed system composed of different fractions, whose balance influences its response under service conditions: elastic at low temperatures, visco-plastic at intermediate temperatures, and fluid at high temperatures.

In this study, a conventional **70/100 penetration grade bitumen** was employed, classified according to European standards based on the penetration test.

4.1.2. Characteristics of Plastic A

The polymer used for bitumen modification, referred to as “**Plastic A**”, is a recycled plastic material supplied in multicolored flakes. It is a polyolefin-based blend, mainly composed of polyethylene (PE) and polypropylene (PP), obtained through the mechanical recycling of post-consumer plastic packaging collected from municipal waste sorting. Due to its characteristics, this blend is not suitable for manufacturing packaging intended for direct contact with food.



Figure 43 - Plastic A

Although it may contain traces of additives, lubricants, or stabilizers, these components are not present in quantities sufficient to classify the product as hazardous. Thanks to its composition and thermoplastic properties, **Plastic A** is suitable for hot processing and can therefore be effectively applied in combination with bitumen. Its main physical and chemical properties are summarized in **Table 4**, providing a clear and concise overview to support the experimental analysis.

Property	Value
Physical state	Solid
Form	Flakes
Color	Multicolor
Odor	Slight
Melting point	50 – 170 °C
Boiling point	Not applicable
Flammability	The polymer burns, but ignition is not easy
Oxidizing	Not considered an oxidizing agent
Decomposition temperature	Not determined
Auto-ignition temperature	>300 °C
Density	960.2 Kg/m ³
Water solubility	Insoluble
Relative vapor density	Not applicable
Vapor pressure	Not applicable
Explosive properties	No data available

Table 4 - Chemical and physical properties of Plastic A

4.1.3. Characteristics of Plastic B

The polymer referred to as “**Plastic B**” in this study is a plastic material derived from a combination of industrial and post-consumer waste, mainly composed of polypropylene (72%), polyamide (17%), and a fraction of elastomers (11%). The blend was supplied in different particle size classes, ranging from more than 4 mm to less than 1 mm.

To accurately characterize the material, reference was made to the results of a parallel experimental thesis, in which *differential scanning calorimetry (DSC)* tests were performed. The analysis revealed thermal peaks corresponding to polypropylene and polyamide, thereby confirming the composition across the different fractions.



Figure 44 - Plastic B

The coexistence of these three polymers suggests a potentially complex behavior when used for bitumen modification. On the one hand, the combination of polypropylene, polyamide, and elastomers may provide an advantageous balance between mechanical strength and flexibility. On the other hand, some challenges may arise, particularly during the mixing phase. Specifically, the presence of polyamides, which exhibit a relatively high melting point compared to bitumen, may lead to only partial melting of the material, affecting its dispersion and interaction with the bituminous matrix. This aspect highlights the need for careful optimization of processing parameters to achieve an effective and stable modification.

4.1.4. Characteristics of Plastic C

The polymer identified as “**Plastic C**” is a compound produced from techno-selected recycled plastics, specifically designed for the modification of bituminous mixtures through the “dry” method. The material was supplied in gray granules with a diameter ranging from 2 to 4 mm. The blend consists of **95% post-consumer recycled plastic** and **5% virgin material**.

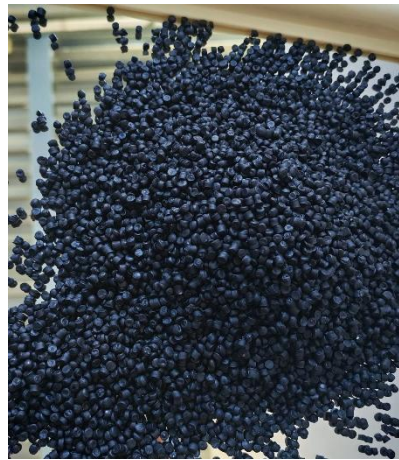


Figure 45 - Plastic C

The recycled plastics used were recovered from waste streams that would otherwise not be included in conventional recycling cycles and were subjected to a patented technological selection process. Due to these features, **Plastic C** represents a sustainable modifier suitable for bituminous binders, with a recommended dosage typically ranging from 4% to 10% by binder weight.

Its main physical and chemical properties are summarized in **Table 5**, its composition enhances the mechanical strength and complex modulus of the binder, reduces

permanent deformation under repeated loading, and improves fatigue performance. These characteristics highlight its potential to extend the service life of asphalt pavements.

Property	Value
Appearance	Granules
Color	Shades of grey
Bulk density at 25 °C	0.4 – 0.6 g/cm ³
Softening point	160 – 180 °C

Table 5 - Physical characteristics of Plastic C

4.2. Preparation of the plastic material

4.2.1. Quartering

In order to ensure the representativeness of the samples to be tested, the plastic material was initially subjected to quartering, carried out in accordance with **BS EN 12697-28:2020** [47]. This procedure allows for a controlled reduction of the original mass while preserving the initial particle size distribution.

In practice, the material was first arranged in a conical shape and then remixed three consecutive times, each time reshaping it into a new cone. As shown in **Figure 46**, the cone was flattened and divided along two orthogonal diameters, resulting in four equal parts. Two opposite quarters were retained, while the other two were discarded. This operation was repeated until the target mass was obtained, corresponding to approximately four times the amount required for each specimen.

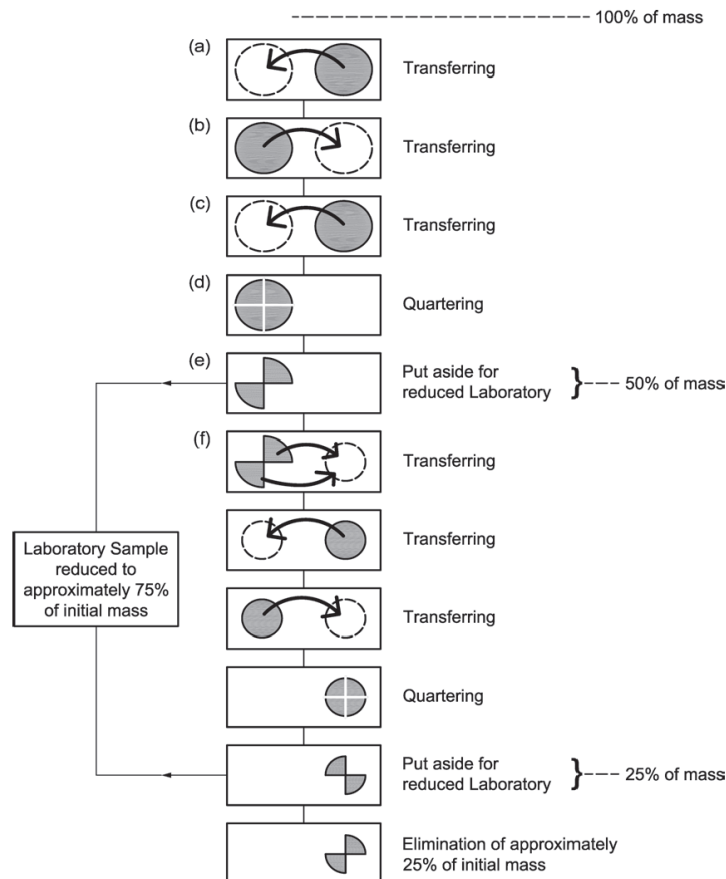


Figure 46 - Quartering method for reducing laboratory sample mass [47]

In addition to the standardized procedure, **Figure 47** illustrates the quartering phases carried out in the laboratory for the preparation of the **Plastic B** sample. The same

methodology was applied to **Plastic A** and **Plastic C**, ensuring consistency in the preparation of all materials.

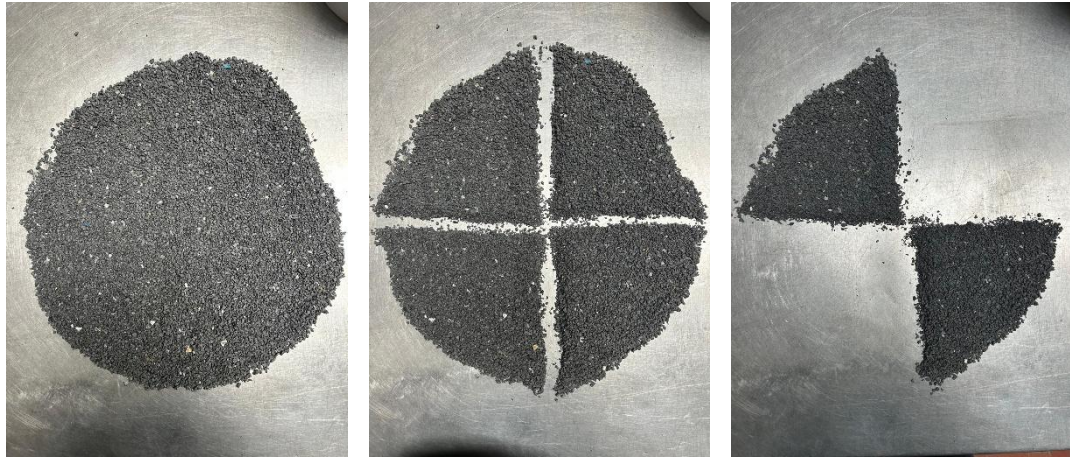


Figure 47 - Laboratory quartering process applied to Plastic B

4.2.2. Grinding process

Given the heterogeneous nature of the post-consumer plastics used in this study, consisting of polymers with different physical and thermal properties, it was necessary to address certain preliminary challenges. One of the main issues is the high melting point of some components, which represents a significant obstacle to the application of the **wet process**, where mixing is carried out at high temperatures.

To promote a more effective interaction between the plastic particles and the bituminous matrix, it was therefore decided to reduce the size of the plastic material through a mechanical crushing process. This approach made it possible to increase the surface area of the particles, improving their dispersion within the binder and, consequently, the overall homogeneity of the mixture.

For this purpose, a high-speed grinder *MoonGiantGo* [Figure 48] was used, which allowed part of the plastic material to be almost completely pulverized. Although the device is typically employed in domestic settings for grinding dry foods and was not originally designed for high-hardness materials, it was nonetheless used for experimental purposes thanks to its performance, reaching **36,000 rpm** with a maximum capacity of **800 g**.

Since the plastic material exhibits considerably higher mechanical resistance compared to the food products, it was necessary to modify the operating conditions recommended by the manufacturer, which specified three minutes of continuous

processing. Specifically, the procedure was carried out through short cycles lasting between 1 and 1.5 minutes, followed by cooling pauses of approximately 15 minutes, in order to prevent overheating of the equipment and minimize the risk of motor damage.



Figure 48 - High-speed grinder MoonGiantGo

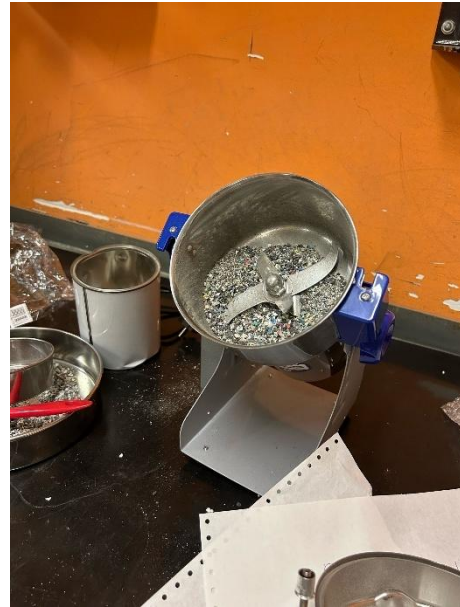


Figure 49 – Grinder process

To optimize the performance of the equipment and achieve a cleaner fracture of the material, the plastic was previously subjected to a **freezing process** lasting approximately **two hours**. This treatment made the material more brittle and, consequently, easier to crush.

After the crushing process, the material was subjected to a **sieving stage** using a **1 mm mesh sieve** [Figure 50], which allowed the separation of the passing fraction from the retained one. Both fractions were subsequently employed in the mixing phase, in predefined proportions, in order to preserve the particle size distribution resulting from the crushing process. This methodological choice was made to ensure the representativeness of the sample with respect to the original material, avoiding the exclusion of a significant portion of the plastic.



Figure 50 - Manual sieving of the fragmented sample using a 1 mm sieve

During the crushing operations, some significant differences emerged among the various types of plastics, mainly related to their physical characteristics and mechanical behavior during shredding.

Plastic A did not show any particular issues: the process was carried out smoothly, with a good yield of fine material. At the end of the operation, the distribution between the finer and coarser fractions appeared balanced, indicating an overall uniform and effective crushing process.



Figure 51 – Fine Fraction Plastic A

Plastic B exhibited a slightly softer consistency compared to **Plastic A**, a feature that facilitated a more intensive crushing process. As a result, a higher proportion of

pulverized material was obtained relative to the retained fraction, indicating a greater tendency toward size reduction.



Figure 52 - Fine Fraction Plastic B



Figure 53 - Coarse Fraction Plastic B

Plastic C proved to be the most challenging case among the analyzed materials. During the crushing process, the finer fraction tended to develop an almost pasty consistency, with a marked tendency to agglomerate, which complicated both the sieving operations and the subsequent processing steps. At the same time, the coarser fraction contained oversized particles, not compatible with hot mixing requirements. For this reason, the portion retained by a 4 mm mesh sieve was excluded from the sample, with this value being considered as a critical threshold based on the results of a parallel experimental study. This operation was feasible in the case of **Plastic C** because it is a processed product, characterized by a more homogeneous composition compared to the other two materials. This ensured that the sample remained representative even after the exclusion of the coarser fraction.



Figure 54 - Fine Fraction Plastic C



Figure 55 - Coarse Fraction Plastic C

The different fractions obtained from the crushing process for each type of plastic are presented in **Table 6**.

Material	Fine Fraction [g]	Coarse Fraction [g]
Plastic A	52	40.2
Plastic B	80.7	46
Plastic C	47.7	97

Table 6 - Fine and Coarse Fraction weights

The discarded portion, corresponding to the fraction retained by the **4 mm sieve**, amounted to **7.8 g**.

4.3. Mixing process

Once the preparation and selection of the plastic material were completed, the mixing phase was carried out using the **wet process**, with the aim of ensuring a homogeneous distribution of plastic particles within the bituminous matrix. As highlighted in the literature, this phase is of crucial importance, since the rheological properties of the binder largely depend on the quality of mixing and the degree of interaction between the polymer and the maltene fraction.

To ensure consistency across the analyzed samples, a standardized procedure was adopted, keeping the main operating parameters constant: temperature, mixing time, and stirring speed.

4.3.1. Mixing Equipment

The equipment used for the mixing process consisted of a system comprising a heating plate and a high-speed mechanical stirrer, the **Silverson L5M-A** [Figure 56]. This device is well known for its versatility and reliability and is widely employed in various laboratory and industrial applications, including mixing, disintegration, emulsification, and material dispersion.



Figure 56 – Silverson L5M-A

The device is equipped with a mixing head [Figure 57], responsible for the disintegration and dispersion of the material through an intense shear action, which ensures both repeatability and efficiency of the tests. For the experimental activity

carried out in this study, the **Square Hole High Shear Screen** configuration was employed, specifically designed to provide rapid solid disintegration and proper distribution within the binder matrix.

The operating principle of the instrument relies on the high-speed rotation of the blades inside the mixing head, which generates strong suction of the material from the bottom of the container towards the center. At the same time, the aspirated material is expelled radially at high velocity against the container walls, thus ensuring continuous recirculation and promoting a uniform dispersion of the particles.



Figure 57 – Square Hole High Shear Screen

4.3.2. Mixing procedure

To ensure an effective mixing process, it was necessary to take into account the operational limitations of the equipment. For this reason, **550 g of bitumen** were used, a quantity considered suitable to guarantee the complete immersion of the mixing head. Subsequently, considering the optimal polymer contents recommended in the literature with respect to bitumen weight [13,17,18], and taking into account the amount of plastic material available in the laboratory, a dosage of **5% by bitumen weight** was selected. The total amount of plastic was then proportionally divided between the fine and coarse fractions, in order to preserve the relative proportions of the different types of plastics within the mixture.

As for the bitumen content in the mixture, it was deemed necessary to define both a minimum and maximum percentage in line with the values specified in the SIIV

Specifications [48]. The reference percentages, reported in **Table 7**, were recalculated through proportioning with respect to the total mixture (bitumen + aggregates):

$$5 : 100 = x : 105$$

$$6.5 : 100 = x : 106.5$$

Where:

- 5 represents the minimum percentage of bitumen specified in the standard.
- 6.5 represents the maximum percentage of bitumen specified in the standard.
- 100 is the mass of the aggregates.
- 105 is the total mass of the mixture, considering the minimum content.
- 106.5 is the total mass of the mixture, considering the maximum content.
- x is the required percentage of bitumen in the total mixture.

Tipologia Impiego	AC32 Base	AC22 Base	AC20 Binder ¹	AC16 Binder ²	AC12 Usura ³	AC10 Usura ⁴	PA11 Usura	SMA11 Usura
Setacci [mm]	Granulometria Passante [%]							
63	100							
31,5	90-100	100						
22		90-100	100					
20	69-82	-	90-100	100				
16		55-85	-	90-100	100		100	100
12,5		-	-	-	90-100	100		-
11,2		-	-	-	-	-	90-100	90-100
10		-	56-68	73-80	-	90-100		-
8	45-56	35-60	-	-	70-90	70-90	20-40	50-65
6,3		-	-	-	-	-		-
5,6		-	-	-	-	-		35-45
4		25-50	37-48	45-56	40-55	40-55		-
2	21-31	20-35	23-33	28-38	25-38	25-38	15-25	20-30
0,5	10-17	6-21	11-17	14-22	14-20	14-20	8-16	-
0,25	6-12	4-16	6-12	7-14	10-15	10-15		-
0,063	4-7	4-8	4-7	4-8	6-10	6-10	5-8	8-12
Contenuto di legante [%] (riferito alla massa degli aggregati)								
	4,0-5,3	4,0-5,5	4,2-5,8	4,5-6,0	5,0-6,5	5,0-6,5	5,0-6,0	6,0-7,5

Table 7 - Linee Guida SHV [48]

At this stage, it was possible to determine the amount of polymer required for bitumen modification, for each type analyzed in the study:

Mix Data		
Minimum binder content	5.25	[%]
Maximum binder content	6.92	[%]
Binder amount	550	[g]
Plastic Dosage	5	[%]

Table 8 – Composition data of the bituminous mixture

Plastic A				
Fine fraction [g]	Coarse fraction [g]	Total [g]	Dosage Fine [g]	Dosage Coarse [g]
52	40.2	92.2	15.51	11.59
Plastic B				
Fine fraction [g]	Coarse fraction [g]	Total [g]	Dosage Fine [g]	Dosage Coarse [g]
80.7	46	126.7	17.52	9.98
Plastic C				
Fine fraction [g]	Coarse fraction [g]	Total [g]	Dosage Fine [g]	Dosage Coarse [g]
47.7	89	136.7	9.60	17.90

Table 9 – Mass and dosage distribution of plastic additives

Once the sample weight and the required amount of material were defined, the actual mixing phase was carried out, structured in the following main steps:

1. **Pre-heating of the bitumen** to 190 °C, in order to achieve a mixing temperature of 180 °C, taking into account the expected heat loss during transfer.
2. **Gradual addition of plastics:** to prevent the formation of lumps, the plastics were progressively introduced into the mixture during the first 10 minutes.
3. **Final mixing:** the resulting blend was then mixed for an additional 15 minutes, for a total duration of approximately 25 minutes.

Throughout the entire process, a stirring speed of **5000 rpm** was maintained, while ensuring that the temperature remained close to 180 °C, thereby allowing for consistent comparison of the samples produced with the different types of plastic.



Figure 58 - Mixing process

During the mixing operations, the initial temperature was slightly below 180 °C, but with the aid of the heating plate it was quickly restored to the target value. Only in the case of **Plastic A** mixing was a peak of about 190 °C recorded, which was immediately corrected by lowering the temperature.

Mixing with **Plastic A** and **Plastic B** did not present significant issues, except for the coarser fractions, which showed some difficulty in fully melting within the bituminous matrix. In contrast, the mixing of **Plastic C** proved more challenging: the fine fraction tended to agglomerate into lumps, while the coarse fraction was difficult to melt due to its high melting temperature.

From the resulting blends, a first visual assessment could be carried out. The mixture containing **Plastic A**, shown in **Figure 59**, displays a relatively smooth surface, though slightly non-uniform, with some indications of partial material segregation.



Figure 59 - Plastic A modified binder

The mixture containing **Plastic B**, shown in **Figure 60**, proved to be the most promising among those analyzed, displaying a highly homogeneous surface appearance with a compact and glossy texture, free of visible irregularities.



Figure 60 - Plastic B modified binder

Finally, the mixture containing **Plastic C** exhibits a markedly irregular and porous surface, characterized by the presence of visible microbubbles and a granular texture. Its appearance is considerably less glossy compared to the other two mixtures, as shown in **Figure 61**.



Figure 61 - Plastic C modified binder

4.4. Experimental procedures

4.4.1. Experimental program

After the material preparation phase, an experimental campaign was carried out to characterize the bituminous binders, both in their original form and in the modified version with the addition of plastic polymers. The selected tests aimed to investigate the material's behavior at different scales and under various operating conditions.

Specifically, the following were performed:

- **Empirical tests**, mainly used to characterize the binder in its original state and to provide an initial direct comparison between the base bitumen and the modified one;
- **Dynamic rheological tests**, conducted with the Dynamic Shear Rheometer (DSR), including the *Frequency Sweep* and *Multiple Stress Creep Recovery (MSCR)* tests, aimed respectively at constructing the master curves and assessing resistance to permanent deformation;
- **Bending Beam Rheometer (BBR) tests**, carried out to evaluate the material's performance at low temperatures, performed after long-term aging to simulate real pavement service conditions.

Table 10 summarizes all the tests performed for each material under the different ageing conditions. The sample codes were defined according to the following convention: the letter **P** followed by the type of plastic (**A**, **B**, **C**) identifies the modified material, while the final letter indicates the aging condition (**O** = **original**, **R** = **RTFOT**, **P** = **PAV**). Number **5** refers to the percentage of plastic incorporated into the mixture.

Materiale	Condizione di invecchiamento	Frequency Sweep Test	MSCR	BBR	Ring and ball	Penetration
O	Originale	✓	-	-	✓	✓
R	RTFOT	✓	✓	-	-	-
P	PAV	✓	-	✓	-	-
PA5_O	Originale	✓	-	-	✓	✓
PA5_R	RTFOT	✓	✓	-	-	-
PA5_P	PAV	✓	-	✓	-	-
PB5_O	Originale	✓	-	-	✓	✓
PB5_R	RTFOT	✓	✓	-	-	-
PB5_P	PAV	✓	-	✓	-	-
PC5_O	Originale	✓	-	-	✓	✓
PC5_R	RTFOT	✓	✓	-	-	-
PC5_P	PAV	✓	-	✓	-	-

Table 10 - Summary of experimental tests carried out for each binder and ageing state

4.4.2. Penetration Test Procedure

The test, already introduced in *Chapter 3.1.1*, was carried out in accordance with the procedure described in **BS EN 1426:2024 [30]**. It was performed exclusively on bitumen samples modified with the three polymers considered, in their original condition.

The first step involved the preparation of the specimens. Each blend was heated until the bitumen became sufficiently fluid to be poured into the appropriate containers. The materials were then left to rest at room temperature for approximately 60 minutes. Once cooled, the surface of the specimens was checked to ensure it was adequately leveled and free of defects. No issues were encountered for the specimens modified with Plastic A and Plastic B, whereas for the one containing Plastic C (**Figure 61**), it was necessary to place it in a ventilated oven for up to 30 minutes at 80 °C to allow for self-leveling. This was followed by an additional cooling step. After complete cooling, the specimens were immersed in a thermostatic bath filled with distilled water and conditioned for 60 minutes at 25 °C in a dedicated refrigerator.

The choice of container was not arbitrary but based on the dimensional requirements established by the relevant standards, as summarized in **Table 11**.

Penetration [0,1 mm]	Internal depth P mm	Internal diameter D mm	Approx. volume of sample cm ³
Penetration < 160	$35 \leq P \leq 60$	$55 \leq D \leq 70$	80
$160 \leq \text{penetration} < 330$	$45 \leq P \leq 60$		170
$330 \leq \text{penetration} \leq 500$ ^a	$45 \leq P \leq 70$		230
^a Determination is performed at 15 °C and the result is between (90 × 0,1) mm and (360 × 0,1) mm.			

Table 11 - Dimensions of the standard test sampel container [30]

Once the specimen was prepared, the test was carried out, preliminarily verifying that the total mass of the instrument, including the needle, was **100 g**. Subsequently, it was checked that the needle was clean and free of defects, in order to avoid possible distortions of the results. Finally, a functional inspection of the equipment was performed to ensure that the vertical movements were smooth and free of friction.

The test was conducted using the penetrometer manufactured by *Matest S.r.l.*, shown in **Figure 62**.



Figure 62 – Penetrometer

For the execution of the test, the needle was positioned so that its tip was just in contact with the surface of the specimen [**Figure 63**]. At least three penetrations were performed using different needles, keeping a minimum distance of **10 mm** from the specimen edge and between the measurement points.



Figure 63 - Positioning of the needle for the penetration test

4.4.3. Ring and Ball Test Procedure

The test, already described in *Chapter 3.1.2*, was carried out in accordance with the procedure specified in **BS EN 1427:2015 [31]**. The equipment used, shown in Figure 64, is an automatic device manufactured by *Matest S.r.l.*, capable of detecting the softening of bitumen through a sensor and recording the corresponding softening temperature.



Figure 64 - Automatic Ring and Ball apparatus (Matest S.r.l.)

The first step consists in the preparation of the specimen. For this purpose, a thin layer of release agent was applied on a plate, on which brass rings were placed. The

bitumen, previously heated to reach a sufficiently fluid state, was then poured into each ring in a slightly excessive amount [**Figure 65**].



Figure 65 - Pouring of bitumen into the brass rings (slightly excessive amount)

After pouring, the bitumen was left to rest at room temperature for **30 minutes**. After this period, the excess material was removed using a heated spatula, in order to obtain a smooth and even surface [**Figure 66**].



Figure 66 - Leveled bitumen specimens after excess removal with a heated spatula

At this stage, the test could be carried out. Since the softening temperature (T_s) was below 80 °C, distilled water was used as the immersion fluid for the specimens.

The entire apparatus (rings, plate, water, and balls) was preconditioned in a refrigerator to reach an initial temperature of $(5 \pm 1) ^\circ\text{C}$, maintaining the conditioning for at least 15 minutes and not exceeding 20 minutes. Once the setup was placed on the testing device [**Figure 67**], the test was initiated by applying a heating rate of **5 °C per minute**. The metal balls, previously cooled, were then positioned according to the indications of the testing equipment.

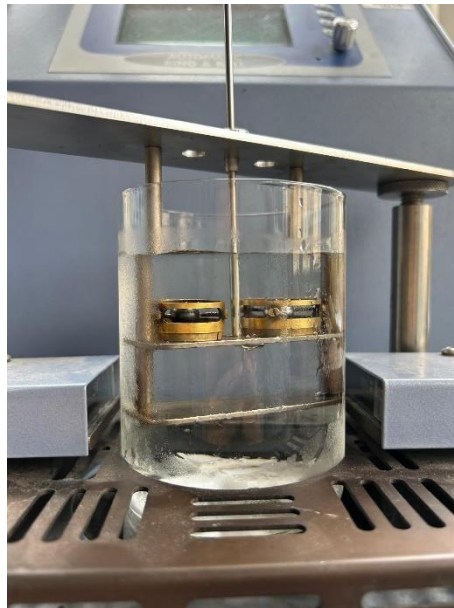


Figure 67 - Placement of bitumen rings inside the bath for the Ring and Ball Test

During the first three minutes after the start of the test, the temperature gradient may be irregular; thereafter, it must remain within the range of **4.4 to 5.6 °C per minute**, otherwise the test is considered invalid.

The test ends when both specimens reach the underlying plate, as shown in **Figure 69**.



Figure 68 - Specimens during the Ring and Ball Test

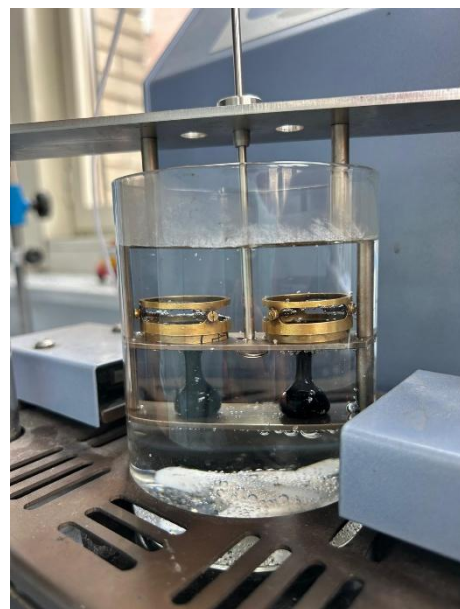


Figure 69 - Completion of the Ring and Ball Test

4.4.4. Rolling Thin Film Oven Test Laboratory Test

The protocol adopted for short-term aging was the one specified in **AASHTO T 240-21** [41], already introduced in *Chapter 3.4.1*. The procedure was repeated for each material blend, with particular attention paid to the cleanliness of both gloves and equipment, to avoid any contamination that could compromise the test.



Figure 70 - RTFOT Oven



Figure 71 - Pouring of bitumen for RTFOT



Figure 72 - Preparation of the film for RTFOT



Figure 73 - Cooling of RTFOT samples

At the end of the test, and after removing the residual material with the aid of a spatula, the beakers were placed inside the **Carbolite**, which allows the temperature to reach

530 °C. In this way, the bituminous binder is completely combusted, and once the container has cooled, the residues can be removed.

4.4.5. Pressure Aging Vessel Laboratory Test

As described in *Chapter 3.4.2*, the procedure adopted for the execution of the test followed the standard **BS EN 14769:2023** [44].

Before starting the test, it was necessary to check that all the dishes used were free from shape irregularities and properly cleaned. Immediately after the completion of the RTFOT test, the material was poured into the dishes, which were then placed inside the pan holder, specifically the one shown in **Figure 74**.



Figure 74 - Pan Holder

According to the standard, once the test has started, the temperature and pressure values must not deviate from the specified ranges for more than **30 minutes**. In the case of this study, for the bitumen modified with the three polymers, an out-of-range period of approximately **8 hours** was recorded for each test.

Nevertheless, it was decided to use the resulting material in order to avoid waste, since the pressure deviation observed was only **0.10 MPa**, a value considered practically negligible.

The bitumen aged in the **PAV** appeared as follows:



Figure 75 - Neat Bitumen PAV-Aged



Figure 76 - Bitumen with Plastic A PAV-Aged



Figure 77 - Bitumen with Plastic B PAV-Aged



Figure 78 - Bitumen with Plastic B PAAged

4.4.6. Bending Beam Rheometer Test Procedure

The BBR test, described in *Chapter 3.3.3*, was carried out in accordance with **BS EN 14771:2023** [39] using the device shown in **Figure 79**. The test was performed on all the materials analyzed in this study after PAV aging.

The equipment consists of a loading frame with specimen support and a loading shaft that applies force at the center of the beam. The shaft is connected to a load cell and a transducer, which respectively measure the applied force and the resulting deformation. In addition, the apparatus includes a temperature-controlled bath filled with ethanol, ensuring stable thermal conditions during the test.



Figure 79 – Bending Beam Rheometer

Before proceeding with specimen preparation and the start of the test, calibration of the equipment was required. After filling the bath with liquid (96° alcohol), the test temperature was set via the dedicated software, and sufficient time was allowed for stabilization. The correct calibration of the temperature was then verified using a precision thermometer.

The deflection constants were subsequently defined and calibrated with the tools provided by the BBR manufacturer. Once the temperature calibration was completed, a waiting time of approximately 30 minutes was observed before proceeding. In addition, calibration of the applied load was carried out using metal beams, also supplied by the manufacturer.

For specimen preparation, the bitumen was heated until it reached a sufficiently fluid consistency to be poured in excess into standard-size molds, previously assembled [Figure 80, Figure 81].



Figure 80 - Pouring bitumen into BBR molds

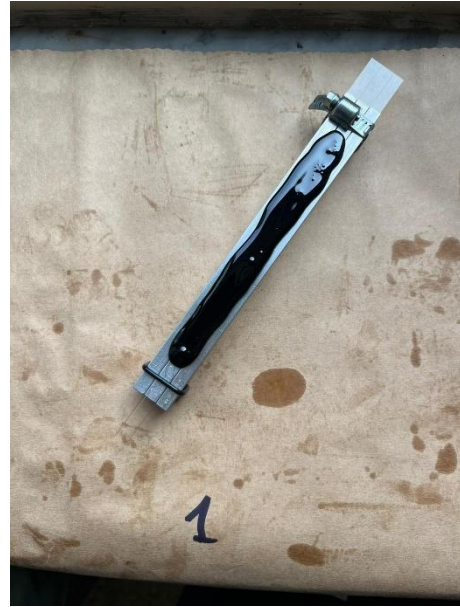


Figure 81 - Excess bitumen in BBR molds

The molds used for specimen preparation consisted of metal bars held together by clamps and lined with plastic strips, applied to facilitate the demolding of the bitumen. The strips were fixed to the bars using glycerin, and it was essential to ensure they were free of bubbles or irregularities that could compromise the quality of the final specimen.

After **15 minutes** from pouring, the excess bitumen was removed using a preheated spatula [Figure 82]. The specimens were then left to rest for an additional **30 minutes**, for a total of **45 minutes at room temperature**. At the end of this stage, the samples were placed in a freezer for a maximum of **5 minutes**, then quickly demolded and immersed in the conditioning bath, where they remained for **one hour**. After conditioning, each specimen was placed on the supports to perform the bending test, with the application of loads as required by the standard.



Figure 82 - Trimmed specimen for BBR test

4.4.7. DSR Preparation of the samples

For the execution of rheological tests with the DSR (*MSCR and Frequency Sweep*), it was necessary to carefully define the sample preparation procedure, while also highlighting the main difficulties encountered during the experimental work and the corresponding solutions adopted.

The tests were performed using two rheometers from the same manufacturer, Anton Paar, models M301 and M302 [Figure 83].



Figure 83 - DSR Aanton Paar M302

For both tests, the **parallel plate configuration** was adopted, employing two different systems depending on the temperature range:

- **PP08**: 8 mm plates, used for low-temperature tests [Figure 84];
- **PP25**: 25 mm plates, used for high-temperature tests [Figure 85].



Figure 84 - PP08 system



Figure 85 - PP25 system

The amount of material to be collected was calculated based on the volume of the cylinder formed between the two plates. Specifically, by setting a **gap** of **1 mm** for the **PP25** system and **2 mm** for the **PP08** system, the corresponding volumes are as follows:

$$V = \pi r^2 h$$

$$V_{PP25} = 3.14 \cdot (12.5)^2 \cdot 1 = 490.625 \text{ mm}^3$$

$$V_{PP08} = 3.14 \cdot (4)^2 \cdot 2 = 100.48 \text{ mm}^3$$

By converting to cm^3 , the calculated volumes correspond to **0.491 cm^3** and **0.101 cm^3** , respectively. Considering that **1 cm^3** is approximately equivalent to **1 g**, twice the weight derived from the volume was assumed, in order to account for the material lost during the trimming phase of the specimen while still ensuring full filling of the cylinder. Accordingly, for the **PP25** and **PP08** plates, the amounts considered were **1 g** and between **0.230 g** and **0.250 g**, respectively.

The collected amount of material was then placed into dedicated silicone molds, which were subsequently introduced into a preheated oven under the following conditions:

- **Virgin bitumen:** 130 °C for 5 minutes;
- **Polymer-modified bitumen (A, B, C):** 150 °C for 10 minutes.

Afterward, the specimens were left to cool at room temperature for about **5 minutes** and then placed in a freezer for an additional **5 minutes**.

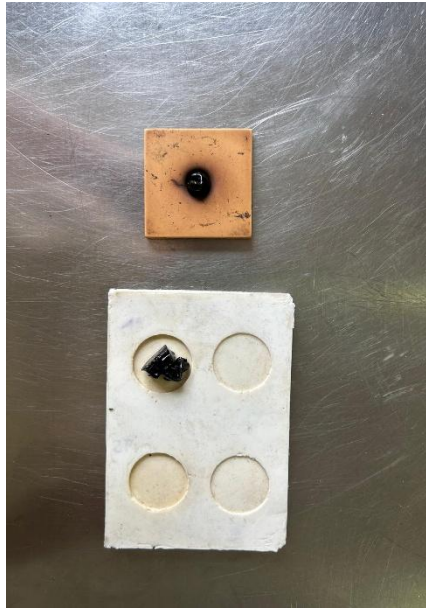


Figure 86 - Bitumen sample collected at room temperature before heating



Figure 87 - Bitumen sample after heating process

The two plates, already mounted on the instrument, must be preheated to a specific **adhesion temperature**, necessary to ensure uniform heating. The adopted values were as follows:

- **Virgin bitumen:** adhesion temperature of 46 °C;
- **Polymer-modified bitumen (A, B, C):** adhesion temperature of 55 °C.

Afterward, the hardened material was demolded and placed on the lower plate of the rheometer. The upper plate was then lowered until reaching a **gap of 1 mm**. Initially, the distance was reduced to a slightly higher value (approximately 0.050 mm more than the set gap) to allow the specimen to be compressed and the excess material to flow out, which was removed using a preheated spatula. At the end of this procedure, the final gap was set, giving the specimen a regular conical shape. At this point, the test was initiated.



Figure 88 - PP08 sample positioning



Figure 89 - PP08 sample after trimming



Figure 90 - PP25 sample positioning

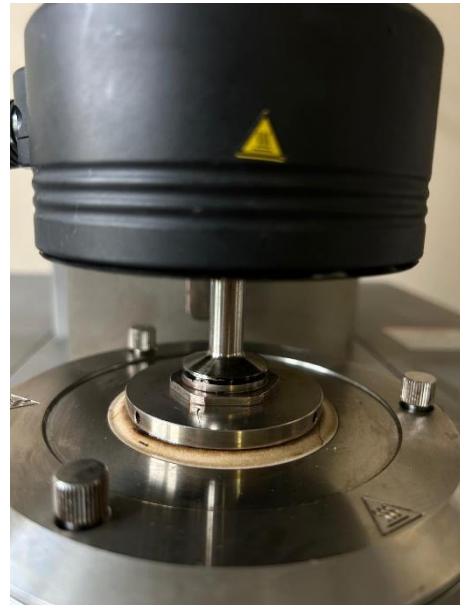


Figure 91 - PP25 sample after trimming

The procedure described was applied to both **virgin bitumen** and bitumen modified with **Plastic A**. Conversely, due to the specific composition of **Plastic B** and **Plastic C**, mixing was not satisfactory: the presence of larger plastic fragments distorted the results obtained with a 1 mm gap. For this reason, the protocol had to be adjusted, and several experimental attempts were carried out.

In the first attempt, the gap was increased to **2 mm** and the plates were preheated to **100 °C**. Once the specimen was placed, the temperature was lowered to **50 °C** to allow trimming. However, this configuration presented some issues: the excessively

high temperature caused the material to melt, as shown in **Figure 92**, while the gap was still too small, leading to polymer crushing.

In a second attempt, the gap was further increased to **3 mm** while maintaining the same procedure. In this case, a clear sedimentation of plastic particles on the lower plate was observed, which compromised the correct preparation of the specimen.



Figure 92 - Melted specimen during DSR test

At this stage, the gap was further increased to **3 mm**, while keeping the plates preheated at **50 °C**. Once the specimen was placed, it was left in position for **5 minutes** in order to relieve internal stresses and prevent plastic sedimentation, before proceeding with conditioning at **34 °C**.

The increase in the gap inevitably led to a higher amount of material required, which was equal to:

$$V = 3.14 \cdot (12.5)^2 \cdot 3 = 1473.88 \text{ mm}^3$$

The calculated volume corresponded to **1.47 cm³**. For practical reasons related to specimen preparation in the laboratory, a slightly higher amount was considered, approximately **1.5 g**.

With this material quantity, it was not possible to use the silicone mold shown in **Figure 86**, as the specimen overflowed from the edges. Therefore, a **perforated metal plate** with holes of **25 mm diameter** was used, placed on a silicone layer, which in turn rested on a solid metal plate [**Figure 93**]. To facilitate demolding,

glycerin was applied along the edges of the hole, and a coin was used as a practical aid.

The heating and cooling procedure followed the same protocol as previously described, with an additional waiting time of **5 minutes** once the specimen was placed on the equipment.



Figure 93 - System for preparing 3 mm gap specimens

In this way, the results appear more realistic compared to the previous configurations, although the fundamental principle underlying DSR testing — namely the use of a homogeneous material — was not fully met.



Figure 94 – Positioning of the sample with 3 mm gap



Figure 95 – Trimmed sample with 3 mm gap

4.4.8. Multiple Stress Creep Recovery Test Procedure

The test, already described in *Chapter 3.3.2*, was carried out on short-term aged material (RTFOT), as this represents the most severe condition. The tests were

conducted using the **25 mm plate**. The test is performed in accordance with **AASHTO T 350-19 (2023) [35]**.

The first step of the procedure involved specimen preparation according to the method described in *Chapter 4.4.7*. The specimen was then conditioned at **46 °C**, the starting temperature of the test, which was performed over a range from **46 °C to 82 °C**, with a gradient of **6 °C**. For each binder, **two repetitions** were performed.

The experimental procedure consisted of the following stages:

- **10 cycles** with a stress of **0.1 kPa** for specimen conditioning;
- **10 cycles** with a stress of **0.1 kPa**;
- **10 cycles** with a stress of **3.2 kPa**.

The total number of cycles produced as output was therefore **30**. Furthermore, according with the reference standard, data were recorded every **0.1 s** during the **creep period (1 s)** and at least every **0.45 s** during the **recovery period (9 s)**.

4.4.9. Frequency Sweep Test Procedure

To determine the complex modulus (G^*) and the phase angle (δ), the Frequency Sweep test was carried out using the DSR in accordance with **AASHTO T 315-12 [46]**.

The test was performed on all aging states of the material (original, RTFOT, and PAV), employing the PP08 plates for low temperatures and the PP25 plates for high temperatures.

After verifying the cleanliness of the equipment and its proper operating conditions, the specimens were prepared according to the procedure described in *Chapter 4.4.7* and then positioned on the instrument, enabling the conditioning phase at **34 °C** for both configurations.

The temperature range considered was **34 °C to 82 °C** for the **25 mm plate**, and **34 °C to 4 °C** for the **8 mm plate**, both with a gradient of **6 °C**. The tests were carried out at angular frequencies between **1 and 100 rad/s**.

The Frequency Sweep test allowed the characterization of the material within the linear viscoelastic (LVE) region.

5. Discussion of results

This chapter presents the experimental data collected during the tests, with the aim of comparing the results of the modified binders with those of the virgin one.

5.1. Penetration Test Results

As previously outlined in *Chapter 4.4.2*, the test was performed on all mixtures in their original condition. The displacements recorded by the instrument at the end of the penetration tests are well detailed reported in the *Annex A*.

According to **BS EN 1426:2024** [30], the results are considered acceptable if the differences between the maximum and minimum values fall within the specified ranges reported in **Table 12**. In the present study, the results meet these requirements and are therefore deemed acceptable.

Penetration	[0,1 mm]	≤ 49	50 to 149	150 to 249	≥ 250
Maximum difference between highest and lowest value of the determinations	[0,1 mm]	2	4	6	8
NOTE These ranges are not necessarily applicable under other conditions.					

Table 12 – Acceptance criteria for the maximum difference between penetration values [30]

According to the standard, the results must also be expressed as the arithmetic mean and rounded to the nearest integer, as shown in **Figure 96**.

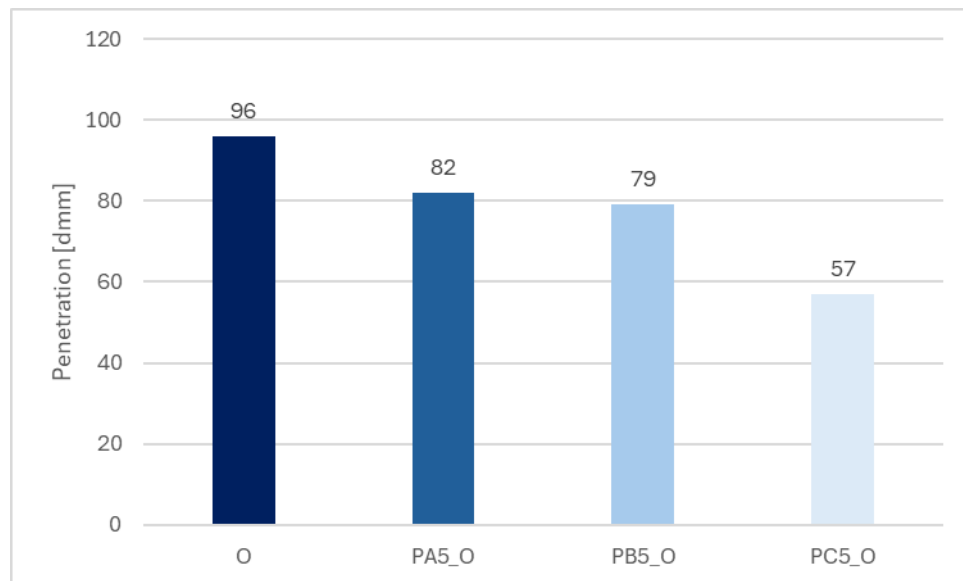


Figure 96 – Histogram of penetration values for standard bitumen and polymer-modified binders

The results obtained are fully consistent with those reported in the literature, for instance in the studies by Mashaan et al. (2022) [18] and Sarkar (2019) [16], which observed a decrease in penetration values with increasing polyolefin polymer content for limited dosages (1–4%). In fact, the outcomes obtained with Plastic A (polyolefin-based) are perfectly in line with the findings described in these previous works. With regard to Plastic B, a greater reduction was observed compared to the first mixture, which can be attributed to its different physical and chemical composition. An even more pronounced effect is evident with Plastic C, which is coherent with its nature as a compound specifically designed to enhance modulus and resistance to permanent deformation.

5.2. Ring and Ball Test Results

The softening point test was carried out on both the standard bitumen and the bitumen modified with the three plastics in their original state, as for the Penetration Test.

Detailed results obtained from this test are reported in *Annex A*.

In order to validate the results, a verification was carried out in accordance with the **BS EN 1427:2015** standard [31]. If the difference between the temperatures of the two specimens exceeds 1 °C for softening points below 80 °C, or 2 °C for softening points above 80 °C, the test must be repeated. In the case of modified binders, the difference shall not exceed 2 °C [31].

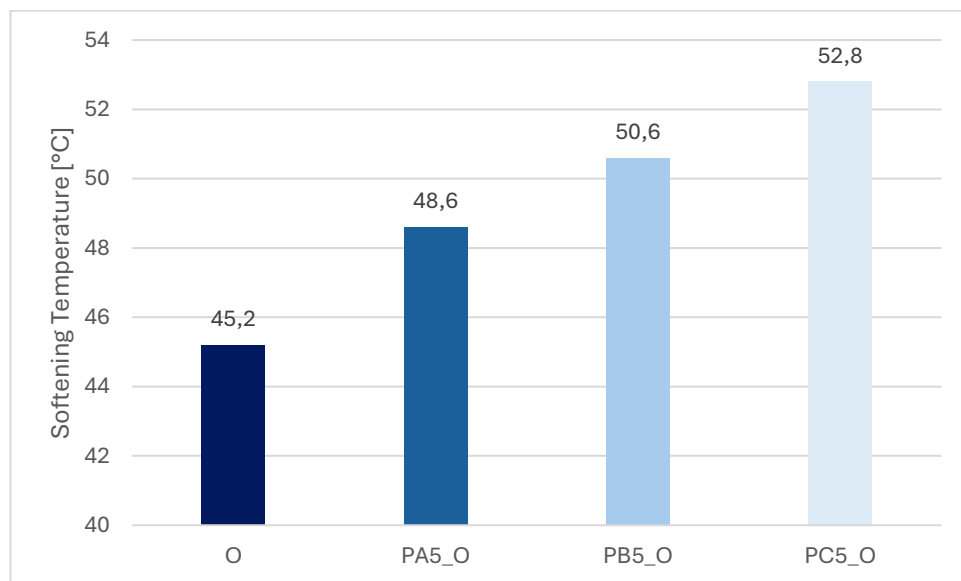


Figure 97 – Histogram of softening point values

The results obtained from the softening point test, visually represented in the histogram in **Figure 97**, reinforce the findings already highlighted by the penetration test. In fact, the highest softening temperature was recorded for Plastic C, which had also shown the lowest penetration value. Overall, all polymers contributed to stiffening the bitumen by increasing the softening point temperature; however, the presence of PP in Plastic B and the specific composition and purpose of Plastic C clearly explain the higher values observed.

5.3. Bending Beam Rheometer Results

The procedure adopted for this test was described in *Chapter 4.4.6*, and was carried out simultaneously on multiple specimens in order to optimize testing time. As previously mentioned in the earlier chapters, the test was performed on the PAV-aged material. The standard also requires at least two repetitions at each temperature, ensuring that the results do not exceed the percentage differences specified in **Table 13**.

	Repeatability, r % of the mean value	Reproducibility, R % of the mean value
Creep stiffness	9	27
m-value	4	13

Table 13 - Estimated repeatability and reproducibility [39]

The results obtained, recorded at 60 seconds and at the reference temperatures, are presented in **Table 14**.

Temperature [°C]	Material	N. sample	Estimated Stiffness [MPa]	m-value
-6	PC5_P	1	81.7	0.345
	PC5_P	2	82.7	0.342
-12	P	1	140	0.341
	P	2	139	0.333
	PA5_P	1	147	0.311
	PA5_P	2	148	0.316
	PB5_P	1	147	0.319
	PB5_P	2	146	0.322
	PC5_P	1	161	0.297
	PC5_P	2	160	0.298
-18	P	1	301	0.270
	P	2	296	0.273
	PA5_P	1	318	0.262
	PA5_P	2	297	0.266
	PB5_P	1	310	0.264
	PB5_P	2	323	0.272

Table 14 - BBR Results: stiffness and m-value of the different binders at the reference temperatures

Based on the results obtained, the percentage differences were subsequently calculated and are reported in **Table 15**.

Material	Temperature [°C]	Estimated stiffness [%]	m-value [%]
P	-12	0.717	2.37
P	-18	1.68	1.10
PA5_P	-12	0.68	1.59
PA5_P	-18	7.16	1.51
PB5_P	-12	0.68	0.93
PB5_P	-18	4.41	2.98
PC5_P	-6	1.22	0.87
PC5_P	-12	0.62	0.34

Table 15 – Percentages differences for repeatability of results

The results of this test are used to determine the **low PG**, which is established by considering threshold values for stiffness and m-value:

- Stiffness must not exceed 300 MPa;
- The m-value must be at least 0.300.

On the basis of these limits, it is possible to calculate the values of T_s e T_m , namely the temperatures obtained through data interpolation that correspond to the threshold values indicated above, for stiffness and m-value, respectively. The interpolation was carried out as follows:

$$T_s = T_1 + \frac{\log(300) - \log(S_1)}{\log(S_2) - \log(S_1)} \cdot (T_2 - T_1)$$

$$T_m = T_1 + \frac{0.300 - m_1}{m_2 - m_1} \cdot (T_2 - T_1)$$

The two temperatures are defined as **pass-fail temperatures**, as they represent the minimum thresholds at which the bituminous binder meets the normative requirements. Specifically, the first corresponds to the temperature at which the bending stiffness reaches the limiting value of 300 MPa, while the second refers to the temperature at which the m-value attains the minimum value of 0.300. These values are shown in **Figure 98 e Figure 99**, whereas all other results are provided in Annex B and are summarized in **Table 16**, which also includes the difference between the two calculated temperatures. In addition, all the other graphs are reported in *Annex B*.

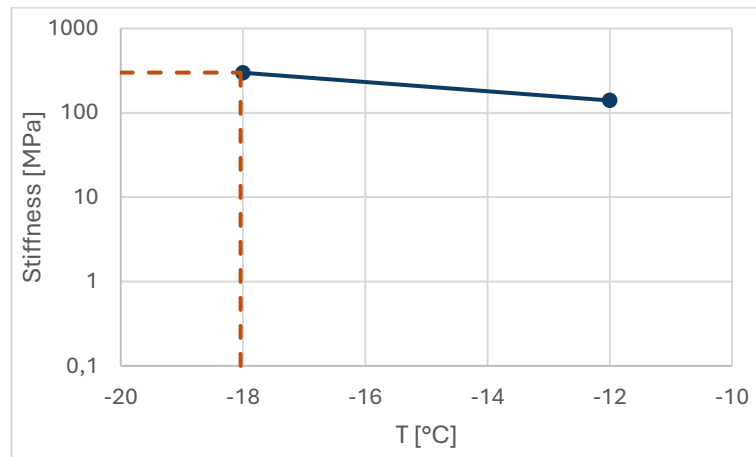


Figure 98 - Pass-fail temperature for bitumen P (Stiffness)

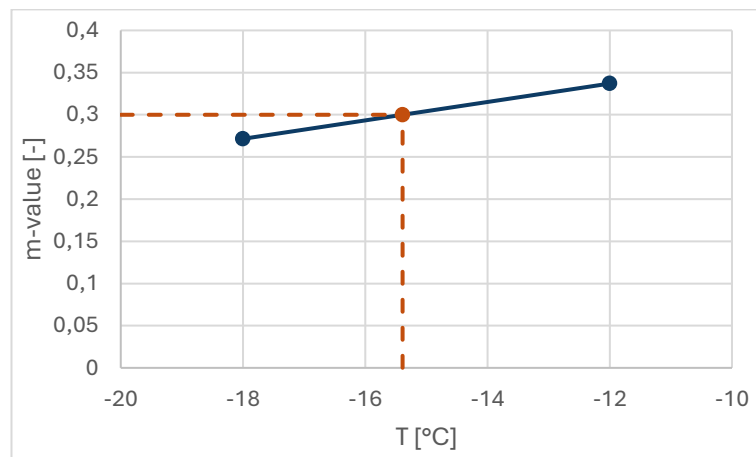


Figure 99 - Pass-fail temperature for bitumen P (m-value)

Material	T_s [°C]	T_m [°C]	ΔT_c [°C]
P	-18.04	-15.39	2.65
PA5_P	-17.81	-13.64	4.17
PB5_P	-17.57	-14.34	3.22
PC5_P	-17.60	-11.67	5.93

Table 16 - Pass-fail temperatures

This analysis highlights significant differences among the various materials, especially between the modified binders and the virgin binder. The latter exhibits an overall balanced behavior between stiffness and relaxation capacity, with a temperature difference of 2.65 °C.

In contrast, the binders modified with plastics show an increase in the pass-fail temperatures, indicating a reduced suitability of the material at low temperatures and a greater susceptibility to thermal cracking. The most critical behavior was observed in the PC5_P sample, which displays a difference between the two temperatures of 5.93 °C, reflecting the binder's inability to adequately relax internal stresses, with poor performance already at -12 °C, a threshold easily met by the other materials.

In conclusion, the low PG values calculated for each material, based on the analyzed results, are presented in **Table 17**.

Material	Low PG [°C]
P	-22
PA5_P	-22
PB5_P	-22
PC5_P	-16

Table 17 - Low PG temperatures

5.4. MSCR Results

The aim of this test is to determine the non-recoverable creep and the elastic recovery values, expressed as percentages, in accordance with **AASHTO T 350-19 (2023)** [35].

Considering the values reported in **Table 3**, in this study, the determination of the High PG refers to the **Standard** condition, namely the temperature that meets the limiting value of $J_{nr\ 3.2}$ equal to 4.5 kPa and a $J_{nr,diff}$ lower than 75%.

The results obtained for each repetition and the average values are presented in greater detail in the tables included in *Annex C*, while the following figures show the average values calculated from the two repetitions carried out for each material.

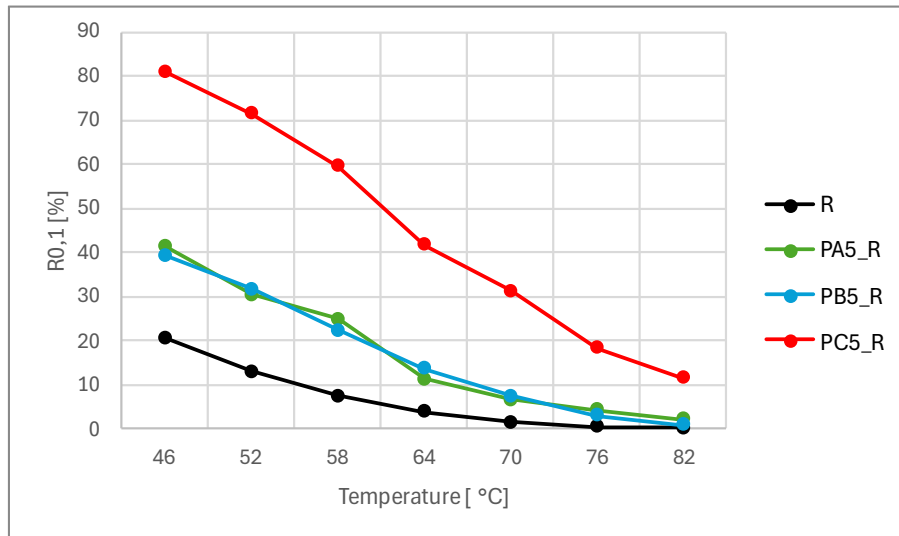


Figure 100 - Recovery percentage at 0.1 kPa as a function of temperature

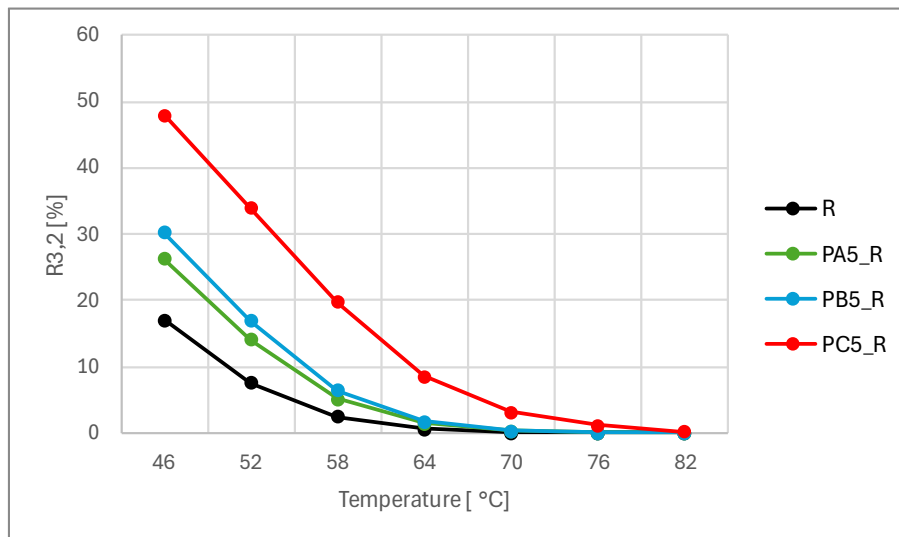


Figure 101 - Recovery percentage at 3.2 kPa as a function of temperature

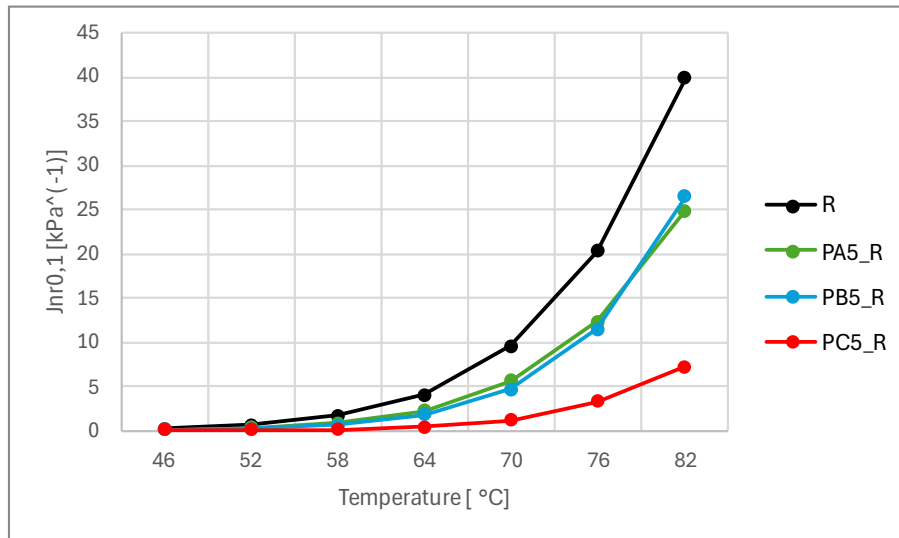


Figure 102 - Non-recoverable creep compliance at 0.1 kPa as a function of temperature

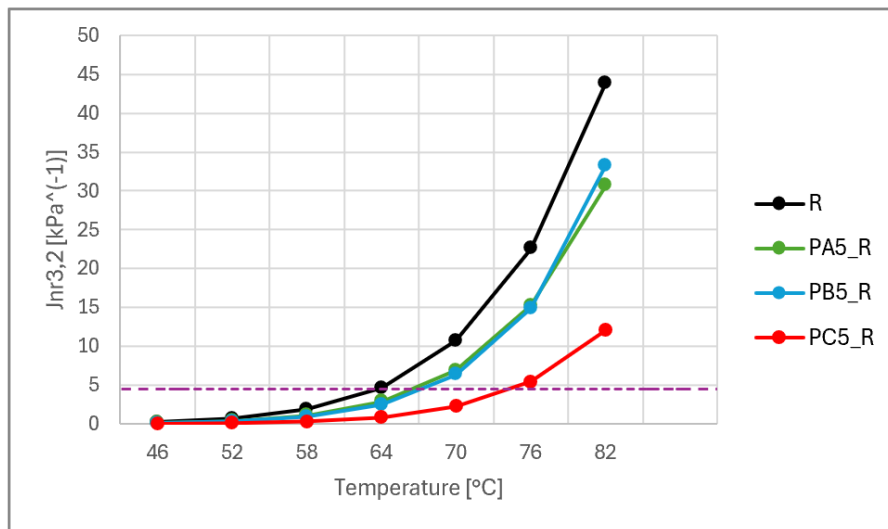


Figure 103 - Non-recoverable creep compliance at 3.2 kPa as a function of temperature

For visual clarity, the $J_{nr,diff}$ values have been presented in a histogram [Figure 104]:

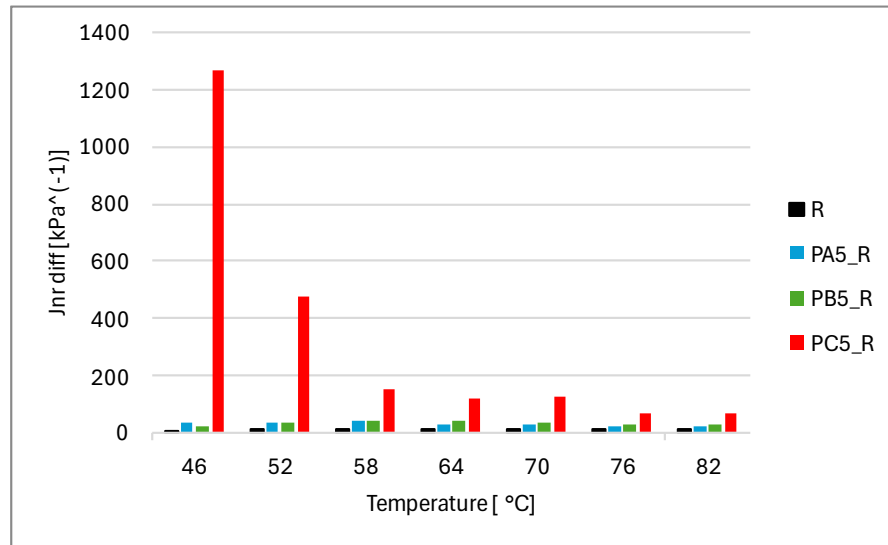


Figure 104 - $J_{nr,diff}$ values as a function of temperature

The presented graphs illustrate the key parameters of the MSCR test applied to the four binders under investigation. As expected, the $R_{0.1}$ and $R_{3.2}$ values, representing the percentage of elastic recovery, progressively decrease with increasing temperature [Figure 100, Figure 101]. Clear differences emerge between the base binder, the binders modified with waste products, and the binder modified with a commercial product. In particular, the responses of PA and PB are positioned in an intermediate range between the base binder and PC.

The subsequent graphs [Figure 102, Figure 103], referring to $J_{nr,0.1}$ and $J_{nr,3.2}$, describe the non-recoverable compliance, which measures the visco-plastic deformability of the material. Once again, the same trend is observed: the curves of PA and PB remain between those of the base binder and PC. It is represented also the limit threshold of 4.5 kPa^{-1} indicated in the Standard [Figure 103].

Finally, the histogram of $J_{nr,diff}$ [Figure 104] allows assessing the material's sensitivity to stress variation. In this case, PC exhibits anomalous values, indicating a marked dependence on the applied stress level, whereas R, PA, and PB remain at very low and nearly constant levels, reflecting more stable behavior.

Overall, the addition of polymers led to an improvement compared to the base binder. PA and PB showed more moderate enhancements combined with higher stability, while PC introduced a stronger elastic component and greater stiffness, though at the expense of stress stability.

The MSCR test results also revealed a progressive increase in High PG temperature when moving from the virgin binder to the one modified with Plastic C. These findings are fully consistent with the literature: according to Nizamuddin et al (2021) [13], both the recovery percentage (%R) and the $J_{nr,diff}$ improve with polymer addition, exactly as observed in this study. Specifically, common polymers such as polyolefin-based ones showed a more gradual increase, whereas a more pronounced effect was achieved with the addition of Plastic C, resulting in a shift of two High PG categories.

To determine the High PG in the next paragraph, the average values reported in tables in the *Annex C*, as defined in **AASHTO T 350-19 (2023)** [35].

In conclusion, the incorporation of polymers enhanced high-temperature stability and improved resistance to permanent deformation.

5.5. Performance Grade determination

Based on the results obtained from the BBR and MSCR tests, it is possible to refer to the AASTHO M 322-23 [37] specification for the classification of the binders analyzed, using the tables reported in *Chapter 3.3.2*. In this study, the Standard traffic condition was considered; therefore, the reference PG values are:

Material	PG
70/100	58S – 22
PA5	64S – 22
PB5	64S – 22
PC5	70S – 16*

Table 18 - Performance Grade

*The performance grade defined for material PC5 has been determined considering only the limitation imposed by $J_{nr,3.2}$, since the results of $J_{nr,diff}$ could not be taken into account.

5.6. Frequency Sweep Test Results

The last test to be analyzed is the *Frequency Sweep*, carried out with the DSR on all the binders considered and in each of their aging states. The temperature range adopted for the test extended from 4 °C to 82 °C: in the interval between 4 °C and 34 °C the parallel-plate configuration with 8 mm plates was used, while from 34 °C to

82 °C the configuration with 25 mm plates was employed. All the results are reported well detailed in *Annex D*.

After performing the tests, the data obtained were subjected to an initial visual analysis using Black Diagrams [Figure 105, Figure 106, Figure 107], in order to check for possible inconsistencies.

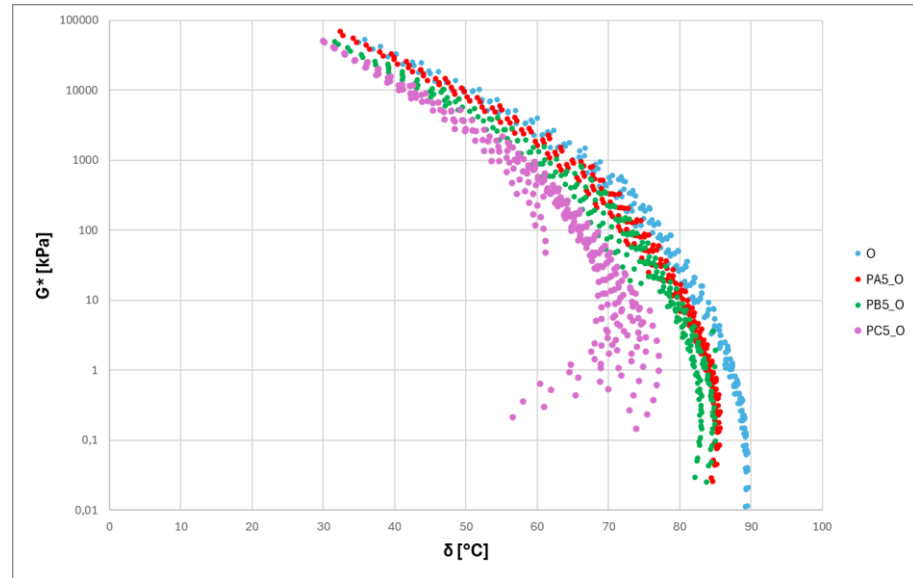


Figure 105 - Black Diagram Original State

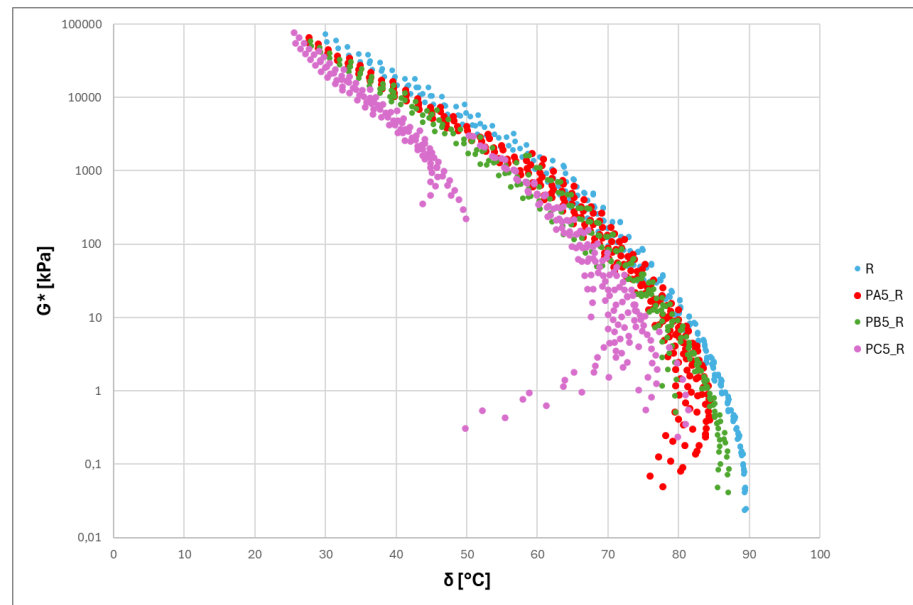


Figure 106 - Black Diagram RTFOT

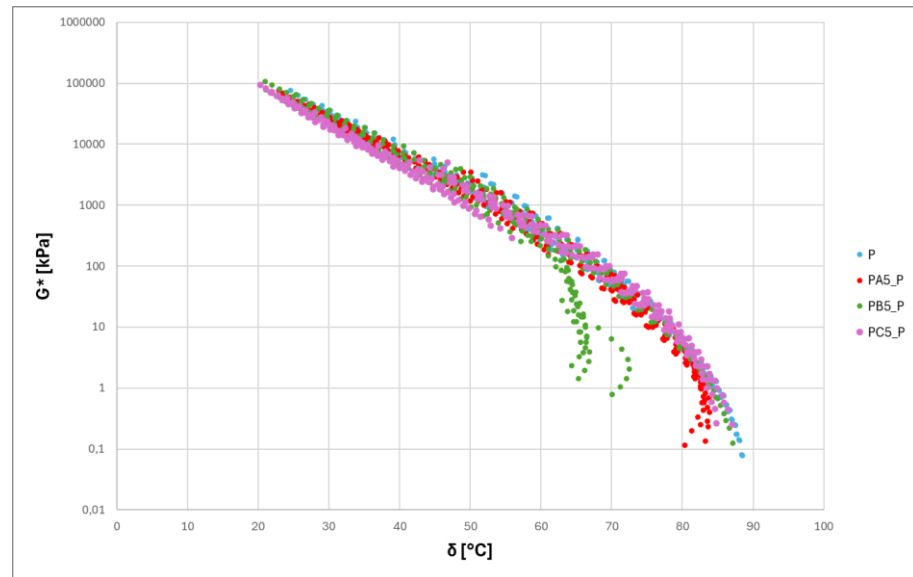


Figure 107 - Black Diagram PAV

All the analyzed materials follow the typical trend of **Black Diagrams**, characterized by a progressive decrease in complex modulus and an increase in phase angle with rising temperature or, equivalently, with decreasing reduced frequency.

When comparing the three polymers with the virgin binder, the material that deviates the most is the one modified with polymer C, which shows a significant dispersion of data, indicating poor compatibility with the bituminous binder. Conversely, the binders modified with plastics A and B exhibit an increase in stiffness, but their overall trend remains close to that of the original binder [Figure 105].

Considering the graph in [Figure 106], which refers to short-term aged binders, the differences become more evident. In particular, the PC5_P material shows an irregular trend, with deviations confirming its limited rheological stability. An anomalous jump at the same temperature is also observed, which may be attributed both to the change in instrument configuration and to the high level of heterogeneity in the mixture. On the other hand, the materials modified with plastics A and B follow more consistent trajectories, suggesting better resistance to the initial oxidative process.

Finally, the third graph [Figure 107], referring to long-term aging, displays an overall more regular behavior compared to the other aging states. In this case, only the PB5_P material shows a discontinuity around a phase angle of approximately 60°, likely due to the presence of polymers not fully dispersed in the mixture. Overall, the PA5_P material appears to be the most stable, with a trend very similar to that of the unmodified binder.

Based on the experimental data obtained from the tests, the **Master Curves** were constructed and modeled using the analytical Christensen-Anderson-Marasteanu (CAM) model, already introduced in *Chapter 3.2.3*. This model provides a continuous description of both the complex modulus and the phase angle as a function of reduced frequency, thereby offering a consistent representation of the viscoelastic behavior of the material.

To achieve this step, the analysis relied on the optimization of four key parameters through the use of a data solver:

- G_g : the glassy modulus, representing the theoretical stiffness of the binder;
- w_c : the crossover frequency, corresponding to the point at which the binder transitions from viscous to elastic behavior;
- R : the shape parameter, which controls the curvature of the master curves and influences how quickly the modulus changes with reduced frequency;
- m : the slope parameter, which governs the transition between the glassy and viscous regimes, and thus the width of the transition zone.

To perform this analysis, it was necessary to define a set of initial values on which to apply the data solver using Excel. In particular, the reference temperature T_0 was set at 20 °C. The parameters C_1 and C_2 , which control the dependence of the shift factor on temperature, were assigned typical values of 19 and 92, respectively, as reported in the literature.

Regarding the four main model parameters, the glassy modulus was fixed at 10^6 MPa, consistent with the theoretical values of the maximum stiffness of binders; the crossover frequency was identified at the point where $G' = G''$, corresponding to $\delta=45^\circ$; the shape parameter R was calculated as the distance between the glassy modulus and the complex modulus at the crossover frequency; finally, the slope parameter m was initially set equal to 1.

The optimization of the CAM model parameters was carried out using Excel's solver, with the objective function defined as the sum of the relative error on the complex modulus (OF G^*) and on the phase angle (OF δ). Through this iterative process, the solver searched for the combination of parameters that minimized the difference between experimental and theoretical values. However, it was observed that the model

did not adequately capture the phase angle; therefore, the optimization was performed primarily with reference to the complex modulus.

The **master curves** of the complex modulus are presented below.

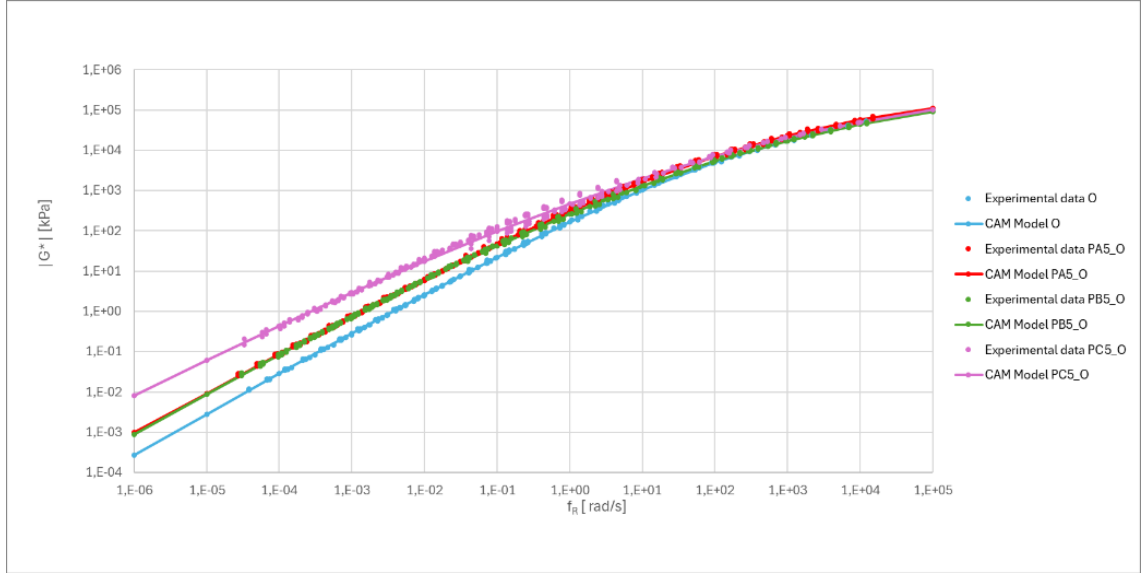


Figure 108 - Master Curve of complex modulus for the original binders

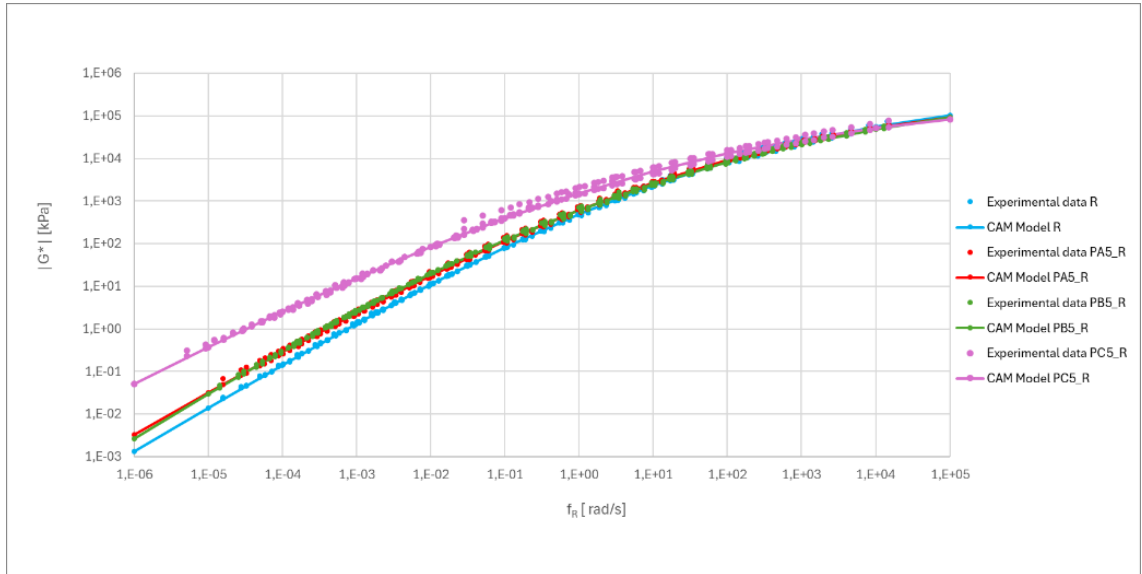


Figure 109 - Master Curve of complex modulus for the RTFOT-aged binders

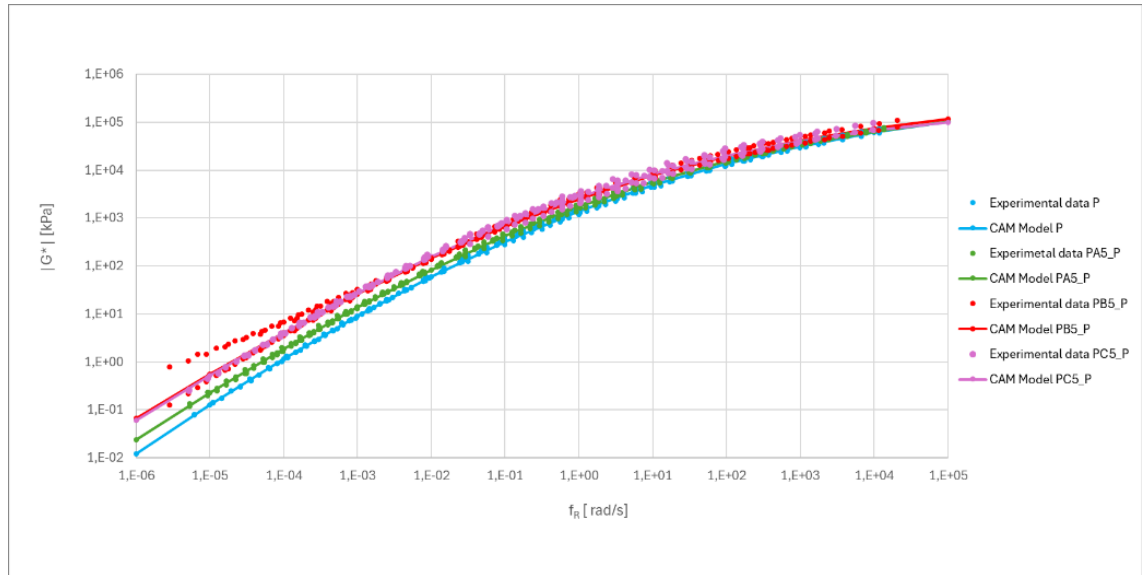


Figure 110 - Master Curve of complex modulus for the PAV-aged binders

From the curves, it can be observed that, overall, the model is able to satisfactorily capture the trend of the experimental data. Already in the original state [Figure 108], it is evident that the binder modified with polymer C deviates more significantly from the base binder compared to the other mixtures, and this behavior continues to appear in the curves corresponding to the subsequent aging states [Figure 109, Figure 110].

As for the complex modulus, the values are consistently higher in the polymer-modified mixtures, starting already from the original state, indicating an increase in material stiffness.

With regard to the phase angle curves, only the experimental data collected during the tests are shown. These data were shifted using the factors derived from Excel's solver, which had been optimized exclusively on the complex modulus.

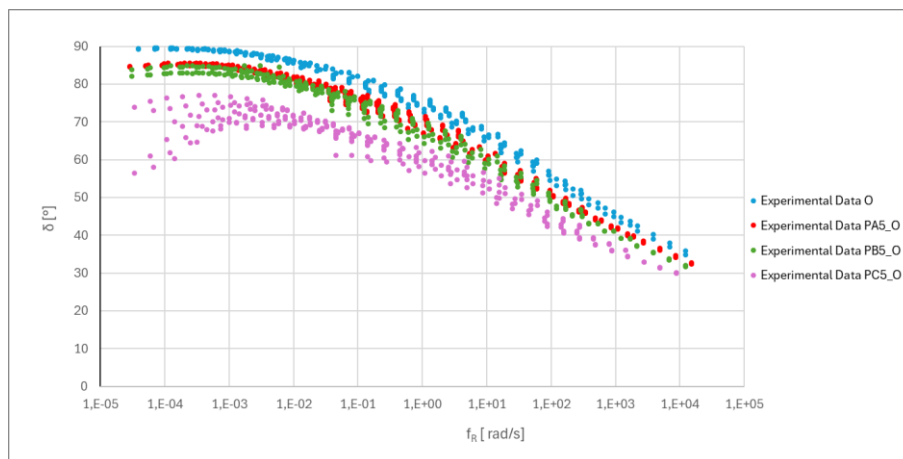


Figure 111 - Experimental phase angle values for the original binders

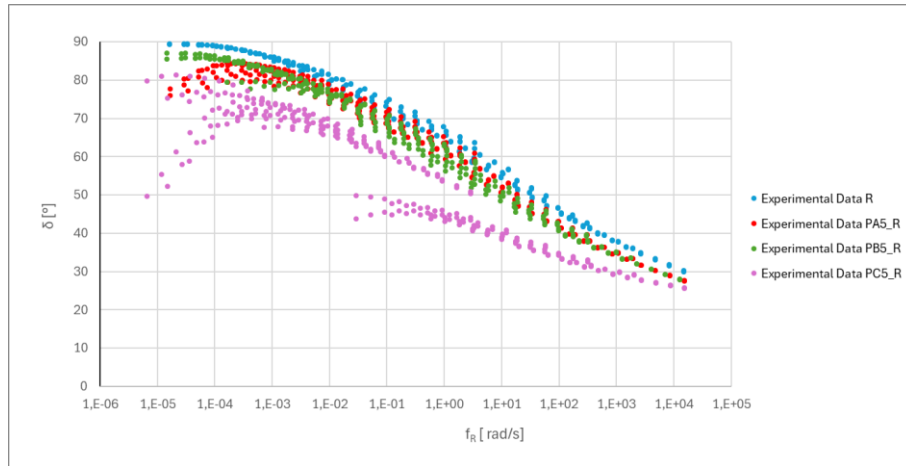


Figure 112 - Experimental phase angle values for RTFOT binders

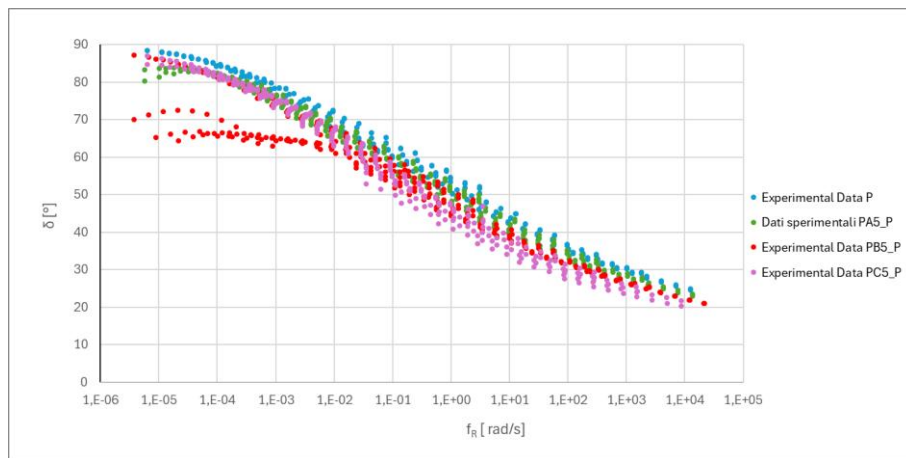


Figure 113 - Experimental phase angle values for PAV binders

The curves clearly show that the phase angle decreases progressively with aging, reflecting the loss of the viscous component and the consequent stiffening of the binder. The comparison among the different materials also highlights that the binder modified with polymer C exhibits more divergent and significantly lower values compared to the others, confirming the greater elasticity of the resulting binder.

The parameters that were varied, along with the corresponding results, are summarized in the **Table 19**.

Material	C_1	C_2	$\log(G_g)$	$\log(w_c)$	R	m	OF G^*	OF δ	SUM
O	12.16	109.15	5.31	2.73	1.18	1.02	0.55	0.31	0.86
R	13.94	118.55	5.43	1.81	1.51	1.06	2.24	0.42	2.66
P	18.18	154.97	5.58	0.00	2.06	1.18	2.00	0.29	2.29
PA5_O	12.35	106.42	5.35	2.53	1.24	0.98	1.21	0.48	1.69
PA5_R	13.87	117.81	5.51	1.61	1.68	1.04	3.31	0.34	3.65
PA5_P	18.17	152.63	5.62	0.00	2.10	1.14	1.94	0.33	2.27
PB5_O	12.88	114.88	5.96	2.29	1.93	1.07	1.36	0.22	1.58
PB5_R	14.95	129.77	5.92	0.35	2.33	1.25	1.43	0.27	1.70
PB5_P	17.06	133.04	5.50	0.00	1.94	1.08	11.01	1.87	12.88
PC5_O	13.88	130.35	7.34	0.16	3.59	1.27	7.20	1.94	9.14
PC5_R	16.72	138.32	5.19	1.05	1.59	0.92	5.28	3.92	9.19
PC5_P	21.24	191.19	5.47	0.00	1.89	1.08	5.94	1.34	7.28

Table 19 - Optimized CAM model parameters and objective function values

The reported parameters exhibit a consistent evolution with aging for all binders.

For the base binder, a progressive increase in C_1 and C_2 is observed with aging, while the low OF and SUM values indicate good representativeness of the model.

For the binders modified with polymers A and B, the behavior is consistent with that of the base bitumen, although higher values of $\log(G_g)$ are recorded, indicating increased stiffness.

In contrast, the binder modified with polymer C clearly stands out from the others: already in the original state, it shows significantly higher values of $\log(G_g)$ and R; however, these results are accompanied by very high errors, suggesting a limited suitability of the CAM model to describe its behavior.

Once the master curves were obtained using the CAM model, a reduced frequency of 10 rad/s was selected as the reference value. From this frequency, the modeled values of complex modulus and phase angle were extracted and subsequently represented in histogram form, in order to immediately highlight the differences in behavior among the binders.

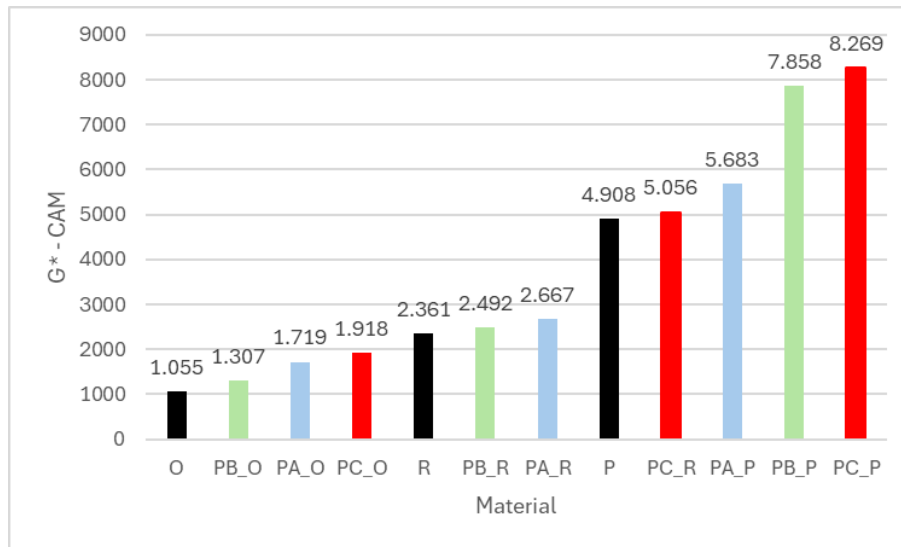


Figure 114 - Comparative histograms of G^* - CAM

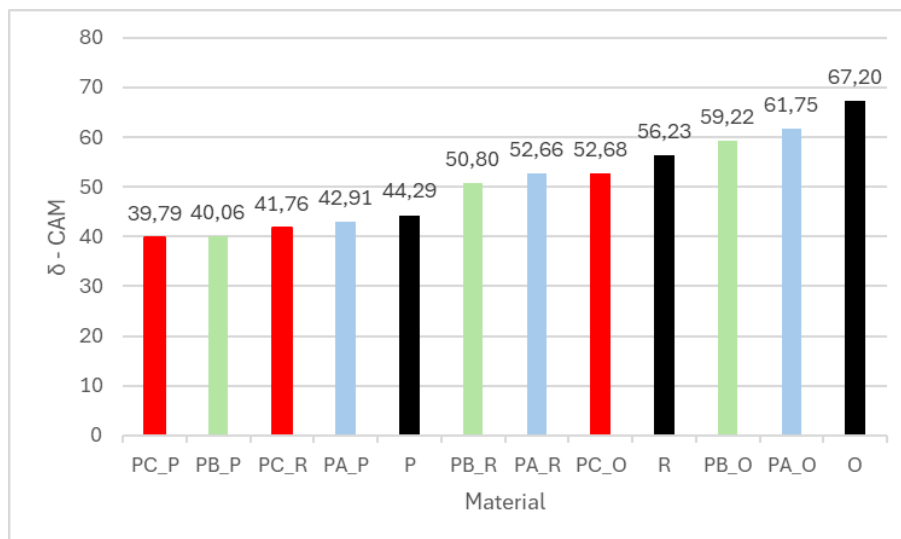


Figure 115 - Comparative histograms of δ

The comparison of the results obtained for all the materials, taking the base binder and the Plastic C-modified binder as references, highlights a clear behavioral gradient. With regard to the complex modulus, the virgin bitumen exhibits the lowest stiffness values, whereas the PC5 binder shows the highest. The PA5 and PB5 binders consistently fall in an intermediate range between the two and, with progressive aging, tend to approach the behavior of PC5, though without ever reaching the same level of stiffness.

A mirrored trend is observed for the phase angle: the base binder exhibits the highest values, while PC5 presents the lowest. Once again, PA5 and PB5 are positioned in an intermediate range.

The comparison between the experimental results and the literature shows a substantial consistency, particularly when considering the compositional characteristics of the materials analyzed. Specifically, for the binders modified with polymer A, of polyolefinic nature, an increase in stiffness and a moderate reduction in phase angle were observed, consistent with the findings of Mashaan et al. (2022) [18] e Sarkar (2019) [16] for bitumens modified with HDPE and LDPE. In these cases, the presence of polyolefins enhances stiffness and improves rutting resistance, while maintaining overall stability.

Regarding Plastic B, characterized by a predominant presence of PP, a similar increase in stiffness was found, consistent with the studies of Xia et al. (2020) [19] e Xu et al. (2022) [20]. However, the behavior appears less regular than that of Plastic A, indicating lower compatibility, though still yielding intermediate values of both G^* and δ .

Finally, Plastic C, being a selected compound, demonstrates more pronounced improvements, with very high G^* values and very low δ values. These performances can be compared to those achieved with “technical” polymers such as ABS or PVC, as reported by (Xu et al. (2021) [7] e Singh et al. (2020) [6]. In these cases, a significant increase in stiffness and a substantial reduction in phase angle are observed, though often accompanied by challenges related to blending and segregation phenomena.

6. Conclusion

Plastics represent one of the major global challenges today, as a large proportion of them cannot be recycled. In this context, the present thesis sets out the following objectives:

- to verify the compatibility between recycled polymers and bituminous binders;
- to evaluate the effectiveness of recycled plastics as bitumen modifiers;
- to analyze the rheological behavior under different aging conditions.

In this study, the **wet process** was adopted to incorporate the polymers into the bitumen binder, although this is not the technique that will be used in the PRIN SWTICHit project. This choice was made in order to better understand and assess the performance contribution of the fraction of polymer actually dissolved in the bituminous matrix.

The research focused on three different types of polymers:

- **Plastic A**, consisting of a polyolefinic blend;
- **Plastic B**, mainly composed of polypropylene, polyamide, and elastomers;
- **Plastic C**, a commercial compound obtained from selected and partially virgin plastics.

The experimental program was carried out through rheological tests with the Dynamic Shear Rheometer (DSR) and the Bending Beam Rheometer (BBR), which enabled the performance characterization of the binders under three aging conditions (original, short-term, and long-term). Additional empirical tests, such as ring-and-ball and penetration, were also performed to provide further comparisons in the characterization.

The analyses revealed that Plastics A and B led to an increase in stiffness and a reduction in phase angle, while maintaining a trend similar to that of the virgin bitumen, but always distinct from the binder modified with Plastic C. The latter, being a validated commercial compound, exhibited significantly superior performance in terms of stiffness and resistance.

The comparison shows that Plastics A and B occupy an intermediate position between the virgin binder and the Plastic C-modified binder. In particular, Plastic A emerges as a more balanced solution, capable of improving the binder's properties without compromising rheological stability; Plastic B provides performance improvements but requires further optimization in the dispersion process; Plastic C, on the other hand, confirms the effectiveness of commercial compounds, capable of delivering the best results in terms of mechanical performance, though with some compatibility issues with the wet process and occasional anomalous values.

Overall, the outcome of this study is positive: the use of recycled plastics as bitumen modifiers represents a promising strategy to combine environmental sustainability with improved binder performance. However, to fully exploit the potential of these materials, further research on compatibility and the long-term evolution of the mixtures will be required, in order to ensure their durability and performance over time.

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Annex A

Repetition	O	PA5_O	PB5_O	PC5_O	Unit of measurement
1	94	80	81	58	dmm
2	96	82	78	55	dmm
3	97	83	77	59	dmm

Table 20 - Recorded penetration displacements (O, PA5, PB5, PC5) under original conditions

Material	T (left) [°C]	T (right) [°C]	T average [°C]
O	45.2	45.0	45.2
PA5_O	49	47.9	48.6
PB5_O	50.8	50.2	50.6
PC5_O	53	52.9	52.8

Table 21 - Recorded softening temperatures for O, PA5, PB5 and PC5 under original conditions

Annex B

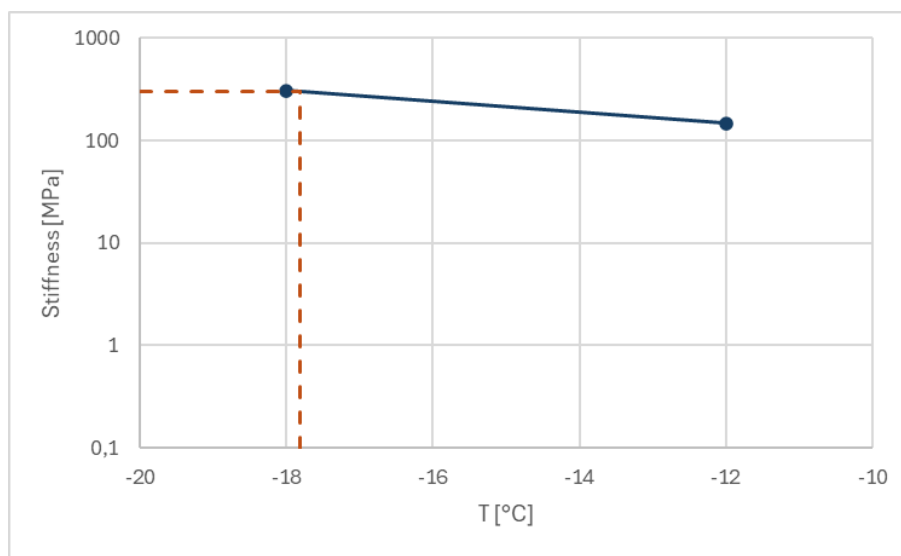


Figure 116 - Pass-fail Temperature for PA5_P (Stiffness)

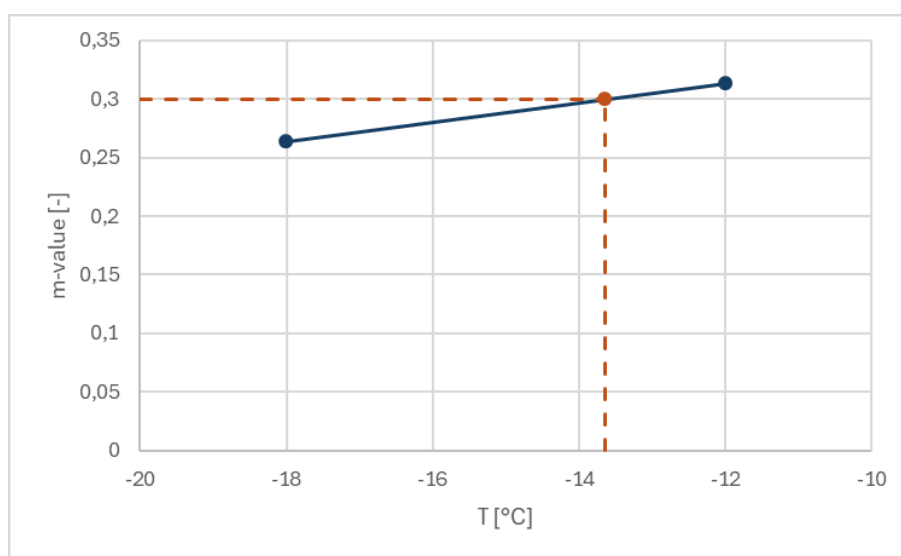


Figure 117 - Pass-fail Temperature for PA5_P (m-value)

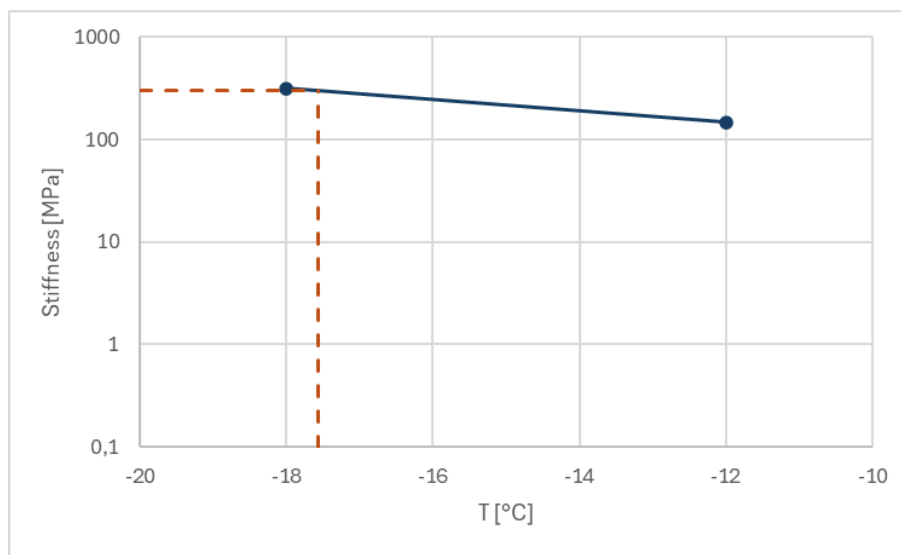


Figure 118 - Pass-fail Temperature for PB5_P (Stiffness)

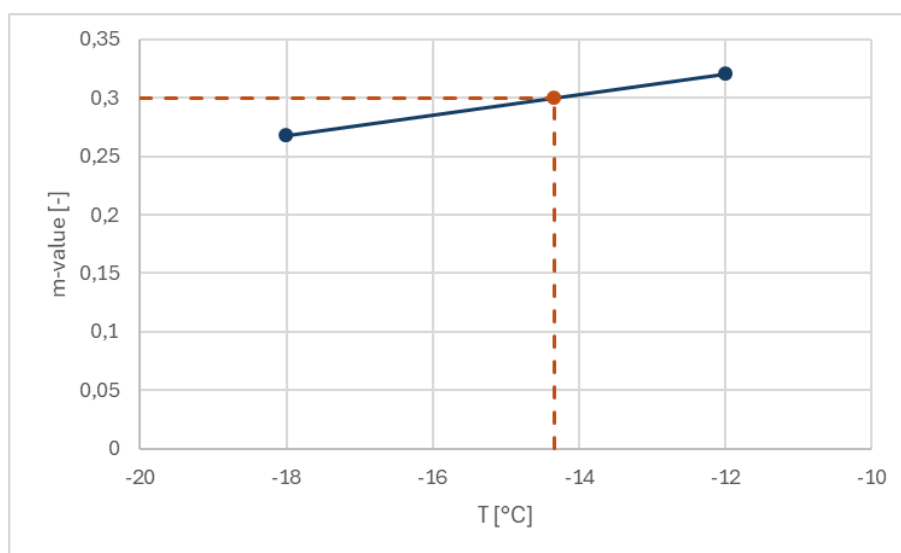


Figure 119 - Pass-fail Temperature for PB5_P (m-value)

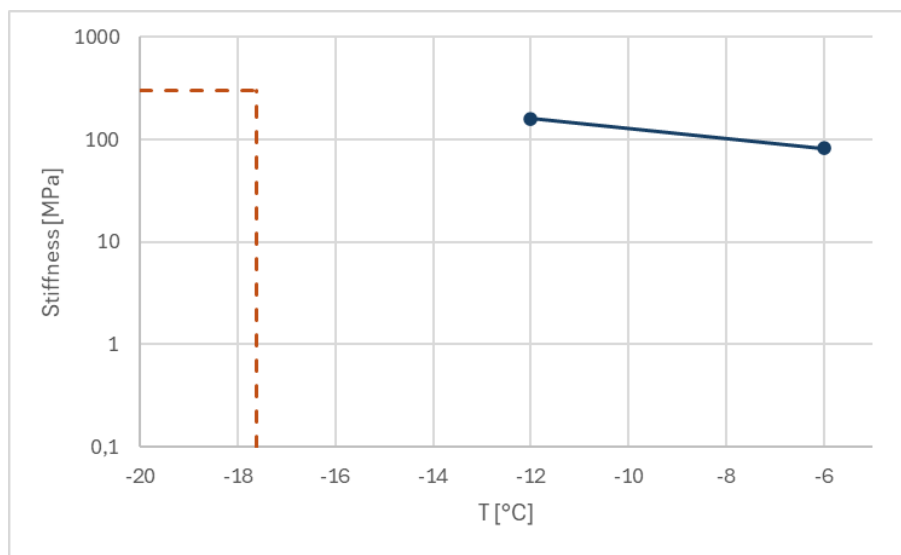


Figure 120 - Pass-fail Temperature for PC5_P (Stiffness)

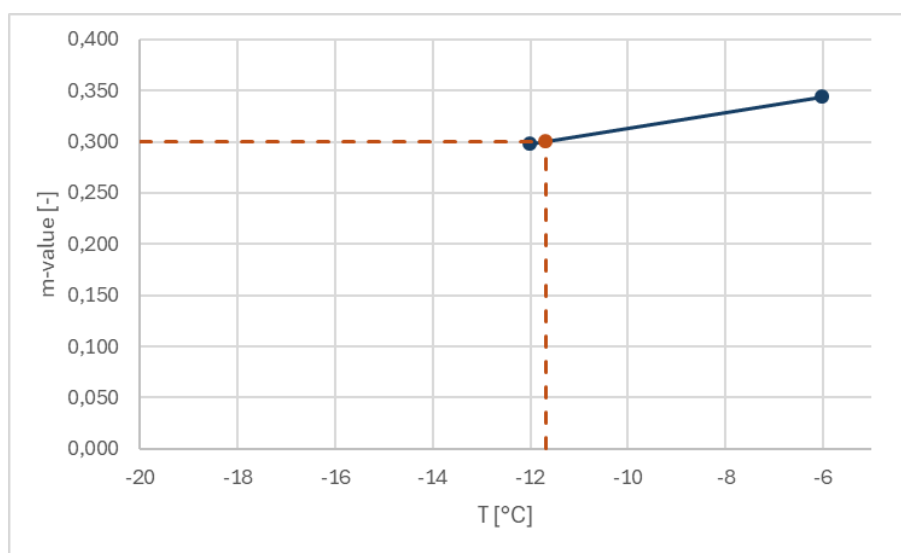


Figure 121 - Pass-fail Temperature for PC5_P (m-value)

Annex C

R REP 1					
T [°]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	21,28	17,38	0,19	0,21	5,96
52	13,41	7,77	0,57	0,63	9,98
58	7,80	2,51	1,56	1,77	13,42
64	4,37	0,65	3,90	4,46	14,39
70	1,83	0,07	9,16	10,35	12,97
76	0,59	0,01	19,48	21,66	11,17
82	0,26	0,00	38,43	42,10	9,54

Table 22 - MSCR Results R (Rep 1)

R REP 2					
T [°]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	20,11	16,74	0,20	0,21	5,19
52	12,55	7,23	0,60	0,66	9,45
58	7,29	2,25	1,65	1,86	12,58
64	3,47	0,54	4,20	4,76	13,30
70	1,49	0,06	9,87	11,10	12,46
76	0,61	0,00	21,08	23,46	11,30
82	0,35	0,00	41,36	45,70	10,51

Table 23 - MSCR Results R (Rep 2)

PA5_R REP 1					
T [°]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	45,83	26,11	0,07	0,11	41,80
52	30,60	13,83	0,26	0,34	32,70
58	24,48	5,04	0,75	1,04	38,25
64	10,18	1,48	2,23	2,82	26,41
70	7,59	0,33	5,41	6,87	27,08
76	5,34	0,05	12,13	15,26	25,83
82	2,64	0,01	24,56	30,81	25,48

Table 24 - MSCR Results PA5_R (Rep 1)

PA5_P REP 2					
T [°]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	37,37	26,50	0,09	0,11	19,56
52	30,34	14,25	0,27	0,35	30,70
58	25,54	5,25	0,77	1,08	40,79
64	12,57	1,52	2,25	2,90	28,90
70	5,82	0,36	5,69	6,91	21,33
76	3,43	0,06	12,54	15,19	21,12
82	1,61	0,01	25,19	30,60	21,47

Table 25 - MSCR Results PA5_R Rep 2

PB5_R REP 1					
T [°]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	40,49	30,44	0,07	0,09	20,71
52	32,79	16,71	0,21	0,30	39,57
58	24,22	6,38	0,63	0,90	43,49
64	15,24	1,81	1,73	2,48	43,15
70	8,91	0,36	4,51	6,26	38,62
76	3,59	0,06	11,18	14,74	31,82
82	1,19	0,01	26,48	33,67	27,17

Table 26 - MSCR Results PB5_R (Rep 1)

PB5_R REP 2					
T [°]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	38,37	30,11	0,07	0,08	16,79
52	30,61	16,96	0,21	0,26	28,28
58	20,42	6,32	0,63	0,85	33,59
64	12,15	1,70	1,81	2,45	35,68
70	6,35	0,29	4,81	6,38	32,65
76	2,49	0,05	11,73	14,91	27,11
82	0,77	0,01	26,36	32,94	24,93

Table 27 - MSCR Results PB5_R (Rep 2)

PC5_P REP 1					
T [°]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	97,75	52,18	0,00	0,02	2463,28
52	92,35	36,28	0,01	0,07	906,87
58	67,27	21,47	0,07	0,23	213,02
64	49,32	9,83	0,26	0,68	160,20
70	36,24	3,76	0,75	1,96	163,20
76	19,88	1,39	2,78	4,84	74,22
82	12,04	0,12	6,20	10,92	76,11

Table 28 - MSCR Results PC5_R (Rep 1)

PC5_P REP 2					
T [°]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	64,58	43,83	0,02	0,03	67,93
52	50,84	31,54	0,06	0,09	45,08
58	52,05	17,97	0,16	0,30	93,28
64	34,20	7,27	0,53	0,93	73,79
70	26,38	2,40	1,41	2,54	79,86
76	16,87	0,80	3,66	5,93	62,14
82	11,29	0,23	8,24	13,21	60,38

Table 29 - MSCR Results PC5_R (Rep 2)

R Average					
Temp. [°C]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	20,70	17,06	0,20	0,21	5,57
52	12,98	7,50	0,59	0,65	9,72
58	7,55	2,38	1,60	1,81	13,00
64	3,92	0,59	4,05	4,61	13,85
70	1,66	0,07	9,52	10,72	12,72
76	0,60	0,01	20,28	22,56	11,23
82	0,31	0,00	39,89	43,90	10,03

Table 30 - R Average Results MSCR

PA5_R Average					
Temp.	R0.1	R3.2	Jnr0.1	Jnr3.2	Jnrdiff
[°C]	[%]	[%]	[kPa ⁻¹]	[kPa ⁻¹]	[%]
46	41,60	26,31	0,08	0,11	30,68
52	30,47	14,04	0,27	0,35	31,70
58	25,01	5,14	0,76	1,06	39,52
64	11,38	1,50	2,24	2,86	27,66
70	6,71	0,35	5,55	6,89	24,21
76	4,38	0,05	12,33	15,22	23,47
82	2,12	0,01	24,87	30,71	23,47

Table 31 - PA5_R Average Results MSCR

PB5_R Average					
Temp.	R0.1	R3.2	Jnr0.1	Jnr3.2	Jnrdiff
[°C]	[%]	[%]	[kPa ⁻¹]	[kPa ⁻¹]	[%]
46	39,43	30,27	0,07	0,08	18,75
52	31,70	16,83	0,21	0,28	33,93
58	22,32	6,35	0,63	0,87	38,54
64	13,70	1,76	1,77	2,47	39,42
70	7,63	0,32	4,66	6,32	35,63
76	3,04	0,06	11,46	14,83	29,46
82	0,98	0,01	26,42	33,30	26,05

Table 32 - PB5_R Average Results MSCR

PC5_R Average					
Temp.	R0.1	R3.2	Jnr0.1	Jnr3.2	Jnrdiff
[°C]	[%]	[%]	[kPa ⁻¹]	[kPa ⁻¹]	[%]
46	81,17	48,01	0,01	0,03	1265,61
52	71,59	33,91	0,04	0,08	475,97
58	59,66	19,72	0,11	0,26	153,15
64	41,76	8,55	0,40	0,80	117,00
70	31,31	3,08	1,08	2,25	121,53
76	18,38	1,10	3,22	5,39	68,18
82	11,67	0,17	7,22	12,06	68,24

Table 33 - PC5_R Average Results MSCR

Annex D

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, (e.g. 2 = polymer waste);
- Y → experimental test:
 - 1 = Complex Modulus and Phase Angle;
 - 2 = Penetration;
 - 3 = Ring and Ball;
 - 4 = Multiple Stress Creep and Recovery;
 - 5 = Bending Beam Rheometer;
- Z → Number of repetition.



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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 3.1.2.1. - 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: Teresa DI MARZO Materiale: 70100 RdP n°: 3.1/3.1.2.1/1

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	11,2294	81,82	4	1,00	5238,66	54,82
34	1,78	18,882	80,73	4	1,78	7432,79	52,26
34	3,16	31,5427	79,58	4	3,16	10348,9	49,69
34	5,62	52,3002	78,44	4	5,62	14145,2	47,21
34	10,00	86,1339	77,29	4	10,00	19010,2	44,81
34	17,80	140,826	76,09	4	17,80	25166,1	42,46
34	31,60	228,532	74,81	4	31,60	32813,5	40,19
34	56,20	367,787	73,41	4	56,20	42166,7	37,98
34	100,00	587,167	71,84	4	100,00	53417,3	35,83
28	1,00	33,6522	78,45				
28	1,78	55,7013	77,38				
28	3,16	91,4574	76,21				
28	5,62	149,014	74,99				
28	10,00	240,513	73,66				
28	17,80	384,796	72,19				
28	31,60	609,869	70,58				
28	56,20	955,929	68,79				
28	100,00	1481,43	66,71				
22	1,00	117,934	74,56				
22	1,78	190,851	73,30				
22	3,16	305,671	71,85				
22	5,62	484,395	70,28				
22	10,00	759,061	68,54				
22	17,80	1174,8	66,63				
22	31,60	1793,06	64,55				
22	56,20	2698,06	62,32				
22	100,00	4001,19	60,00				
16	1,00	431,13	69,71				
16	1,78	676,433	67,98				
16	3,16	1046,29	66,01				
16	5,62	1593,94	63,93				
16	10,00	2392,09	61,70				
16	17,80	3534,39	59,36				
16	31,60	5128,7	56,93				
16	56,20	7307,88	54,37				
16	100,00	10333,5	51,90				
10	1,00	1558,7	63,12				
10	1,78	2338,07	60,83				
10	3,16	3446,3	58,39				
10	5,62	4987,48	55,94				
10	10,00	7096,28	53,46				
10	17,80	9921,24	50,99				
10	31,60	13657,8	48,54				
10	56,20	18502,1	46,13				
10	100,00	24670,3	43,77				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements

Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP08
Materiale: 70100

Aging: Original
Ripetizione: 2
RdP n°: 3.1/3.1.2.1/2

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	10,40	81,33	4	1,00	5179,99	53,07
34	1,78	17,44	80,33	4	1,78	7262,29	50,55
34	3,16	29,06	79,22	4	3,16	9991,23	48,04
34	5,62	48,09	78,11	4	5,62	13499,8	45,66
34	10,00	79,02	76,97	4	10,00	17949,3	43,36
34	17,80	128,95	75,76	4	17,80	23518,6	41,15
34	31,60	208,80	74,43	4	31,60	30388,7	39,01
34	56,20	335,56	72,91	4	56,20	38728,4	36,94
34	100,00	535,16	71,38	4	100,00	48707,5	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	17,80	356,14	71,72				
28	31,60	562,48	70,06				
28	56,20	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	17,80	1114,56	65,84				
22	31,60	1692,20	63,73				
22	56,20	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	17,80	3350,56	58,33				
16	31,60	4829,96	55,90				
16	56,20	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	17,80	9362,12	49,70				
10	31,60	12780,80	47,31				
10	56,20	17177,40	44,97				
10	100,00	22738,80	42,70				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data: 06/05/2025 **Strumento:** MCR 301 **Aging:** Original
Unità: POLITO **Geometria:** PP25 **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** 70100 **RdP n°:** 3.1/3.1.2.1/3

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	72,37	64	100,00	7,47427	84,78
34	56,20	307,441	73,81	64	56,20	4,32927	85,58
34	31,60	190,505	75,14	64	31,60	2,49218	86,30
34	17,80	117,155	76,39	64	17,80	1,4298	87,01
34	10,00	71,509	77,56	64	10,00	0,816832	87,63
34	5,62	43,344	78,70	64	5,62	0,464258	88,13
34	3,16	26,100	79,82	64	3,16	0,263188	88,52
34	1,78	15,610	80,92	64	1,78	0,148777	88,79
34	1,00	9,274	82,00	64	1,00	0,0840155	88,97
40	100,00	201,487	75,83	70	100,00	3,7019	85,54
40	56,20	123,541	77,06	70	56,20	2,12966	86,72
40	31,60	75,206	78,21	70	31,60	1,21817	87,43
40	17,80	45,433	79,31	70	17,80	0,693596	88,00
40	10,00	27,249	80,38	70	10,00	0,393622	88,48
40	5,62	16,223	81,44	70	5,62	0,222625	88,81
40	3,16	9,588	82,48	70	3,16	0,12575	89,03
40	1,78	5,629	83,48	70	1,78	0,0710119	89,14
40	1,00	3,284	84,44	70	1,00	0,0400614	89,20
46	100,00	83,326	78,75	76	100	1,95244	86,87
46	56,20	50,168	79,84	76	56,2	1,11559	87,44
46	31,60	29,989	80,88	76	31,6	0,634321	88,21
46	17,80	17,802	81,90	76	17,8	0,359217	88,75
46	10,00	10,496	82,89	76	10	0,202798	88,98
46	5,62	6,149	83,83	76	5,62	0,11445	89,24
46	3,16	3,582	84,72	76	3,16	0,0645012	89,35
46	1,78	2,076	85,55	76	1,78	0,0363433	89,36
46	1,00	1,196	86,31	76	1,00	0,0204767	89,36
52	100,00	35,525	81,12	82	100	1,08153	86,43
52	56,20	21,055	82,16	82	56,2	0,616082	87,60
52	31,60	12,402	83,14	82	31,6	0,349034	88,48
52	17,80	7,260	84,05	82	17,8	0,196694	88,91
52	10,00	4,225	84,90	82	10	0,110866	89,24
52	5,62	2,445	85,68	82	5,62	0,0624576	89,32
52	3,16	1,407	86,40	82	3,16	0,0351483	89,32
52	1,78	0,807	87,06	82	1,78	0,0198251	89,31
52	1,00	0,460	87,65	82	1,00	0,0112011	89,25
58	100,00	15,895	82,97				
58	56,20	9,313	84,04				
58	31,60	5,423	84,93				
58	17,80	3,138	85,71				
58	10,00	1,806	86,40				
58	5,62	1,036	87,05				
58	3,16	0,591	87,63				
58	1,78	0,336	88,12				
58	1,00	0,191	88,51				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data:	06/05/2025	Strumento:	MCR 301	Aging:	Original
Unità:	POLITO	Geometria:	PP25	Ripetizione:	2
Operatore:	Teresa DI MARZO	Materiale:	70100	RdP n°:	3.1/3.1.2.1/4

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	72,08	64	100,00	7,55283	84,76
34	56,20	321,384	73,56	64	56,20	4,37419	85,56
34	31,60	199,669	74,97	64	31,60	2,51794	86,32
34	17,80	122,987	76,26	64	17,80	1,44439	87,09
34	10,00	75,172	77,48	64	10,00	0,824984	87,78
34	5,62	45,618	78,66	64	5,62	0,46857	88,34
34	3,16	27,488	79,83	64	3,16	0,265354	88,78
34	1,78	16,437	80,97	64	1,78	0,149877	89,09
34	1,00	9,761	82,10	64	1,00	0,0846036	89,29
40	100,00	210,378	75,72	70	100,00	3,81445	85,53
40	56,20	128,780	76,95	70	56,20	2,19424	86,70
40	31,60	78,253	78,12	70	31,60	1,25488	87,44
40	17,80	47,222	79,25	70	17,80	0,714475	88,08
40	10,00	28,312	80,36	70	10,00	0,405068	88,62
40	5,62	16,863	81,45	70	5,62	0,228846	89,00
40	3,16	9,975	82,52	70	3,16	0,129106	89,27
40	1,78	5,860	83,54	70	1,78	0,0727801	89,41
40	1,00	3,417	84,52	70	1,00	0,0409959	89,50
46	100,00	86,202	78,65	76	100	2,01776	86,78
46	56,20	51,940	79,76	76	56,2	1,15328	87,15
46	31,60	31,063	80,83	76	31,6	0,656017	88,12
46	17,80	18,437	81,87	76	17,8	0,371404	88,82
46	10,00	10,862	82,89	76	10	0,209507	89,11
46	5,62	6,359	83,88	76	5,62	0,118185	89,36
46	3,16	3,703	84,81	76	3,16	0,0665488	89,50
46	1,78	2,146	85,69	76	1,78	0,0374721	89,55
46	1,00	1,235	86,51	76	1,00	0,0210966	89,59
52	100,00	36,214	80,95	82	100	1,12774	87,31
52	56,20	21,479	82,05	82	56,2	0,644485	87,78
52	31,60	12,673	83,09	82	31,6	0,364739	88,50
52	17,80	7,432	84,05	82	17,8	0,20602	89,09
52	10,00	4,327	84,95	82	10	0,116079	89,32
52	5,62	2,501	85,78	82	5,62	0,0653935	89,47
52	3,16	1,439	86,57	82	3,16	0,0368155	89,54
52	1,78	0,824	87,30	82	1,78	0,0207312	89,55
52	1,00	0,469	87,96	82	1,00	0,0116721	89,51
58	100,00	16,068	83,23				
58	56,20	9,396	84,08				
58	31,60	5,462	84,94				
58	17,80	3,161	85,78				
58	10,00	1,820	86,55				
58	5,62	1,042	87,26				
58	3,16	0,594	87,90				
58	1,78	0,337	88,43				
58	1,00	0,190	88,85				



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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 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data:	06/05/2025	Strumento:	MCR 301	Aging:	RTFOT
Unità:	POLITO	Geometria:	PP08	Ripetizione:	1
Operatore:	Teresa DI MARZO	Materiale:	70100	RdP n°:	3.1/3.1.2.1/5

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	41,6571	74,13	4	1,00	11172,1	43,77
34	1,78	66,5557	72,72	4	1,78	14755,8	41,78
34	3,16	105,49	71,31	4	3,16	19223,7	39,87
34	5,62	165,745	69,91	4	5,62	24699,8	38,06
34	10,00	258,166	68,50	4	10,00	31354,5	36,33
34	17,80	398,648	67,05	4	17,80	39383,1	34,68
34	31,60	610,011	65,54	4	31,60	48935,7	33,08
34	56,20	924,12	63,95	4	56,20	60180,6	31,53
34	100,00	1386,12	62,19	4	100,00	73297	30,01
28	1,00	123,243	69,80				
28	1,78	192,455	68,38				
28	3,16	297,48	66,91				
28	5,62	455,354	65,38				
28	10,00	689,814	63,80				
28	17,80	1033,71	62,13				
28	31,60	1532,12	60,35				
28	56,20	2245,96	58,49				
28	100,00	3252,44	56,59				
22	1,00	413,583	64,55				
22	1,78	625,324	62,93				
22	3,16	934,258	61,22				
22	5,62	1379,44	59,41				
22	10,00	2011,23	57,55				
22	17,80	2895,5	55,63				
22	31,60	4111,09	53,65				
22	56,20	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	17,80	7537,31	48,47				
16	31,60	10200,6	46,49				
16	56,20	13670,9	44,56				
16	100,00	18060,5	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	10428,5	45,04				
10	10,00	13832,5	43,11				
10	17,80	18120,5	41,25				
10	31,60	23466	39,45				
10	56,20	30043,5	37,73				
10	100,00	38034,6	36,05				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements

Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP08
Materiale: 70100

Aging: RTFOT
Ripetizione: 2
RdP n°: 3.1/3.1.2.1/6

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	31,35	74,39	4	1,00	8564,49	44,07
34	1,78	50,21	72,94	4	1,78	11325,4	42,06
34	3,16	79,72	71,52	4	3,16	14770,1	40,13
34	5,62	125,45	70,11	4	5,62	18999,4	38,32
34	10,00	195,75	68,72	4	10,00	24136	36,59
34	17,80	302,64	67,27	4	17,80	30355,9	34,92
34	31,60	463,70	65,72	4	31,60	37769,6	33,31
34	56,20	704,25	64,06	4	56,20	46526,9	31,76
34	100,00	1061,23	62,10	4	100,00	56765,2	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	17,80	798,89	62,30				
28	31,60	1186,78	60,54				
28	56,20	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	17,80	2219,73	55,88				
22	31,60	3157,57	53,91				
22	56,20	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	17,80	5760,97	48,76				
16	31,60	7802,30	46,78				
16	56,20	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	17,80	13937,80	41,50				
10	31,60	18091,80	39,69				
10	56,20	23188,60	37,94				
10	100,00	29404,90	36,25				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data:	06/05/2025	Strumento:	MCR 302	Aging:	RTFOT
Unità:	POLITO	Geometria:	PP25	Ripetizione:	1
Operatore:	Teresa DI MARZO	Materiale:	70100	RdP n°:	3.1/3.1.2.1/7

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	63,65	64	100,00	17,6138	80,15
34	56,20	775,827	65,13	64	56,20	10,4941	81,46
34	31,60	508,940	66,57	64	31,60	6,20224	82,68
34	17,80	330,832	67,98	64	17,80	3,63639	83,84
34	10,00	213,237	69,34	64	10,00	2,11673	84,93
34	5,62	136,347	70,69	64	5,62	1,22323	85,95
34	3,16	86,470	72,05	64	3,16	0,702034	86,90
34	1,78	54,378	73,45	64	1,78	0,400016	87,71
34	1,00	33,902	74,89	64	1,00	0,22681	88,38
40	100,00	490,986	67,93	70	100,00	8,48823	82,23
40	56,20	316,464	69,27	70	56,20	4,9837	83,45
40	31,60	202,296	70,58	70	31,60	2,9052	84,55
40	17,80	128,306	71,87	70	17,80	1,6829	85,60
40	10,00	80,714	73,17	70	10,00	0,968621	86,58
40	5,62	50,347	74,51	70	5,62	0,553963	87,45
40	3,16	31,128	75,91	70	3,16	0,314887	88,18
40	1,78	19,064	77,36	70	1,78	0,178173	88,74
40	1,00	11,558	78,84	70	1,00	0,10043	89,14
46	100,00	202,271	71,72	76	100	4,32202	83,71
46	56,20	127,341	72,97	76	56,2	2,51151	85,00
46	31,60	79,539	74,21	76	31,6	1,45046	86,05
46	17,80	49,292	75,49	76	17,8	0,832028	86,98
46	10,00	30,301	76,82	76	10	0,47454	87,80
46	5,62	18,461	78,18	76	5,62	0,269179	88,47
46	3,16	11,143	79,59	76	3,16	0,152105	88,97
46	1,78	6,662	80,98	76	1,78	0,0857308	89,28
46	1,00	3,945	82,33	76	1,00	0,0482575	89,45
52	100,00	87,298	74,89	82	100	2,32675	84,67
52	56,20	53,892	76,13	82	56,2	1,33994	86,04
52	31,60	33,009	77,40	82	31,6	0,767286	87,16
52	17,80	20,049	78,70	82	17,8	0,436776	88,01
52	10,00	12,069	80,03	82	10	0,247398	88,64
52	5,62	7,197	81,36	82	5,62	0,13961	89,08
52	3,16	4,253	82,65	82	3,16	0,0786812	89,34
52	1,78	2,493	83,87	82	1,78	0,0442932	89,46
52	1,00	1,449	85,01	82	1,00	0,0248923	89,49
58	100,00	38,285	77,74				
58	56,20	23,178	79,00				
58	31,60	13,924	80,28				
58	17,80	8,298	81,55				
58	10,00	4,904	82,80				
58	5,62	2,874	83,98				
58	3,16	1,671	85,09				
58	1,78	0,964	86,12				
58	1,00	0,552	87,05				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data:	06/05/2025	Strumento:	MCR 302	Aging:	RTFOT
Unità:	POLITO	Geometria:	PP25	Ripetizione:	2
Operatore:	Teresa DI MARZO	Materiale:	70100	RdP n°:	3.1/3.1.2.1/8

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	63,74	64	100,00	17,0278	80,20
34	56,20	751,708	65,22	64	56,20	10,14	81,52
34	31,60	492,743	66,67	64	31,60	5,9901	82,72
34	17,80	320,037	68,08	64	17,80	3,5105	83,87
34	10,00	206,092	69,45	64	10,00	2,04277	84,95
34	5,62	131,595	70,81	64	5,62	1,18058	85,96
34	3,16	83,350	72,18	64	3,16	0,678171	86,89
34	1,78	52,350	73,59	64	1,78	0,386561	87,70
34	1,00	32,603	75,06	64	1,00	0,219202	88,36
40	100,00	475,934	67,88	70	100,00	8,17246	82,41
40	56,20	306,955	69,26	70	56,20	4,79986	83,61
40	31,60	196,430	70,60	70	31,60	2,79711	84,65
40	17,80	124,646	71,90	70	17,80	1,61912	85,66
40	10,00	78,468	73,22	70	10,00	0,931461	86,59
40	5,62	49,000	74,57	70	5,62	0,532614	87,43
40	3,16	30,323	75,98	70	3,16	0,30277	88,14
40	1,78	18,585	77,44	70	1,78	0,171336	88,70
40	1,00	11,270	78,93	70	1,00	0,0966119	89,09
46	100,00	197,209	71,69	76	100	4,1199	83,74
46	56,20	124,057	72,94	76	56,2	2,39395	85,00
46	31,60	77,481	74,20	76	31,6	1,38204	86,07
46	17,80	48,008	75,49	76	17,8	0,792677	86,98
46	10,00	29,504	76,81	76	10	0,452085	87,77
46	5,62	17,982	78,20	76	5,62	0,256575	88,40
46	3,16	10,858	79,61	76	3,16	0,14508	88,87
46	1,78	6,493	81,02	76	1,78	0,0818584	89,19
46	1,00	3,846	82,38	76	1,00	0,0460614	89,36
52	100,00	83,672	74,98	82	100	2,19118	84,76
52	56,20	51,589	76,19	82	56,2	1,26157	86,06
52	31,60	31,571	77,45	82	31,6	0,721668	87,05
52	17,80	19,167	78,74	82	17,8	0,410711	87,90
52	10,00	11,533	80,07	82	10	0,232892	88,54
52	5,62	6,878	81,40	82	5,62	0,131525	88,95
52	3,16	4,065	82,69	82	3,16	0,074148	89,19
52	1,78	2,383	83,91	82	1,78	0,0417604	89,32
52	1,00	1,386	85,06	82	1,00	0,0235091	89,35
58	100,00	36,612	77,75				
58	56,20	22,150	79,04				
58	31,60	13,302	80,32				
58	17,80	7,928	81,59				
58	10,00	4,687	82,82				
58	5,62	2,748	83,99				
58	3,16	1,597	85,10				
58	1,78	0,921	86,13				
58	1,00	0,527	87,06				



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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 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data:	06/05/2025	Strumento:	MCR 301	Aging:	PAV
Unità:	POLITO	Geometria:	PP08	Ripetizione:	1
Operatore:	Teresa DI MARZO	Materiale:	70100	RdP n°:	3.1/3.1.2.1/9

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	126,158	63,04	4	1,00	13218,7	34,66
34	1,78	187,726	61,43	4	1,78	16459,6	33,23
34	3,16	276,653	59,81	4	3,16	20308,6	31,85
34	5,62	403,358	58,21	4	5,62	24819,9	30,57
34	10,00	581,852	56,61	4	10,00	30079,2	29,37
34	17,80	831,02	55,03	4	17,80	36204,4	28,21
34	31,60	1175,07	53,44	4	31,60	43253,9	27,10
34	56,20	1644,47	51,86	4	56,20	51316,8	26,03
34	100,00	2277,83	50,30	4	100,00	60444,4	24,99
28	1,00	341,666	57,99				
28	1,78	493,868	56,31				
28	3,16	705,216	54,61				
28	5,62	995,02	52,93				
28	10,00	1388,54	51,28				
28	17,80	1917,25	49,64				
28	31,60	2619,84	48,01				
28	56,20	3545,31	46,42				
28	100,00	4748,01	44,91				
22	1,00	947,7	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	17,80	4424,78	43,77				
22	31,60	5822,15	42,23				
22	56,20	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	17,80	9557,65	38,12				
16	31,60	12139,5	36,73				
16	56,20	15289,4	35,39				
16	100,00	19078,8	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	12421,5	35,58				
10	10,00	15532,6	34,22				
10	17,80	19258	32,92				
10	31,60	23686,4	31,68				
10	56,20	28907,2	30,50				
10	100,00	35014,4	29,36				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP08
Materiale: 70100

Aging: PAV
Ripetizione: 2
RdP n°: 3.1/3.1.2.1/10

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	152,06	63,07	4	1,00	16944	34,23
34	1,78	226,12	61,46	4	1,78	21030,2	32,79
34	3,16	333,18	59,84	4	3,16	25850,3	31,43
34	5,62	485,69	58,24	4	5,62	31491,1	30,15
34	10,00	700,95	56,64	4	10,00	38039,7	28,95
34	17,80	1001,48	55,06	4	17,80	45623,2	27,80
34	31,60	1416,56	53,47	4	31,60	54308,5	26,70
34	56,20	1983,70	51,89	4	56,20	64218,4	25,62
34	100,00	2749,97	50,33	4	100,00	75448,9	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	17,80	2331,19	49,64				
28	31,60	3183,14	48,02				
28	56,20	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	17,80	5482,41	43,62				
22	31,60	7202,33	42,07				
22	56,20	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	17,80	11963,30	37,87				
16	31,60	15173,60	36,47				
16	56,20	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	17,80	24177,50	32,59				
10	31,60	29651,20	31,36				
10	56,20	36086,40	30,18				
10	100,00	43606,50	29,03				



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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 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data: 06/05/2025 **Strumento:** MCR 302 **Aging:** PAV
Unità: POLITO **Geometria:** PP25 **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** 70100 **RdP n°:** 3.1/3.1.2.1/11

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	52,13	64	100,00	55,9269	72,20
34	56,20	2197,860	53,30	64	56,20	35,1309	73,68
34	31,60	1559,480	54,58	64	31,60	21,8784	75,18
34	17,80	1096,600	55,95	64	17,80	13,4949	76,73
34	10,00	764,038	57,36	64	10,00	8,23662	78,32
34	5,62	527,486	58,82	64	5,62	4,96993	79,92
34	3,16	360,738	60,31	64	3,16	2,96362	81,49
34	1,78	244,402	61,84	64	1,78	1,74736	82,96
34	1,00	164,134	63,41	64	1,00	1,02067	84,28
40	100,00	1385,250	56,61	70	100,00	26,8655	75,49
40	56,20	961,220	57,91	70	56,20	16,5262	76,93
40	31,60	661,098	59,27	70	31,60	10,0648	78,40
40	17,80	450,658	60,67	70	17,80	6,06615	79,91
40	10,00	304,376	62,09	70	10,00	3,61627	81,40
40	5,62	203,878	63,54	70	5,62	2,13332	82,83
40	3,16	135,251	65,04	70	3,16	1,24646	84,15
40	1,78	88,863	66,61	70	1,78	0,72077	85,29
40	1,00	57,741	68,24	70	1,00	0,415511	86,29
46	100,00	610,839	61,14	76	100	12,9209	78,33
46	56,20	411,785	62,45	76	56,2	7,79134	79,73
46	31,60	275,187	63,79	76	31,6	4,65159	81,18
46	17,80	182,211	65,17	76	17,8	2,75118	82,59
46	10,00	119,580	66,60	76	10	1,61174	83,91
46	5,62	77,744	68,10	76	5,62	0,936063	85,08
46	3,16	50,043	69,66	76	3,16	0,538953	86,09
46	1,78	31,891	71,32	76	1,78	0,30895	86,93
46	1,00	20,098	73,07	76	1,00	0,176405	87,60
52	100,00	272,465	65,23	82	100	6,44384	80,81
52	56,20	178,834	66,52	82	56,2	3,82569	82,15
52	31,60	116,400	67,86	82	31,6	2,24853	83,44
52	17,80	75,105	69,27	82	17,8	1,3105	84,66
52	10,00	48,008	70,76	82	10	0,758381	85,76
52	5,62	30,386	72,33	82	5,62	0,435585	86,66
52	3,16	19,038	73,99	82	3,16	0,248789	87,39
52	1,78	11,796	75,73	82	1,78	0,141593	87,96
52	1,00	7,226	77,52	82	1,00	0,0801846	88,40
58	100,00	122,285	68,94				
58	56,20	78,458	70,27				
58	31,60	49,904	71,67				
58	17,80	31,457	73,14				
58	10,00	19,640	74,70				
58	5,62	12,128	76,33				
58	3,16	7,402	78,02				
58	1,78	4,466	79,72				
58	1,00	2,660	81,35				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Neat Bitumen

Data:	06/05/2025	Strumento:	MCR 302	Aging:	PAV
Unità:	POLITO	Geometria:	PP25	Ripetizione:	2
Operatore:	Teresa DI MARZO	Materiale:	70100	RdP n°:	3.1/3.1.2.1/12

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	51,73	64	100,00	56,5524	72,43
34	56,20	2232,530	52,91	64	56,20	35,4448	73,83
34	31,60	1587,220	54,29	64	31,60	22,0145	75,29
34	17,80	1117,690	55,73	64	17,80	13,5381	76,83
34	10,00	779,661	57,20	64	10,00	8,23795	78,43
34	5,62	538,400	58,71	64	5,62	4,95728	80,04
34	3,16	368,478	60,23	64	3,16	2,95012	81,61
34	1,78	249,702	61,80	64	1,78	1,73813	83,10
34	1,00	167,749	63,37	64	1,00	1,01286	84,43
40	100,00	1411,920	56,26	70	100,00	26,5077	75,47
40	56,20	981,057	57,66	70	56,20	16,2754	76,98
40	31,60	675,679	59,07	70	31,60	9,90073	78,52
40	17,80	461,018	60,50	70	17,80	5,96173	80,04
40	10,00	311,952	61,94	70	10,00	3,55154	81,55
40	5,62	209,117	63,42	70	5,62	2,09388	82,99
40	3,16	138,807	64,94	70	3,16	1,22273	84,31
40	1,78	91,252	66,51	70	1,78	0,706432	85,44
40	1,00	59,369	68,15	70	1,00	0,406477	86,45
46	100,00	612,745	60,96	76	100	12,7673	78,17
46	56,20	413,116	62,33	76	56,2	7,69086	79,77
46	31,60	276,265	63,70	76	31,6	4,58929	81,28
46	17,80	183,107	65,09	76	17,8	2,71273	82,71
46	10,00	120,308	66,53	76	10	1,58856	84,03
46	5,62	78,338	68,02	76	5,62	0,922462	85,21
46	3,16	50,547	69,60	76	3,16	0,531511	86,23
46	1,78	32,270	71,25	76	1,78	0,304318	87,07
46	1,00	20,383	73,00	76	1,00	0,173226	87,74
52	100,00	271,143	65,19	82	100	6,40092	80,59
52	56,20	178,030	66,53	82	56,2	3,79336	82,15
52	31,60	115,912	67,90	82	31,6	2,22722	83,54
52	17,80	74,816	69,31	82	17,8	1,29694	84,77
52	10,00	47,857	70,81	82	10	0,749339	85,87
52	5,62	30,315	72,39	82	5,62	0,430029	86,79
52	3,16	19,001	74,06	82	3,16	0,24545	87,53
52	1,78	11,778	75,81	82	1,78	0,139492	88,10
52	1,00	7,212	77,60	82	1,00	0,0790507	88,48
58	100,00	123,220	68,97				
58	56,20	78,959	70,31				
58	31,60	50,170	71,71				
58	17,80	31,579	73,20				
58	10,00	19,679	74,77				
58	5,62	12,133	76,42				
58	3,16	7,397	78,12				
58	1,78	4,459	79,82				
58	1,00	2,658	81,47				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic A

Data: 06/05/2025 Strumento: MCR 301 Aging: Original
Unità: POLITO Geometria: PP08 Ripetizione: 1
Operatore: Teresa DI MARZO Materiale: PA5 RdP n°: 3.1/3.1.2.1/13

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	24,7888	75,67	4	1,00	8835,42	48,46
34	1,78	39,9711	74,68	4	1,78	12022	46,24
34	3,16	64,1211	73,60	4	3,16	16097,1	44,04
34	5,62	102,189	72,52	4	5,62	21217,9	41,93
34	10,00	161,762	71,42	4	10,00	27567	39,90
34	17,80	254,261	70,27	4	17,80	35388,2	37,92
34	31,60	396,974	69,06	4	31,60	44842,8	36,01
34	56,20	615,037	67,73	4	56,20	56131,9	34,14
34	100,00	947,223	66,14	4	100,00	69450,7	32,32
28	1,00	70,3726	72,45				
28	1,78	111,745	71,40				
28	3,16	176,104	70,26				
28	5,62	275,49	69,07				
28	10,00	427,487	67,81				
28	17,80	658,076	66,43				
28	31,60	1003,99	64,91				
28	56,20	1516,57	63,27				
28	100,00	2266,06	61,51				
22	1,00	240,882	68,12				
22	1,78	372,975	66,95				
22	3,16	572,513	65,61				
22	5,62	869,871	64,15				
22	10,00	1307,81	62,54				
22	17,80	1944,86	60,79				
22	31,60	2856,87	58,89				
22	56,20	4145,81	56,84				
22	100,00	5944,09	54,79				
16	1,00	839,622	63,04				
16	1,78	1257,66	61,48				
16	3,16	1862,83	59,70				
16	5,62	2723,32	57,81				
16	10,00	3927,15	55,81				
16	17,80	5583,82	53,72				
16	31,60	7811,76	51,58				
16	56,20	10813,7	49,40				
16	100,00	14696,8	47,05				
10	1,00	2822,5	56,50				
10	1,78	4050,55	54,46				
10	3,16	5726,8	52,29				
10	5,62	7965,99	50,12				
10	10,00	10917	47,95				
10	17,80	14723,7	45,80				
10	31,60	19633,9	43,68				
10	56,20	25798,5	41,61				
10	100,00	33448	39,58				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements

Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic A

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP08
Materiale: PA5

Aging: Original
Ripetizione: 2
RdP n°: 3.1/3.1.2.1/14

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	21,43	76,38	4	1,00	7576,55	48,98
34	1,78	34,73	75,32	4	1,78	10326,1	46,78
34	3,16	55,94	74,17	4	3,16	13857,7	44,58
34	5,62	89,48	73,01	4	5,62	18313,1	42,47
34	10,00	142,07	71,85	4	10,00	23852,4	40,42
34	17,80	223,92	70,63	4	17,80	30694,6	38,44
34	31,60	350,46	69,37	4	31,60	38998,3	36,50
34	56,20	544,16	68,03	4	56,20	48944,5	34,61
34	100,00	839,29	66,51	4	100,00	60725,9	32,76
28	1,00	62,48	72,79				
28	1,78	99,51	71,71				
28	3,16	157,18	70,53				
28	5,62	246,29	69,29				
28	10,00	382,73	67,99				
28	17,80	589,96	66,59				
28	31,60	901,14	65,07				
28	56,20	1362,70	63,44				
28	100,00	2038,40	61,70				
22	1,00	212,61	68,37				
22	1,78	329,72	67,19				
22	3,16	506,82	65,82				
22	5,62	771,01	64,35				
22	10,00	1160,19	62,75				
22	17,80	1727,63	61,00				
22	31,60	2542,87	59,12				
22	56,20	3696,98	57,11				
22	100,00	5308,25	55,07				
16	1,00	729,23	63,33				
16	1,78	1095,33	61,78				
16	3,16	1626,24	60,01				
16	5,62	2381,52	58,14				
16	10,00	3440,42	56,17				
16	17,80	4901,54	54,09				
16	31,60	6873,32	51,96				
16	56,20	9527,14	49,78				
16	100,00	12998,20	47,45				
10	1,00	2452,37	56,85				
10	1,78	3526,69	54,83				
10	3,16	4996,18	52,68				
10	5,62	6964,06	50,53				
10	10,00	9563,36	48,36				
10	17,80	12925,80	46,21				
10	31,60	17262,20	44,08				
10	56,20	22725,10	41,99				
10	100,00	29529,90	39,94				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic A

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 302
Geometria: PP25
Materiale: PA5

Aging: Original
Ripetizione: 1
RdP n°: 3.1/3.1.2.1/15

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	810,597	67,80	64	100,00	13,2239	80,80
34	56,20	522,894	69,20	64	56,20	7,84708	81,74
34	31,60	334,404	70,52	64	31,60	4,63088	82,59
34	17,80	212,124	71,77	64	17,80	2,72076	83,38
34	10,00	133,540	72,97	64	10,00	1,59118	84,08
34	5,62	83,487	74,13	64	5,62	0,925709	84,68
34	3,16	51,786	75,30	64	3,16	0,536505	85,15
34	1,78	31,882	76,51	64	1,78	0,310104	85,41
34	1,00	19,419	77,77	64	1,00	0,178937	85,53
40	100,00	331,734	71,54	70	100,00	6,66315	82,01
40	56,20	208,922	72,76	70	56,20	3,9174	83,05
40	31,60	130,627	73,92	70	31,60	2,29226	83,85
40	17,80	81,082	75,07	70	17,80	1,33512	84,53
40	10,00	49,977	76,21	70	10,00	0,774509	85,07
40	5,62	30,578	77,35	70	5,62	0,447735	85,45
40	3,16	18,570	78,49	70	3,16	0,258362	85,65
40	1,78	11,198	79,61	70	1,78	0,149095	85,67
40	1,00	6,704	80,69	70	1,00	0,0860316	85,62
46	100,00	138,365	74,57	76	100	3,5513	82,80
46	56,20	85,550	75,67	76	56,2	2,07491	83,79
46	31,60	52,561	76,76	76	31,6	1,20667	84,53
46	17,80	32,064	77,85	76	17,8	0,699174	85,06
46	10,00	19,419	78,94	76	10	0,404197	85,40
46	5,62	11,678	80,00	76	5,62	0,233395	85,51
46	3,16	6,973	81,01	76	3,16	0,134837	85,49
46	1,78	4,137	81,96	76	1,78	0,0780566	85,34
46	1,00	2,439	82,85	76	1,00	0,0451774	85,15
52	100,00	60,476	77,06	82	100	2,01504	83,15
52	56,20	36,790	78,09	82	56,2	1,17209	84,14
52	31,60	22,239	79,12	82	31,6	0,678844	84,86
52	17,80	13,357	80,12	82	17,8	0,392577	85,27
52	10,00	7,969	81,09	82	10	0,226761	85,37
52	5,62	4,725	82,00	82	5,62	0,131195	85,31
52	3,16	2,787	82,84	82	3,16	0,0760572	85,15
52	1,78	1,635	83,62	82	1,78	0,0442153	84,90
52	1,00	0,954	84,31	82	1,00	0,0257559	84,65
58	100,00	27,643	79,08				
58	56,20	16,600	80,09				
58	31,60	9,908	81,04				
58	17,80	5,880	81,93				
58	10,00	3,471	82,76				
58	5,62	2,037	83,52				
58	3,16	1,189	84,20				
58	1,78	0,691	84,76				
58	1,00	0,400	85,16				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic A

Data:	06/05/2025	Strumento:	MCR 302	Aging:	Original
Unità:	POLITO	Geometria:	PP25	Ripetizione:	2
Operatore:	Teresa DI MARZO	Materiale:	PA5	RdP n°:	3.1/3.1.2.1/16

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	799,664	67,45	64	100,00	14,0944	80,31
34	56,20	516,618	68,84	64	56,20	8,40238	81,22
34	31,60	331,015	70,15	64	31,60	4,97483	82,00
34	17,80	210,468	71,38	64	17,80	2,93227	82,78
34	10,00	132,918	72,54	64	10,00	1,72068	83,49
34	5,62	83,397	73,74	64	5,62	1,00372	84,08
34	3,16	51,969	74,94	64	3,16	0,584669	84,52
34	1,78	32,162	76,14	64	1,78	0,339391	84,76
34	1,00	19,777	77,33	64	1,00	0,196643	84,86
40	100,00	322,740	70,84	70	100,00	7,19513	81,28
40	56,20	204,885	72,14	70	56,20	4,25131	82,42
40	31,60	129,338	73,35	70	31,60	2,49791	83,19
40	17,80	81,090	74,49	70	17,80	1,46094	83,87
40	10,00	50,491	75,62	70	10,00	0,851385	84,43
40	5,62	31,209	76,78	70	5,62	0,494206	84,80
40	3,16	19,139	77,94	70	3,16	0,286447	85,00
40	1,78	11,643	79,06	70	1,78	0,166095	85,00
40	1,00	7,023	80,13	70	1,00	0,0963332	84,97
46	100,00	140,584	73,99	76	100	3,93874	81,87
46	56,20	87,168	75,09	76	56,2	2,31248	83,22
46	31,60	53,757	76,15	76	31,6	1,3502	83,90
46	17,80	32,972	77,24	76	17,8	0,785438	84,44
46	10,00	20,103	78,34	76	10	0,45581	84,82
46	5,62	12,160	79,40	76	5,62	0,263976	84,98
46	3,16	7,293	80,43	76	3,16	0,152977	84,98
46	1,78	4,341	81,37	76	1,78	0,0887525	84,85
46	1,00	2,569	82,25	76	1,00	0,0515877	84,70
52	100,00	62,060	76,26	82	100	2,21845	83,24
52	56,20	37,938	77,39	82	56,2	1,30841	83,97
52	31,60	23,084	78,48	82	31,6	0,760335	84,53
52	17,80	13,957	79,51	82	17,8	0,440865	84,91
52	10,00	8,369	80,49	82	10	0,255383	85,06
52	5,62	4,978	81,41	82	5,62	0,148216	85,04
52	3,16	2,945	82,26	82	3,16	0,0860684	84,92
52	1,78	1,735	83,01	82	1,78	0,0500636	84,72
52	1,00	1,016	83,66	82	1,00	0,0291548	84,48
58	100,00	28,719	78,25				
58	56,20	17,348	79,43				
58	31,60	10,416	80,45				
58	17,80	6,206	81,34				
58	10,00	3,673	82,17				
58	5,62	2,163	82,92				
58	3,16	1,267	83,59				
58	1,78	0,739	84,09				
58	1,00	0,430	84,46				



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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 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic A

Data: 06/05/2025 Strumento: MCR 301 Aging: RTFOT
Unità: POLITO Geometria: PP08 Ripetizione: 1
Operatore: Teresa DI MARZO Materiale: PA5 RdP n°: 3.1/3.1.2.1/17

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	42,8241	70,90	4	1,00	10204,5	39,77
34	1,78	66,9342	69,54	4	1,78	13115,1	37,99
34	3,16	103,781	68,15	4	3,16	16651,7	36,28
34	5,62	159,776	66,76	4	5,62	20885,3	34,69
34	10,00	243,847	65,34	4	10,00	25923,9	33,18
34	17,80	368,864	63,86	4	17,80	31893,6	31,72
34	31,60	552,667	62,30	4	31,60	38869,8	30,32
34	56,20	819,293	60,69	4	56,20	46972,7	28,95
34	100,00	1201,08	59,02	4	100,00	56286,5	27,60
28	1,00	123,562	66,49				
28	1,78	188,851	65,10				
28	3,16	286,049	63,62				
28	5,62	428,802	62,07				
28	10,00	636,047	60,45				
28	17,80	932,997	58,73				
28	31,60	1352,16	56,94				
28	56,20	1936,09	55,08				
28	100,00	2738,49	53,20				
22	1,00	406,923	60,98				
22	1,78	601,367	59,38				
22	3,16	878,099	57,65				
22	5,62	1266,13	55,83				
22	10,00	1801,5	53,97				
22	17,80	2528,39	52,06				
22	31,60	3500,7	50,14				
22	56,20	4792	48,18				
22	100,00	6494,93	46,28				
16	1,00	1294,21	54,62				
16	1,78	1832,11	52,71				
16	3,16	2558,05	50,72				
16	5,62	3519,79	48,77				
16	10,00	4778,56	46,85				
16	17,80	6404,34	44,98				
16	31,60	8463,31	43,16				
16	56,20	11097,2	41,40				
16	100,00	14374,8	39,62				
10	1,00	3842,46	47,17				
10	1,78	5176,54	45,20				
10	3,16	6882,21	43,26				
10	5,62	9021,45	41,43				
10	10,00	11686,2	39,68				
10	17,80	14949,5	38,02				
10	31,60	18974,6	36,42				
10	56,20	23821,4	34,88				
10	100,00	29629,6	33,38				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements

Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic A

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP08
Materiale: PA5

Aging: RTFOT
Ripetizione: 2
RdP n°: 3.1/3.1.2.1/18

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	49,18	70,87	4	1,00	11599,1	39,73
34	1,78	76,89	69,50	4	1,78	14927,3	37,95
34	3,16	119,35	68,09	4	3,16	18979,3	36,25
34	5,62	183,59	66,67	4	5,62	23835	34,67
34	10,00	279,84	65,22	4	10,00	29629,4	33,17
34	17,80	422,56	63,69	4	17,80	36512,8	31,73
34	31,60	631,85	62,06	4	31,60	44594	30,34
34	56,20	935,74	60,31	4	56,20	53972,9	28,99
34	100,00	1371,97	58,47	4	100,00	64747,3	27,66
28	1,00	142,48	66,48				
28	1,78	217,71	65,05				
28	3,16	329,53	63,54				
28	5,62	493,58	61,95				
28	10,00	731,17	60,30				
28	17,80	1071,29	58,56				
28	31,60	1550,51	56,75				
28	56,20	2216,64	54,89				
28	100,00	3130,46	52,99				
22	1,00	466,75	60,95				
22	1,78	688,96	59,32				
22	3,16	1004,98	57,56				
22	5,62	1447,34	55,72				
22	10,00	2059,16	53,83				
22	17,80	2892,39	51,92				
22	31,60	4007,10	50,00				
22	56,20	5482,92	48,07				
22	100,00	7421,55	46,29				
16	1,00	1474,16	54,56				
16	1,78	2087,74	52,64				
16	3,16	2915,97	50,63				
16	5,62	4012,74	48,66				
16	10,00	5448,41	46,74				
16	17,80	7301,11	44,86				
16	31,60	9644,79	43,06				
16	56,20	12655,00	41,33				
16	100,00	16367,10	39,57				
10	1,00	4387,93	47,10				
10	1,78	5912,35	45,11				
10	3,16	7859,15	43,16				
10	5,62	10305,00	41,33				
10	10,00	13349,90	39,60				
10	17,80	17105,50	37,95				
10	31,60	21702,20	36,37				
10	56,20	27263,00	34,86				
10	100,00	33910,70	33,40				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic A

Data: 06/05/2025 Strumento: MCR 302 Aging: RTFOT
Unità: POLITO Geometria: PP25 Ripetizione: 1
Operatore: Teresa DI MARZO Materiale: PA5 RdP n°: 3.1/3.1.2.1/19

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	1725,000	59,30	64	100,00	29,18	74,84
34	56,20	1178,000	60,67	64	56,20	17,95	76,52
34	31,60	796,700	62,08	64	31,60	10,99	77,77
34	17,80	533,700	63,48	64	17,80	6,695	78,74
34	10,00	354,400	64,85	64	10,00	4,054	79,48
34	5,62	233,300	66,20	64	5,62	2,44	80,01
34	3,16	152,300	67,52	64	3,16	1,459	80,23
34	1,78	98,590	68,83	64	1,78	0,8699	80,04
34	1,00	63,310	70,16	64	1,00	0,5193	79,43
40	100,00	745,000	63,60	70	100,00	14,75	78,40
40	56,20	494,500	64,93	70	56,20	8,915	79,22
40	31,60	325,300	66,24	70	31,60	5,355	80,04
40	17,80	212,100	67,53	70	17,80	3,205	80,72
40	10,00	137,200	68,79	70	10,00	1,913	81,17
40	5,62	88,090	70,05	70	5,62	1,141	81,30
40	3,16	56,030	71,32	70	3,16	0,682	80,99
40	1,78	35,320	72,59	70	1,78	0,4103	79,95
40	1,00	22,030	73,87	70	1,00	0,2494	78,16
46	100,00	320,600	67,61	76	100	7,654	80,22
46	56,20	207,500	68,76	76	56,2	4,581	80,57
46	31,60	133,200	69,92	76	31,6	2,727	81,10
46	17,80	84,800	71,08	76	17,8	1,622	81,61
46	10,00	53,550	72,26	76	10	0,9652	81,81
46	5,62	33,530	73,45	76	5,62	0,5735	81,55
46	3,16	20,800	74,63	76	3,16	0,3431	80,68
46	1,78	12,790	75,72	76	1,78	0,2073	79,20
46	1,00	7,789	76,69	76	1,00	0,127	77,15
52	100,00	139,800	70,97	82	100	4,142	82,59
52	56,20	88,370	71,97	82	56,2	2,463	82,39
52	31,60	55,430	73,03	82	31,6	1,455	82,49
52	17,80	34,530	74,13	82	17,8	0,8596	82,66
52	10,00	21,350	75,25	82	10	0,5098	82,62
52	5,62	13,120	76,31	82	5,62	0,3034	82,00
52	3,16	8,009	77,25	82	3,16	0,1822	80,85
52	1,78	4,865	77,96	82	1,78	0,1111	78,83
52	1,00	2,940	78,44	82	1,00	0,06948	75,92
58	100,00	62,690	73,70				
58	56,20	38,980	74,69				
58	31,60	24,080	75,75				
58	17,80	14,770	76,80				
58	10,00	9,008	77,78				
58	5,62	5,456	78,62				
58	3,16	3,286	79,27				
58	1,78	1,974	79,58				
58	1,00	1,184	79,60				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic A

Data:	06/05/2025	Strumento:	MCR 302	Aging:	RTFOT
Unità:	POLITO	Geometria:	PP25	Ripetizione:	2
Operatore:	Teresa DI MARZO	Materiale:	PA5	RdP n°:	3.1/3.1.2.1/20

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	1455,030	60,86	64	100,00	25,579	77,78
34	56,20	982,427	62,29	64	56,20	15,4906	78,93
34	31,60	656,863	63,72	64	31,60	9,30671	80,00
34	17,80	435,130	65,14	64	17,80	5,548	81,01
34	10,00	285,731	66,52	64	10,00	3,28635	81,96
34	5,62	186,057	67,88	64	5,62	1,93595	82,82
34	3,16	120,205	69,24	64	3,16	1,13508	83,47
34	1,78	77,011	70,62	64	1,78	0,662228	83,83
34	1,00	48,959	72,05	64	1,00	0,38496	83,86
40	100,00	623,172	65,20	70	100,00	12,7162	80,00
40	56,20	408,553	66,56	70	56,20	7,58578	81,06
40	31,60	265,582	67,88	70	31,60	4,49481	82,00
40	17,80	171,265	69,19	70	17,80	2,6486	82,85
40	10,00	109,599	70,49	70	10,00	1,55396	83,57
40	5,62	69,570	71,82	70	5,62	0,90779	84,07
40	3,16	43,789	73,19	70	3,16	0,528604	84,25
40	1,78	27,315	74,62	70	1,78	0,307792	83,90
40	1,00	16,872	76,09	70	1,00	0,180061	82,92
46	100,00	266,005	69,16	76	100	6,53407	81,41
46	56,20	170,029	70,39	76	56,2	3,85558	82,42
46	31,60	107,900	71,61	76	31,6	2,26282	83,25
46	17,80	67,924	72,87	76	17,8	1,32186	83,88
46	10,00	42,418	74,16	76	10	0,769637	84,29
46	5,62	26,264	75,51	76	5,62	0,447303	84,34
46	3,16	16,117	76,88	76	3,16	0,259909	83,78
46	1,78	9,802	78,24	76	1,78	0,151774	82,62
46	1,00	5,909	79,54	76	1,00	0,0897903	80,56
52	100,00	116,766	72,35	82	100	3,48246	82,72
52	56,20	73,203	73,57	82	56,2	2,03741	83,48
52	31,60	45,575	74,80	82	31,6	1,18775	84,16
52	17,80	28,152	76,07	82	17,8	0,690255	84,50
52	10,00	17,239	77,36	82	10	0,40085	84,40
52	5,62	10,468	78,64	82	5,62	0,233642	83,83
52	3,16	6,302	79,85	82	3,16	0,137141	82,34
52	1,78	3,764	80,96	82	1,78	0,0814386	80,32
52	1,00	2,232	81,92	82	1,00	0,049228	77,81
58	100,00	53,469	75,21				
58	56,20	32,908	76,42				
58	31,60	20,105	77,64				
58	17,80	12,188	78,83				
58	10,00	7,332	79,98				
58	5,62	4,377	81,05				
58	3,16	2,593	81,99				
58	1,78	1,527	82,74				
58	1,00	0,894	83,30				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic A

Data: 06/05/2025 Strumento: MCR 301 Aging: PAV
Unità: POLITO Geometria: PP08 Ripetizione: 1
Operatore: Teresa DI MARZO Materiale: PA5 RdP n°: 3.1/3.1.2.1/21

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	184,996	60,49	4	1,00	19067,1	31,65
34	1,78	270,649	58,90	4	1,78	23283,3	30,37
34	3,16	392,276	57,31	4	3,16	28183,8	29,16
34	5,62	562,667	55,74	4	5,62	33842,7	28,02
34	10,00	799,17	54,18	4	10,00	40332,2	26,94
34	17,80	1123,84	52,65	4	17,80	47740,2	25,90
34	31,60	1564,93	51,11	4	31,60	56157	24,89
34	56,20	2159,12	49,60	4	56,20	65649,9	23,91
34	100,00	2950,31	48,12	4	100,00	76282,6	22,93
28	1,00	500,402	55,20				
28	1,78	709,858	53,57				
28	3,16	996,164	51,94				
28	5,62	1382,72	50,33				
28	10,00	1898,95	48,76				
28	17,80	2580,09	47,22				
28	31,60	3468,53	45,70				
28	56,20	4622,61	44,18				
28	100,00	6108,93	42,75				
22	1,00	1409,3	49,13				
22	1,78	1924,61	47,48				
22	3,16	2597,4	45,85				
22	5,62	3466,66	44,26				
22	10,00	4576,81	42,73				
22	17,80	5984,23	41,26				
22	31,60	7744,87	39,83				
22	56,20	9929,59	38,42				
22	100,00	12676,1	37,10				
16	1,00	3694,5	42,94				
16	1,78	4844,41	41,34				
16	3,16	6286,11	39,77				
16	5,62	8068,34	38,31				
16	10,00	10257,9	36,92				
16	17,80	12921	35,59				
16	31,60	16161,8	34,33				
16	56,20	20044,2	33,11				
16	100,00	24629,1	31,88				
10	1,00	8869,39	36,92				
10	1,78	11194,2	35,47				
10	3,16	13997,6	34,08				
10	5,62	17330,4	32,80				
10	10,00	21276,1	31,58				
10	17,80	25939,5	30,42				
10	31,60	31388,4	29,31				
10	56,20	37714,6	28,24				
10	100,00	45026,1	27,19				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements

Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic A

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP08
Materiale: PA5

Aging: PAV
Ripetizione: 2
RdP n°: 3.1/3.1.2.1/22

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	156,77	61,04	4	1,00	16590,4	32,50
34	1,78	230,03	59,52	4	1,78	20402,1	31,17
34	3,16	334,61	57,97	4	3,16	24866,9	29,93
34	5,62	481,87	56,44	4	5,62	30053,4	28,75
34	10,00	686,89	54,90	4	10,00	36030,8	27,63
34	17,80	969,67	53,36	4	17,80	42880,1	26,56
34	31,60	1356,02	51,82	4	31,60	50695	25,53
34	56,20	1878,41	50,28	4	56,20	59523	24,52
34	100,00	2578,07	48,73	4	100,00	69424,3	23,52
28	1,00	418,62	55,99				
28	1,78	596,56	54,41				
28	3,16	840,88	52,79				
28	5,62	1172,03	51,19				
28	10,00	1616,62	49,61				
28	17,80	2207,96	48,05				
28	31,60	2985,68	46,51				
28	56,20	4001,93	45,00				
28	100,00	5315,58	43,56				
22	1,00	1180,21	49,99				
22	1,78	1618,98	48,36				
22	3,16	2197,12	46,74				
22	5,62	2950,70	45,14				
22	10,00	3920,72	43,60				
22	17,80	5158,95	42,11				
22	31,60	6720,64	40,68				
22	56,20	8671,80	39,26				
22	100,00	11124,10	37,97				
16	1,00	3092,08	43,94				
16	1,78	4081,65	42,33				
16	3,16	5333,85	40,74				
16	5,62	6892,25	39,26				
16	10,00	8823,51	37,84				
16	17,80	11187,60	36,50				
16	31,60	14078,10	35,20				
16	56,20	17566,50	33,96				
16	100,00	21719,70	32,71				
10	1,00	7509,46	37,92				
10	1,78	9550,65	36,45				
10	3,16	12030,30	35,02				
10	5,62	14999,50	33,70				
10	10,00	18537,50	32,45				
10	17,80	22738,30	31,26				
10	31,60	27682,70	30,12				
10	56,20	33462,60	29,02				
10	100,00	40152,50	27,96				



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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 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic A

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 302
Geometria: PP25
Materiale: PA5

Aging: PAV
Ripetizione: 1
RdP n°: 3.1/3.1.2.1/23

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	3473,440	50,10	64	100,00	70,5856	70,48
34	56,20	2522,420	51,10	64	56,20	44,8185	71,79
34	31,60	1816,640	52,29	64	31,60	28,1931	73,21
34	17,80	1297,150	53,59	64	17,80	17,5672	74,71
34	10,00	917,771	54,96	64	10,00	10,8291	76,26
34	5,62	643,296	56,40	64	5,62	6,60289	77,83
34	3,16	446,699	57,88	64	3,16	3,98419	79,33
34	1,78	307,150	59,40	64	1,78	2,38116	80,67
34	1,00	209,263	60,95	64	1,00	1,40885	81,78
40	100,00	1602,600	54,35	70	100,00	33,4234	73,67
40	56,20	1129,170	55,61	70	56,20	20,7774	75,07
40	31,60	788,491	56,94	70	31,60	12,7969	76,53
40	17,80	545,555	58,31	70	17,80	7,8037	78,00
40	10,00	373,916	59,73	70	10,00	4,71202	79,43
40	5,62	253,973	61,18	70	5,62	2,81603	80,74
40	3,16	170,956	62,67	70	3,16	1,66725	81,82
40	1,78	113,912	64,22	70	1,78	0,979923	82,60
40	1,00	75,150	65,83	70	1,00	0,570467	83,02
46	100,00	728,718	58,83	76	100	16,2717	76,54
46	56,20	498,228	60,14	76	56,2	9,93501	78,01
46	31,60	337,735	61,48	76	31,6	6,00402	79,37
46	17,80	226,951	62,86	76	17,8	3,58837	80,62
46	10,00	151,126	64,28	76	10	2,1246	81,71
46	5,62	99,693	65,75	76	5,62	1,24903	82,53
46	3,16	65,149	67,28	76	3,16	0,731578	82,96
46	1,78	42,138	68,90	76	1,78	0,42748	82,96
46	1,00	26,976	70,59	76	1,00	0,25012	82,55
52	100,00	332,314	63,00	82	100	7,89693	79,22
52	56,20	221,168	64,31	82	56,2	4,73611	80,35
52	31,60	146,013	65,66	82	31,6	2,81215	81,37
52	17,80	95,535	67,06	82	17,8	1,6574	82,22
52	10,00	61,928	68,52	82	10	0,972236	82,72
52	5,62	39,764	70,08	82	5,62	0,568267	82,73
52	3,16	25,270	71,71	82	3,16	0,332462	82,22
52	1,78	15,886	73,43	82	1,78	0,19627	81,36
52	1,00	9,867	75,18	82	1,00	0,116789	80,35
58	100,00	151,972	66,87				
58	56,20	98,720	68,17				
58	31,60	63,575	69,55				
58	17,80	40,577	71,00				
58	10,00	25,642	72,54				
58	5,62	16,035	74,15				
58	3,16	9,916	75,81				
58	1,78	6,066	77,47				
58	1,00	3,668	79,05				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic A

Data:	06/05/2025	Strumento:	MCR 302	Aging:	PAV
Unità:	POLITO	Geometria:	PP25	Ripetizione:	2
Operatore:	Teresa DI MARZO	Materiale:	PA5	RdP n°:	3.1/3.1.2.1/24

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	3490,550	49,01	64	100,00	74,4752	69,91
34	56,20	2553,180	50,26	64	56,20	47,4768	71,37
34	31,60	1849,170	51,62	64	31,60	30,0135	72,85
34	17,80	1326,780	53,04	64	17,80	18,7942	74,38
34	10,00	942,572	54,52	64	10,00	11,6472	75,95
34	5,62	663,062	56,03	64	5,62	7,13565	77,53
34	3,16	461,992	57,58	64	3,16	4,31936	79,06
34	1,78	318,796	59,15	64	1,78	2,58333	80,44
34	1,00	217,848	60,74	64	1,00	1,53135	81,59
40	100,00	1622,860	53,67	70	100,00	36,4345	73,27
40	56,20	1147,880	55,06	70	56,20	22,754	74,70
40	31,60	804,703	56,47	70	31,60	14,0648	76,16
40	17,80	558,659	57,92	70	17,80	8,60004	77,65
40	10,00	384,318	59,39	70	10,00	5,20025	79,12
40	5,62	261,991	60,88	70	5,62	3,1119	80,49
40	3,16	176,969	62,41	70	3,16	1,84469	81,66
40	1,78	118,373	63,98	70	1,78	1,08593	82,56
40	1,00	78,400	65,60	70	1,00	0,634548	83,14
46	100,00	749,107	58,36	76	100	18,3231	76,17
46	56,20	513,785	59,74	76	56,2	11,2122	77,55
46	31,60	349,111	61,13	76	31,6	6,79178	78,96
46	17,80	235,234	62,55	76	17,8	4,07408	80,32
46	10,00	157,026	64,00	76	10	2,4199	81,55
46	5,62	103,878	65,49	76	5,62	1,42551	82,55
46	3,16	68,109	67,03	76	3,16	0,83416	83,25
46	1,78	44,199	68,64	76	1,78	0,48625	83,58
46	1,00	28,390	70,31	76	1,00	0,283677	83,59
52	100,00	347,834	62,69	82	100	9,43625	78,66
52	56,20	231,946	64,02	82	56,2	5,67997	80,02
52	31,60	153,384	65,39	82	31,6	3,38316	81,25
52	17,80	100,476	66,81	82	17,8	1,99725	82,35
52	10,00	65,224	68,29	82	10	1,17103	83,20
52	5,62	41,943	69,85	82	5,62	0,682637	83,72
52	3,16	26,687	71,48	82	3,16	0,396991	83,87
52	1,78	16,797	73,18	82	1,78	0,231359	83,69
52	1,00	10,458	74,92	82	1,00	0,135293	83,29
58	100,00	158,507	66,45				
58	56,20	103,333	67,83				
58	31,60	66,759	69,24				
58	17,80	42,762	70,72				
58	10,00	27,124	72,27				
58	5,62	17,026	73,89				
58	3,16	10,567	75,55				
58	1,78	6,481	77,20				
58	1,00	3,929	78,78				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic B

Data: 06/05/2025 Strumento: MCR 301 Aging: Original
Unità: POLITO Geometria: PP08 Ripetizione: 1
Operatore: Teresa DI MARZO Materiale: PB5 RdP n°: 3.1/3.1.2.1/25

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	19,0853	73,05	4	1,00	6020,24	47,13
34	1,78	30,2412	72,03	4	1,78	8107,86	45,09
34	3,16	47,6709	70,91	4	3,16	10764,9	43,05
34	5,62	74,5729	69,80	4	5,62	14091,8	41,09
34	10,00	115,923	68,70	4	10,00	18203,4	39,19
34	17,80	179,04	67,59	4	17,80	23238	37,35
34	31,60	274,719	66,48	4	31,60	29327,2	35,55
34	56,20	418,825	65,32	4	56,20	36590,2	33,80
34	100,00	636,189	63,92	4	100,00	45168,9	32,05
28	1,00	53,7057	69,58				
28	1,78	83,6126	68,55				
28	3,16	129,392	67,45				
28	5,62	198,705	66,31				
28	10,00	302,766	65,15				
28	17,80	457,646	63,91				
28	31,60	686,537	62,57				
28	56,20	1022,47	61,09				
28	100,00	1511,83	59,43				
22	1,00	175,11	65,38				
22	1,78	265,977	64,31				
22	3,16	400,8	63,09				
22	5,62	598,944	61,79				
22	10,00	887,245	60,40				
22	17,80	1301,65	58,89				
22	31,60	1889,97	57,25				
22	56,20	2716,84	55,49				
22	100,00	3863,6	53,64				
16	1,00	585,182	60,69				
16	1,78	862,989	59,32				
16	3,16	1260,18	57,76				
16	5,62	1818,68	56,11				
16	10,00	2594,16	54,36				
16	17,80	3654,57	52,51				
16	31,60	5075,24	50,58				
16	56,20	6953,04	48,52				
16	100,00	9459,64	46,55				
10	1,00	1938,54	54,67				
10	1,78	2747,57	52,86				
10	3,16	3842,87	50,91				
10	5,62	5297,19	48,94				
10	10,00	7200,78	46,96				
10	17,80	9654,28	44,98				
10	31,60	12789	43,02				
10	56,20	16730,7	41,09				
10	100,00	21625	39,17				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements

Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic B

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP08
Materiale: PB5

Aging: Original
Ripetizione: 2
RdP n°: 3.1/3.1.2.1/26

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	17,57	74,61	4	1,00	6567,91	47,69
34	1,78	28,15	73,64	4	1,78	8880,48	45,49
34	3,16	44,87	72,57	4	3,16	11831,8	43,30
34	5,62	71,08	71,50	4	5,62	15524,3	41,19
34	10,00	111,91	70,43	4	10,00	20075,9	39,16
34	17,80	174,88	69,32	4	17,80	25646,9	37,19
34	31,60	271,42	68,12	4	31,60	32358,9	35,29
34	56,20	418,86	66,78	4	56,20	40322	33,43
34	100,00	643,67	65,32	4	100,00	49683,5	31,62
28	1,00	50,53	71,34				
28	1,78	79,67	70,33				
28	3,16	124,77	69,21				
28	5,62	193,90	68,05				
28	10,00	298,89	66,84				
28	17,80	457,36	65,54				
28	31,60	694,31	64,15				
28	56,20	1044,22	62,67				
28	100,00	1555,77	61,01				
22	1,00	171,42	67,20				
22	1,78	263,53	66,05				
22	3,16	402,11	64,74				
22	5,62	607,90	63,34				
22	10,00	909,97	61,83				
22	17,80	1348,25	60,20				
22	31,60	1975,35	58,42				
22	56,20	2860,06	56,52				
22	100,00	4088,08	54,49				
16	1,00	596,74	62,27				
16	1,78	890,73	60,77				
16	3,16	1314,06	59,05				
16	5,62	1912,76	57,25				
16	10,00	2749,06	55,33				
16	17,80	3898,44	53,32				
16	31,60	5444,50	51,22				
16	56,20	7493,78	49,01				
16	100,00	10234,50	46,86				
10	1,00	2062,37	55,78				
10	1,78	2946,88	53,79				
10	3,16	4149,69	51,66				
10	5,62	5749,84	49,53				
10	10,00	7851,76	47,38				
10	17,80	10555,00	45,26				
10	31,60	14012,30	43,15				
10	56,20	18346,00	41,08				
10	100,00	23708,20	39,05				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic B

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP25
Materiale: PB5

Aging: Original
Ripetizione: 1
RdP n°: 3.1/3.1.2.1/27

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	828,100	66,14	64	100,00	14,67	78,58
34	56,20	539,700	67,45	64	56,20	8,868	79,21
34	31,60	349,000	68,68	64	31,60	5,322	80,05
34	17,80	224,100	69,85	64	17,80	3,178	80,82
34	10,00	142,900	70,99	64	10,00	1,888	81,51
34	5,62	90,570	72,12	64	5,62	1,116	82,08
34	3,16	57,010	73,27	64	3,16	0,6574	82,51
34	1,78	35,620	74,42	64	1,78	0,3864	82,74
34	1,00	22,100	75,59	64	1,00	0,2265	82,83
40	100,00	355,200	69,49	70	100,00	7,33	80,27
40	56,20	226,800	70,61	70	56,20	4,4	80,62
40	31,60	143,900	71,70	70	31,60	2,62	81,24
40	17,80	90,690	72,79	70	17,80	1,553	81,88
40	10,00	56,760	73,88	70	10,00	0,916	82,43
40	5,62	35,270	75,00	70	5,62	0,5384	82,81
40	3,16	21,760	76,13	70	3,16	0,3157	83,02
40	1,78	13,320	77,22	70	1,78	0,1851	83,01
40	1,00	8,094	78,26	70	1,00	0,1083	82,93
46	100,00	151,000	72,39	76	100	3,817	81,72
46	56,20	94,720	73,42	76	56,2	2,283	81,56
46	31,60	59,070	74,46	76	31,6	1,351	82,05
46	17,80	36,580	75,52	76	17,8	0,7964	82,57
46	10,00	22,480	76,59	76	10	0,4679	82,87
46	5,62	13,720	77,64	76	5,62	0,2744	83,01
46	3,16	8,313	78,64	76	3,16	0,1609	82,95
46	1,78	5,006	79,55	76	1,78	0,09448	82,75
46	1,00	2,992	80,38	76	1,00	0,05547	82,50
52	100,00	67,470	74,75	82	100	2,062	82,74
52	56,20	41,700	75,76	82	56,2	1,225	83,16
52	31,60	25,600	76,77	82	31,6	0,7244	82,86
52	17,80	15,610	77,77	82	17,8	0,4254	83,08
52	10,00	9,456	78,74	82	10	0,2495	83,13
52	5,62	5,691	79,64	82	5,62	0,1462	83,05
52	3,16	3,403	80,47	82	3,16	0,08579	82,82
52	1,78	2,025	81,18	82	1,78	0,05049	82,45
52	1,00	1,198	81,81	82	1,00	0,0297	82,10
58	100,00	30,890	76,71				
58	56,20	18,850	77,71				
58	31,60	11,430	78,62				
58	17,80	6,884	79,50				
58	10,00	4,124	80,32				
58	5,62	2,456	81,06				
58	3,16	1,455	81,70				
58	1,78	0,859	82,19				
58	1,00	0,504	82,54				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic B

Data:	06/05/2025	Strumento:	MCR 302	Aging:	Original
Unità:	POLITO	Geometria:	PP25	Ripetizione:	2
Operatore:	Teresa DI MARZO	Materiale:	PB5	RdP n°:	3.1/3.1.2.1/28

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	796,200	66,27	64	100,00	14,76	79,53
34	56,20	517,800	67,66	64	56,20	8,843	80,43
34	31,60	334,300	68,97	64	31,60	5,266	81,33
34	17,80	214,200	70,23	64	17,80	3,117	82,21
34	10,00	136,300	71,46	64	10,00	1,835	83,00
34	5,62	86,100	72,68	64	5,62	1,074	83,70
34	3,16	54,000	73,92	64	3,16	0,6258	84,27
34	1,78	33,600	75,18	64	1,78	0,3634	84,67
34	1,00	20,750	76,44	64	1,00	0,2103	84,92
40	100,00	339,500	69,70	70	100,00	7,236	80,91
40	56,20	216,200	70,95	70	56,20	4,29	82,08
40	31,60	137,000	72,15	70	31,60	2,531	82,64
40	17,80	86,310	73,35	70	17,80	1,487	83,43
40	10,00	53,940	74,55	70	10,00	0,8683	84,00
40	5,62	33,350	75,76	70	5,62	0,5046	84,46
40	3,16	20,420	76,99	70	3,16	0,2924	84,77
40	1,78	12,400	78,19	70	1,78	0,1694	84,93
40	1,00	7,489	79,34	70	1,00	0,09786	84,98
46	100,00	144,400	72,98	76	100	3,656	84,59
46	56,20	90,080	74,01	76	56,2	2,156	82,52
46	31,60	55,820	75,13	76	31,6	1,266	83,64
46	17,80	34,400	76,30	76	17,8	0,7389	83,89
46	10,00	21,090	77,47	76	10	0,43	84,33
46	5,62	12,800	78,62	76	5,62	0,2496	84,58
46	3,16	7,692	79,72	76	3,16	0,1447	84,61
46	1,78	4,597	80,74	76	1,78	0,08392	84,55
46	1,00	2,733	81,70	76	1,00	0,04853	84,42
52	100,00	65,050	75,51	82	100	1,92	84,98
52	56,20	40,100	76,63	82	56,2	1,122	84,93
52	31,60	24,460	77,66	82	31,6	0,655	84,07
52	17,80	14,800	78,73	82	17,8	0,3815	84,44
52	10,00	8,921	79,81	82	10	0,2218	84,58
52	5,62	5,338	80,83	82	5,62	0,1289	84,53
52	3,16	3,164	81,77	82	3,16	0,07497	84,34
52	1,78	1,870	82,63	82	1,78	0,04368	84,09
52	1,00	1,096	83,41	82	1,00	0,02545	83,80
58	100,00	30,390	78,01				
58	56,20	18,410	78,66				
58	31,60	11,080	79,67				
58	17,80	6,643	80,73				
58	10,00	3,945	81,63				
58	5,62	2,330	82,49				
58	3,16	1,370	83,27				
58	1,78	0,801	83,92				
58	1,00	0,466	84,45				



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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 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic B

Data: 06/05/2025 Strumento: MCR 301 Aging: RTFOT
Unità: POLITO Geometria: PP08 Ripetizione: 1
Operatore: Teresa DI MARZO Materiale: PB5 RdP n°: 3.1/3.1.2.1/29

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	49,7351	68,40	4	1,00	8879,29	39,30
34	1,78	76,5007	66,80	4	1,78	11398,2	37,70
34	3,16	116,59	65,20	4	3,16	14482	36,20
34	5,62	175,86	63,60	4	5,62	18198,8	34,70
34	10,00	262,503	61,90	4	10,00	22644,9	33,30
34	17,80	387,764	60,30	4	17,80	27945	32,00
34	31,60	566,926	58,70	4	31,60	34177,3	30,60
34	56,20	820,506	57,10	4	56,20	41443,1	29,30
34	100,00	1178,81	55,50	4	100,00	49840,1	28,00
28	1,00	136,26	63,70				
28	1,78	204,256	62,10				
28	3,16	302,696	60,40				
28	5,62	443,457	58,70				
28	10,00	642,247	57,10				
28	17,80	919,823	55,40				
28	31,60	1303,86	53,80				
28	56,20	1831,64	52,20				
28	100,00	2550,68	50,70				
22	1,00	419,096	57,90				
22	1,78	605,375	56,20				
22	3,16	864,687	54,50				
22	5,62	1220,74	52,80				
22	10,00	1703,47	51,20				
22	17,80	2352,41	49,60				
22	31,60	3215,04	48,10				
22	56,20	4355,37	46,60				
22	100,00	5848,25	45,10				
16	1,00	1230,65	51,90				
16	1,78	1711,03	50,20				
16	3,16	2352,04	48,50				
16	5,62	3194,18	46,90				
16	10,00	4290,57	45,30				
16	17,80	5705,96	43,80				
16	31,60	7504,96	42,30				
16	56,20	9769,39	40,70				
16	100,00	12676,6	39,30				
10	1,00	3480,78	45,50				
10	1,78	4644,39	43,80				
10	3,16	6130,27	42,20				
10	5,62	7993,87	40,60				
10	10,00	10323,5	39,10				
10	17,80	13191	37,70				
10	31,60	16736,6	36,30				
10	56,20	21020	34,90				
10	100,00	26171,1	33,50				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements

Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic B

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP08
Materiale: PB5

Aging: RTFOT
Ripetizione: 2
RdP n°: 3.1/3.1.2.1/30

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	50,87	69,20	4	1,00	10342,9	39,70
34	1,78	78,73	67,70	4	1,78	13303,2	38,10
34	3,16	120,89	66,30	4	3,16	16921,9	36,40
34	5,62	183,80	64,80	4	5,62	21280,4	34,90
34	10,00	276,76	63,40	4	10,00	26484,1	33,40
34	17,80	412,89	61,80	4	17,80	32677	32,00
34	31,60	610,12	60,30	4	31,60	39948,2	30,60
34	56,20	892,62	58,70	4	56,20	48422,9	29,20
34	100,00	1294,46	57,00	4	100,00	58164,7	27,90
28	1,00	144,08	64,60				
28	1,78	217,53	63,20				
28	3,16	325,17	61,60				
28	5,62	480,93	60,10				
28	10,00	703,70	58,50				
28	17,80	1018,87	56,90				
28	31,60	1458,85	55,20				
28	56,20	2066,07	53,60				
28	100,00	2895,28	51,90				
22	1,00	452,90	59,10				
22	1,78	660,39	57,60				
22	3,16	952,12	55,90				
22	5,62	1357,37	54,20				
22	10,00	1912,29	52,50				
22	17,80	2662,70	50,80				
22	31,60	3664,17	49,10				
22	56,20	4990,64	47,40				
22	100,00	6733,61	45,80				
16	1,00	1375,52	53,10				
16	1,78	1929,31	51,40				
16	3,16	2672,09	49,60				
16	5,62	3653,33	47,80				
16	10,00	4936,41	46,10				
16	17,80	6594,67	44,40				
16	31,60	8699,72	42,80				
16	56,20	11397,40	41,20				
16	100,00	14756,20	39,60				
10	1,00	3921,46	46,50				
10	1,78	5268,89	44,70				
10	3,16	6993,33	42,90				
10	5,62	9166,07	41,20				
10	10,00	11879,80	39,60				
10	17,80	15216,60	38,10				
10	31,60	19349,70	36,50				
10	56,20	24342,40	35,10				
10	100,00	30326,50	33,60				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic B

Data: 06/05/2025 Strumento: MCR 301 Aging: RTFOT
Unità: POLITO Geometria: PP25 Ripetizione: 1
Operatore: Teresa DI MARZO Materiale: PB5 RdP n°: 3.1/3.1.2.1/31

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	1605,900	58,84	64	100,00	29,8541	75,76
34	56,20	1097,100	60,39	64	56,20	18,3038	76,84
34	31,60	741,560	61,92	64	31,60	11,1337	77,72
34	17,80	496,118	63,43	64	17,80	6,73628	78,51
34	10,00	328,764	64,89	64	10,00	4,05298	79,10
34	5,62	215,977	66,31	64	5,62	2,42923	79,46
34	3,16	140,777	67,70	64	3,16	1,45064	79,65
34	1,78	91,041	69,07	64	1,78	0,866695	79,43
34	1,00	58,427	70,43	64	1,00	0,513878	79,53
40	100,00	708,052	63,29	70	100,00	14,3859	78,13
40	56,20	469,239	64,74	70	56,20	8,70244	79,09
40	31,60	308,144	66,15	70	31,60	5,21662	80,28
40	17,80	200,735	67,52	70	17,80	3,10287	81,30
40	10,00	129,793	68,85	70	10,00	1,83301	82,29
40	5,62	83,215	70,17	70	5,62	1,07401	83,32
40	3,16	52,839	71,49	70	3,16	0,621439	84,43
40	1,78	33,240	72,79	70	1,78	0,356426	85,38
40	1,00	20,716	74,06	70	1,00	0,19838	86,58
46	100,00	302,945	67,36	76	100	6,809	80,50
46	56,20	195,981	68,68	76	56,2	4,05305	81,48
46	31,60	125,730	69,95	76	31,6	2,38733	82,88
46	17,80	80,011	71,20	76	17,8	1,3956	84,03
46	10,00	50,503	72,43	76	10	0,809825	85,01
46	5,62	31,613	73,64	76	5,62	0,466334	85,85
46	3,16	19,612	74,79	76	3,16	0,267136	86,47
46	1,78	12,070	75,81	76	1,78	0,152445	86,89
46	1,00	7,364	76,62	76	1,00	0,0865637	87,12
52	100,00	135,582	70,73	82	100	3,36531	82,05
52	56,20	85,934	71,95	82	56,2	1,98817	82,77
52	31,60	54,018	73,13	82	31,6	1,16008	84,04
52	17,80	33,663	74,28	82	17,8	0,672321	85,08
52	10,00	20,823	75,39	82	10	0,387444	85,89
52	5,62	12,789	76,39	82	5,62	0,22227	86,44
52	3,16	7,793	77,20	82	3,16	0,12712	86,79
52	1,78	4,719	77,67	82	1,78	0,0727099	86,94
52	1,00	2,848	77,63	82	1,00	0,0415113	87,02
58	100,00	62,268	73,51				
58	56,20	38,765	74,70				
58	31,60	23,937	75,79				
58	17,80	14,657	76,79				
58	10,00	8,922	77,66				
58	5,62	5,392	78,33				
58	3,16	3,247	78,66				
58	1,78	1,949	78,44				
58	1,00	1,169	77,69				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic B

Data:	06/05/2025	Strumento:	MCR 302	Aging:	RTFOT
Unità:	POLITO	Geometria:	PP25	Ripetizione:	2
Operatore:	Teresa DI MARZO	Materiale:	PB5	RdP n°:	3.1/3.1.2.1/32

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	1612,060	58,30	64	100,00	30,3084	76,37
34	56,20	1105,000	59,86	64	56,20	18,5	77,71
34	31,60	750,001	61,42	64	31,60	11,1982	79,04
34	17,80	504,181	62,95	64	17,80	6,71748	80,28
34	10,00	335,707	64,45	64	10,00	3,9986	81,46
34	5,62	221,399	65,92	64	5,62	2,36186	82,55
34	3,16	144,652	67,38	64	3,16	1,38483	83,55
34	1,78	93,633	68,86	64	1,78	0,806784	84,42
34	1,00	60,115	70,37	64	1,00	0,467125	85,14
40	100,00	710,764	62,84	70	100,00	15,1553	78,76
40	56,20	472,963	64,33	70	56,20	9,12195	79,85
40	31,60	311,780	65,78	70	31,60	5,44135	81,12
40	17,80	203,682	67,21	70	17,80	3,2215	82,21
40	10,00	131,912	68,62	70	10,00	1,89511	83,22
40	5,62	84,682	70,06	70	5,62	1,10735	84,13
40	3,16	53,848	71,53	70	3,16	0,642959	84,89
40	1,78	33,909	73,05	70	1,78	0,371391	85,47
40	1,00	21,132	74,62	70	1,00	0,213833	85,84
46	100,00	308,201	67,01	76	100	7,64316	80,58
46	56,20	199,620	68,38	76	56,2	4,55079	81,53
46	31,60	128,212	69,75	76	31,6	2,68343	82,64
46	17,80	81,721	71,13	76	17,8	1,5723	83,60
46	10,00	51,672	72,54	76	10	0,915572	84,44
46	5,62	32,350	73,99	76	5,62	0,53011	85,11
46	3,16	20,031	75,48	76	3,16	0,305542	85,58
46	1,78	12,289	76,96	76	1,78	0,175793	85,82
46	1,00	7,460	78,42	76	1,00	0,100836	85,91
52	100,00	136,674	70,59	82	100	3,79968	81,37
52	56,20	86,696	71,96	82	56,2	2,24352	82,55
52	31,60	54,505	73,32	82	31,6	1,31188	83,72
52	17,80	33,942	74,72	82	17,8	0,762626	84,52
52	10,00	20,948	76,15	82	10	0,441256	85,14
52	5,62	12,810	77,58	82	5,62	0,254349	85,52
52	3,16	7,752	78,99	82	3,16	0,146322	85,67
52	1,78	4,647	80,32	82	1,78	0,0842444	85,64
52	1,00	2,761	81,55	82	1,00	0,0484138	85,49
58	100,00	63,248	73,68				
58	56,20	39,315	75,05				
58	31,60	24,211	76,41				
58	17,80	14,777	77,78				
58	10,00	8,941	79,13				
58	5,62	5,357	80,42				
58	3,16	3,184	81,63				
58	1,78	1,878	82,73				
58	1,00	1,099	83,73				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic B

Data: 06/05/2025 Strumento: MCR 301 Aging: PAV
Unità: POLITO Geometria: PP08 Ripetizione: 1
Operatore: Teresa DI MARZO Materiale: PB5 RdP n°: 3.1/3.1.2.1/33

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	325,641	58,10	4	1,00	29776,8	29,70
34	1,78	469,662	56,50	4	1,78	35909,2	28,40
34	3,16	670,082	54,90	4	3,16	42934,8	27,20
34	5,62	945,722	53,30	4	5,62	50905,2	26,10
34	10,00	1322,71	51,80	4	10,00	59948,6	25,00
34	17,80	1832,93	50,20	4	17,80	70121,4	24,00
34	31,60	2515,73	48,70	4	31,60	81487,5	23,00
34	56,20	3418,73	47,30	4	56,20	94092,7	22,00
34	100,00	4601,02	45,80	4	100,00	108022	21,00
28	1,00	862,004	52,80				
28	1,78	1204,62	51,10				
28	3,16	1665,7	49,50				
28	5,62	2278,21	47,90				
28	10,00	3081,78	46,40				
28	17,80	4126,07	44,90				
28	31,60	5469,22	43,40				
28	56,20	7182,01	42,00				
28	100,00	9344,44	40,60				
22	1,00	2374,05	46,70				
22	1,78	3195,44	45,10				
22	3,16	4250,41	43,50				
22	5,62	5585,92	42,00				
22	10,00	7267,27	40,50				
22	17,80	9359,55	39,10				
22	31,60	11950,2	37,70				
22	56,20	15124,8	36,40				
22	100,00	19003,4	35,10				
16	1,00	6048,35	40,70				
16	1,78	7822,81	39,10				
16	3,16	10003,7	37,60				
16	5,62	12667,1	36,20				
16	10,00	15882,5	34,90				
16	17,80	19739,2	33,60				
16	31,60	24344,3	32,40				
16	56,20	29805,4	31,20				
16	100,00	36238,4	30,00				
10	1,00	13997,1	34,90				
10	1,78	17454,1	33,50				
10	3,16	21553,8	32,20				
10	5,62	26370,1	30,90				
10	10,00	31999,6	29,70				
10	17,80	38546,1	28,60				
10	31,60	46105,1	27,50				
10	56,20	54757	26,40				
10	100,00	64619,8	25,40				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements

Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic B

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP08
Materiale: PB5

Aging: PAV
Ripetizione: 2
RdP n°: 3.1/3.1.2.1/34

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	254,33	57,20	4	1,00	21736,1	29,50
34	1,78	365,32	55,60	4	1,78	26207,5	28,30
34	3,16	518,42	54,00	4	3,16	31311,9	27,10
34	5,62	727,25	52,40	4	5,62	37123,8	26,00
34	10,00	1008,25	50,90	4	10,00	43701,8	25,00
34	17,80	1383,34	49,40	4	17,80	51096	23,90
34	31,60	1880,49	47,90	4	31,60	59350,8	23,00
34	56,20	2537,78	46,30	4	56,20	68525,8	22,00
34	100,00	3420,28	44,30	4	100,00	78579,5	21,10
28	1,00	672,74	51,80				
28	1,78	932,42	50,10				
28	3,16	1276,44	48,60				
28	5,62	1727,35	47,10				
28	10,00	2315,07	45,60				
28	17,80	3073,73	44,10				
28	31,60	4047,23	42,60				
28	56,20	5291,97	41,10				
28	100,00	6890,45	39,50				
22	1,00	1790,14	45,90				
22	1,78	2390,49	44,30				
22	3,16	3157,44	42,80				
22	5,62	4126,43	41,30				
22	10,00	5344,80	39,80				
22	17,80	6858,84	38,40				
22	31,60	8732,15	37,10				
22	56,20	11031,40	35,80				
22	100,00	13846,30	34,50				
16	1,00	4472,08	40,00				
16	1,78	5767,48	38,50				
16	3,16	7354,88	37,10				
16	5,62	9284,22	35,70				
16	10,00	11617,50	34,40				
16	17,80	14414,20	33,10				
16	31,60	17747,60	32,00				
16	56,20	21694,80	30,80				
16	100,00	26331,20	29,80				
10	1,00	10304,20	34,50				
10	1,78	12818,80	33,10				
10	3,16	15793,40	31,80				
10	5,62	19292,50	30,60				
10	10,00	23377,10	29,40				
10	17,80	28122,90	28,30				
10	31,60	33591,50	27,30				
10	56,20	39853,20	26,30				
10	100,00	46957,30	25,30				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic B

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP25
Materiale: PB5

Aging: PAV
Ripetizione: 1
RdP n°: 3.1/3.1.2.1/35

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	3968,390	48,64	64	100,00	87,8227	69,76
34	56,20	2900,770	49,97	64	56,20	55,9849	71,31
34	31,60	2101,310	51,40	64	31,60	35,3219	72,90
34	17,80	1507,480	52,89	64	17,80	22,0334	74,54
34	10,00	1071,030	54,43	64	10,00	13,5998	76,23
34	5,62	753,258	56,01	64	5,62	8,30543	77,92
34	3,16	524,391	57,62	64	3,16	5,00774	79,57
34	1,78	361,219	59,27	64	1,78	2,98771	81,13
34	1,00	246,435	60,95	64	1,00	1,76208	82,57
40	100,00	1872,570	53,33	70	100,00	42,0243	73,01
40	56,20	1327,000	54,79	70	56,20	26,2072	74,61
40	31,60	931,939	56,29	70	31,60	16,1709	76,22
40	17,80	647,602	57,82	70	17,80	9,87139	77,82
40	10,00	445,330	59,38	70	10,00	5,96197	79,40
40	5,62	303,019	60,97	70	5,62	3,56186	80,94
40	3,16	204,009	62,59	70	3,16	2,10687	82,34
40	1,78	135,978	64,27	70	1,78	1,23539	83,60
40	1,00	89,533	66,01	70	1,00	0,717181	84,72
46	100,00	859,370	58,08	76	100	19,8021	75,71
46	56,20	590,643	59,56	76	56,2	12,107	77,49
46	31,60	401,905	61,07	76	31,6	7,32389	79,06
46	17,80	270,681	62,59	76	17,8	4,38419	80,55
46	10,00	180,551	64,15	76	10	2,59875	81,95
46	5,62	119,144	65,76	76	5,62	1,52566	83,24
46	3,16	77,793	67,44	76	3,16	0,888053	84,39
46	1,78	50,256	69,18	76	1,78	0,513144	85,37
46	1,00	32,093	71,01	76	1,00	0,294002	86,21
52	100,00	397,208	62,43	82	100	9,26886	78,09
52	56,20	265,211	63,89	82	56,2	5,5798	79,74
52	31,60	175,469	65,38	82	31,6	3,32034	81,30
52	17,80	114,924	66,92	82	17,8	1,95816	82,67
52	10,00	74,517	68,53	82	10	1,14584	83,90
52	5,62	47,830	70,21	82	5,62	0,665274	84,98
52	3,16	30,369	71,96	82	3,16	0,38333	85,89
52	1,78	19,068	73,78	82	1,78	0,219749	86,60
52	1,00	11,814	75,63	82	1,00	0,125152	87,15
58	100,00	185,687	66,28				
58	56,20	120,975	67,75				
58	31,60	78,093	69,29				
58	17,80	49,951	70,88				
58	10,00	31,624	72,56				
58	5,62	19,784	74,28				
58	3,16	12,223	76,05				
58	1,78	7,463	77,81				
58	1,00	4,502	79,52				



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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 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic B

Data:	06/05/2025	Strumento:	MCR 302	Aging:	PAV
Unità:	POLITO	Geometria:	PP25	Ripetizione:	2
Operatore:	Teresa DI MARZO	Materiale:	PB5	RdP n°:	3.1/3.1.2.1/36

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	3911,540	47,98	64	100,00	95,4583	63,67
34	56,20	2868,800	49,20	64	56,20	63,1701	63,98
34	31,60	2085,670	50,50	64	31,60	41,8849	64,17
34	17,80	1503,000	51,85	64	17,80	27,7719	64,36
34	10,00	1073,400	53,22	64	10,00	18,4516	64,65
34	5,62	759,882	54,61	64	5,62	12,3047	65,06
34	3,16	533,359	55,98	64	3,16	8,24423	65,44
34	1,78	371,216	57,32	64	1,78	5,57035	65,64
34	1,00	256,501	58,63	64	1,00	3,79324	66,02
40	100,00	1864,220	52,31	70	100,00	50,0647	64,48
40	56,20	1329,630	53,62	70	56,20	33,0577	64,86
40	31,60	939,942	54,93	70	31,60	21,9674	65,22
40	17,80	658,663	56,24	70	17,80	14,6608	65,74
40	10,00	457,485	57,51	70	10,00	9,84178	66,24
40	5,62	315,081	58,74	70	5,62	6,67376	66,48
40	3,16	215,255	59,90	70	3,16	4,58808	66,29
40	1,78	146,094	61,00	70	1,78	3,22848	65,44
40	1,00	98,367	62,07	70	1,00	2,33181	64,39
46	100,00	863,390	56,58	76	100	27,2137	62,97
46	56,20	598,819	57,82	76	56,2	18,1503	63,74
46	31,60	411,890	58,99	76	31,6	12,2125	64,59
46	17,80	281,153	60,09	76	17,8	8,26871	65,59
46	10,00	190,605	61,09	76	10	5,62702	66,39
46	5,62	128,316	62,01	76	5,62	3,87717	66,85
46	3,16	85,872	62,87	76	3,16	2,72337	66,75
46	1,78	57,145	63,67	76	1,78	1,95449	66,18
46	1,00	37,809	64,41	76	1,00	1,4316	65,28
52	100,00	404,383	60,16	82	100	14,7688	66,01
52	56,20	273,640	61,17	82	56,2	9,71353	68,11
52	31,60	184,134	62,04	82	31,6	6,44915	69,94
52	17,80	123,379	62,79	82	17,8	4,32451	71,47
52	10,00	82,293	63,46	82	10	2,94158	72,32
52	5,62	54,668	64,07	82	5,62	2,02739	72,51
52	3,16	36,170	64,61	82	3,16	1,44085	72,13
52	1,78	23,853	65,03	82	1,78	1,05181	71,21
52	1,00	15,701	65,29	82	1,00	0,79263	70,04
58	100,00	193,902	62,65				
58	56,20	129,073	63,32				
58	31,60	85,726	63,85				
58	17,80	56,854	64,37				
58	10,00	37,615	64,93				
58	5,62	24,821	65,50				
58	3,16	16,346	65,99				
58	1,78	10,780	66,30				
58	1,00	7,142	66,45				



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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 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic C

Data: 06/05/2025 Strumento: MCR 301 Aging: Original
Unità: POLITO Geometria: PP08 Ripetizione: 1
Operatore: Teresa DI MARZO Materiale: PC5 RdP n°: 3.1/3.1.2.1/37

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	48,3052	61,19	4	1,00	7678,5	42,27
34	1,78	70,9214	61,14	4	1,78	10033,6	40,62
34	3,16	104,398	60,87	4	3,16	12962,7	38,96
34	5,62	153,495	60,50	4	5,62	16555,5	37,38
34	10,00	225,13	60,04	4	10,00	20910,3	35,87
34	17,80	329,42	59,48	4	17,80	26178,8	34,40
34	31,60	480,577	58,80	4	31,60	32483,6	32,98
34	56,20	697,898	58,00	4	56,20	39949,8	31,58
34	100,00	1011,21	56,90	4	100,00	48744,6	30,20
28	1,00	116,886	59,73				
28	1,78	170,775	59,40				
28	3,16	249,209	58,89				
28	5,62	362,601	58,27				
28	10,00	525,395	57,55				
28	17,80	757,48	56,69				
28	31,60	1085,64	55,68				
28	56,20	1545,71	54,55				
28	100,00	2185,34	53,29				
22	1,00	330,664	57,17				
22	1,78	476,305	56,52				
22	3,16	683,114	55,69				
22	5,62	973,946	54,71				
22	10,00	1378,77	53,60				
22	17,80	1936,9	52,35				
22	31,60	2696,85	50,98				
22	56,20	3722,97	49,50				
22	100,00	5096,36	47,98				
16	1,00	964,719	53,62				
16	1,78	1357,42	52,57				
16	3,16	1897,33	51,29				
16	5,62	2626,08	49,92				
16	10,00	3598,91	48,45				
16	17,80	4881,64	46,92				
16	31,60	6546,56	45,36				
16	56,20	8680,45	43,72				
16	100,00	11470,4	42,16				
10	1,00	2802,66	48,46				
10	1,78	3812,38	47,00				
10	3,16	5135,91	45,40				
10	5,62	6834,98	43,80				
10	10,00	9000,24	42,20				
10	17,80	11713,2	40,64				
10	31,60	15117,3	39,10				
10	56,20	19312,7	37,59				
10	100,00	24450,7	36,10				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements

Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic C

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP08
Materiale: PC5

Aging: Original
Ripetizione: 2
RdP n°: 3.1/3.1.2.1/38

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	36,99	67,70	4	1,00	7882,22	43,01
34	1,78	56,48	66,96	4	1,78	10347,9	41,20
34	3,16	86,12	66,09	4	3,16	13420,3	39,39
34	5,62	130,56	65,19	4	5,62	17178,2	37,67
34	10,00	196,94	64,25	4	10,00	21731,3	36,02
34	17,80	295,38	63,25	4	17,80	27221,9	34,43
34	31,60	440,25	62,18	4	31,60	33763	32,89
34	56,20	650,93	61,06	4	56,20	41457,6	31,40
34	100,00	956,27	59,68	4	100,00	50445,1	29,93
28	1,00	98,26	64,77				
28	1,78	148,14	63,90				
28	3,16	222,29	62,92				
28	5,62	331,37	61,86				
28	10,00	490,45	60,72				
28	17,80	720,18	59,48				
28	31,60	1048,51	58,10				
28	56,20	1513,45	56,62				
28	100,00	2163,39	55,11				
22	1,00	302,00	60,88				
22	1,78	444,53	59,82				
22	3,16	649,91	58,59				
22	5,62	942,08	57,25				
22	10,00	1353,86	55,81				
22	17,80	1925,50	54,25				
22	31,60	2709,06	52,59				
22	56,20	3772,49	50,86				
22	100,00	5197,52	49,17				
16	1,00	930,38	56,07				
16	1,78	1329,18	54,68				
16	3,16	1880,76	53,09				
16	5,62	2630,60	51,45				
16	10,00	3637,43	49,73				
16	17,80	4970,97	47,96				
16	31,60	6707,74	46,18				
16	56,20	8936,01	44,35				
16	100,00	11842,40	42,63				
10	1,00	2806,70	49,99				
10	1,78	3852,48	48,27				
10	3,16	5228,28	46,45				
10	5,62	7001,93	44,64				
10	10,00	9265,59	42,85				
10	17,80	12107,00	41,11				
10	31,60	15667,10	39,41				
10	56,20	20045,70	37,76				
10	100,00	25373,60	36,15				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic C

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 302
Geometria: PP25
Materiale: PC5

Aging: Original
Ripetizione: 1
RdP n°: 3.1/3.1.2.1/39

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	1637,000	56,09	64	100,00	43,62	69,92
34	56,20	1140,000	57,43	64	56,20	27,71	70,81
34	31,60	786,300	58,77	64	31,60	17,49	71,38
34	17,80	537,900	60,08	64	17,80	11,01	71,71
34	10,00	365,000	61,34	64	10,00	6,914	71,76
34	5,62	245,900	62,55	64	5,62	4,337	71,57
34	3,16	164,400	63,71	64	3,16	2,722	71,01
34	1,78	109,200	64,78	64	1,78	1,713	70,06
34	1,00	72,060	65,79	64	1,00	1,078	68,97
40	100,00	768,800	59,68	70	100,00	22,85	72,41
40	56,20	522,800	61,00	70	56,20	14,31	73,16
40	31,60	352,700	62,25	70	31,60	8,928	73,77
40	17,80	236,100	63,45	70	17,80	5,555	74,15
40	10,00	156,800	64,58	70	10,00	3,451	74,23
40	5,62	103,400	65,65	70	5,62	2,145	73,99
40	3,16	67,660	66,62	70	3,16	1,339	73,24
40	1,78	43,980	67,42	70	1,78	0,8468	71,75
40	1,00	28,400	68,07	70	1,00	0,5389	70,01
46	100,00	361,200	62,90	76	100	12,57	73,76
46	56,20	240,500	64,11	76	56,2	7,799	74,35
46	31,60	159,000	65,22	76	31,6	4,823	74,90
46	17,80	104,300	66,25	76	17,8	2,974	75,20
46	10,00	67,930	67,17	76	10	1,832	75,21
46	5,62	43,960	67,93	76	5,62	1,13	74,86
46	3,16	28,310	68,48	76	3,16	0,6994	74,25
46	1,78	18,170	68,66	76	1,78	0,4365	73,48
46	1,00	11,620	68,57	76	1,00	0,2707	72,99
52	100,00	172,500	65,84	82	100	7,123	75,80
52	56,20	112,800	66,89	82	56,2	4,364	76,24
52	31,60	73,210	67,83	82	31,6	2,67	76,78
52	17,80	47,230	68,64	82	17,8	1,63	77,08
52	10,00	30,300	69,25	82	10	0,9956	77,05
52	5,62	19,360	69,60	82	5,62	0,6104	76,74
52	3,16	12,340	69,59	82	3,16	0,3749	76,31
52	1,78	7,889	69,06	82	1,78	0,2332	75,41
52	1,00	5,041	68,24	82	1,00	0,1459	73,89
58	100,00	85,230	68,19				
58	56,20	54,790	69,09				
58	31,60	35,030	69,88				
58	17,80	22,290	70,48				
58	10,00	14,120	70,83				
58	5,62	8,934	70,90				
58	3,16	5,635	70,66				
58	1,78	3,570	69,85				
58	1,00	2,255	68,98				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic C

Data:	06/05/2025	Strumento:	MCR 302	Aging:	Original
Unità:	POLITO	Geometria:	PP25	Ripetizione:	2
Operatore:	Teresa DI MARZO	Materiale:	PC5	RdP n°:	3.1/3.1.2.1/40

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	1777,000	55,87	64	100,00	47,65	70,26
34	56,20	1239,000	57,33	64	56,20	30,19	71,24
34	31,60	856,400	58,77	64	31,60	19	71,85
34	17,80	586,400	60,16	64	17,80	11,9	72,09
34	10,00	398,000	61,50	64	10,00	7,437	71,89
34	5,62	268,000	62,76	64	5,62	4,656	71,18
34	3,16	179,000	63,95	64	3,16	2,924	69,85
34	1,78	118,600	65,04	64	1,78	1,865	67,59
34	1,00	78,100	66,06	64	1,00	1,205	64,67
40	100,00	841,100	59,70	70	100,00	24,26	72,32
40	56,20	571,800	61,08	70	56,20	15,16	73,06
40	31,60	385,500	62,40	70	31,60	9,433	73,32
40	17,80	257,500	63,64	70	17,80	5,864	73,07
40	10,00	170,600	64,81	70	10,00	3,655	72,19
40	5,62	112,200	65,90	70	5,62	2,292	70,56
40	3,16	73,370	66,89	70	3,16	1,457	68,04
40	1,78	47,690	67,73	70	1,78	0,9502	64,52
40	1,00	30,760	68,45	70	1,00	0,6366	60,36
46	100,00	394,900	63,01	76	100	13,19	73,29
46	56,20	263,000	64,27	76	56,2	8,191	73,45
46	31,60	173,800	65,42	76	31,6	5,066	73,39
46	17,80	114,000	66,47	76	17,8	3,136	72,69
46	10,00	74,100	67,42	76	10	1,955	71,18
46	5,62	47,830	68,25	76	5,62	1,231	68,89
46	3,16	30,690	68,89	76	3,16	0,7902	65,81
46	1,78	19,620	69,20	76	1,78	0,5255	61,93
46	1,00	12,520	69,22	76	1,00	0,3572	58,00
52	100,00	192,600	66,03	82	100	7,462	74,27
52	56,20	125,900	67,11	82	56,2	4,589	74,55
52	31,60	81,590	68,10	82	31,6	2,813	74,35
52	17,80	52,470	68,99	82	17,8	1,735	73,28
52	10,00	33,540	69,72	82	10	1,08	71,44
52	5,62	21,360	70,20	82	5,62	0,6838	68,80
52	3,16	13,560	70,33	82	3,16	0,444	65,42
52	1,78	8,618	69,88	82	1,78	0,3023	60,97
52	1,00	5,476	68,99	82	1,00	0,2128	56,54
58	100,00	93,380	68,52				
58	56,20	59,880	69,51				
58	31,60	38,130	70,38				
58	17,80	24,160	71,05				
58	10,00	15,250	71,43				
58	5,62	9,582	71,45				
58	3,16	6,014	70,95				
58	1,78	3,801	69,71				
58	1,00	2,402	68,07				



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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 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic C

Data: 06/05/2025 Strumento: MCR 301 Aging: RTFOT
Unità: POLITO Geometria: PP08 Ripetizione: 1
Operatore: Teresa DI MARZO Materiale: PC5 RdP n°: 3.1/3.1.2.1/41

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	219,977	49,90	4	1,00	12530,7	32,40
34	1,78	297,038	49,50	4	1,78	15365,7	31,40
34	3,16	402,853	48,90	4	3,16	18725,5	30,30
34	5,62	545,462	48,30	4	5,62	22654	29,40
34	10,00	737,026	47,60	4	10,00	27254,3	28,60
34	17,80	993,033	46,80	4	17,80	32635,1	27,90
34	31,60	1332,47	46,00	4	31,60	38928,7	27,20
34	56,20	1778,01	45,10	4	56,20	46250,8	26,50
34	100,00	2357,28	44,10	4	100,00	54731,2	25,80
28	1,00	465,877	47,80				
28	1,78	626,841	47,30				
28	3,16	842,778	46,60				
28	5,62	1127,89	45,80				
28	10,00	1502,31	44,80				
28	17,80	1990,83	43,80				
28	31,60	2621,93	42,80				
28	56,20	3432,24	41,70				
28	100,00	4463,17	40,80				
22	1,00	1094,91	44,90				
22	1,78	1450,23	44,10				
22	3,16	1913,54	43,10				
22	5,62	2509,93	42,00				
22	10,00	3270,09	40,90				
22	17,80	4230,95	39,80				
22	31,60	5434,19	38,80				
22	56,20	6933,4	37,70				
22	100,00	8797,1	36,80				
16	1,00	2555,23	41,20				
16	1,78	3304,22	40,20				
16	3,16	4251,66	39,00				
16	5,62	5428,55	37,90				
16	10,00	6882,47	36,80				
16	17,80	8664,09	35,80				
16	31,60	10821,9	34,80				
16	56,20	13475	33,90				
16	100,00	16682	33,00				
10	1,00	5861,64	36,70				
10	1,78	7379,67	35,60				
10	3,16	9230,14	34,50				
10	5,62	11452,3	33,40				
10	10,00	14112,9	32,40				
10	17,80	17282	31,60				
10	31,60	21074,6	30,70				
10	56,20	25573,5	30,00				
10	100,00	30895,1	29,30				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements

Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic C

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP08
Materiale: PC5

Aging: RTFOT
Ripetizione: 2
RdP n°: 3.1/3.1.2.1/42

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	351,85	43,80	4	1,00	17577,4	32,30
34	1,78	463,90	44,90	4	1,78	21600,9	31,20
34	3,16	619,57	45,60	4	3,16	26328,1	30,20
34	5,62	831,91	45,90	4	5,62	31851,6	29,30
34	10,00	1117,65	45,80	4	10,00	38307,6	28,40
34	17,80	1499,82	45,40	4	17,80	45839,8	27,70
34	31,60	2005,95	44,80	4	31,60	54583,8	27,00
34	56,20	2669,27	44,10	4	56,20	64755,7	26,30
34	100,00	3526,49	43,40	4	100,00	76491,6	25,60
28	1,00	713,10	44,90				
28	1,78	952,11	45,10				
28	3,16	1273,69	44,90				
28	5,62	1699,89	44,40				
28	10,00	2259,31	43,70				
28	17,80	2985,01	42,90				
28	31,60	3916,77	41,90				
28	56,20	5106,80	41,00				
28	100,00	6610,87	40,10				
22	1,00	1623,71	43,80				
22	1,78	2150,17	43,10				
22	3,16	2834,26	42,30				
22	5,62	3712,18	41,30				
22	10,00	4826,30	40,20				
22	17,80	6228,91	39,20				
22	31,60	7973,72	38,10				
22	56,20	10128,90	37,10				
22	100,00	12822,20	36,30				
16	1,00	3709,82	40,60				
16	1,78	4796,59	39,60				
16	3,16	6165,53	38,50				
16	5,62	7857,27	37,40				
16	10,00	9940,41	36,30				
16	17,80	12478,80	35,20				
16	31,60	15579,60	34,30				
16	56,20	19331,70	33,40				
16	100,00	23814,70	32,60				
10	1,00	8207,48	36,50				
10	1,78	10339,70	35,40				
10	3,16	12928,30	34,30				
10	5,62	16036,40	33,30				
10	10,00	19753,10	32,30				
10	17,80	24198,60	31,40				
10	31,60	29479,80	30,60				
10	56,20	35742,60	29,80				
10	100,00	43135,80	29,10				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic C

Data: 06/05/2025 **Strumento:** MCR 302 **Aging:** RTFOT
Unità: POLITO **Geometria:** PP25 **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PC5 **RdP n°:** 3.1/3.1.2.1/43

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	3036,000	50,33	64	100,00	76,2	69,92
34	56,20	2194,000	51,91	64	56,20	48,35	71,18
34	31,60	1568,000	53,59	64	31,60	30,42	72,11
34	17,80	1108,000	55,31	64	17,80	18,98	72,70
34	10,00	773,500	57,02	64	10,00	11,78	72,83
34	5,62	534,200	58,69	64	5,62	7,305	72,32
34	3,16	365,100	60,33	64	3,16	4,531	70,96
34	1,78	247,100	61,91	64	1,78	2,844	68,49
34	1,00	165,700	63,46	64	1,00	1,808	65,16
40	100,00	1467,000	54,95	70	100,00	38,25	72,32
40	56,20	1029,000	56,63	70	56,20	23,84	73,35
40	31,60	713,400	58,32	70	31,60	14,78	73,85
40	17,80	489,100	59,96	70	17,80	9,118	73,77
40	10,00	331,600	61,55	70	10,00	5,628	72,93
40	5,62	222,500	63,09	70	5,62	3,493	71,15
40	3,16	147,600	64,57	70	3,16	2,193	68,22
40	1,78	96,910	65,97	70	1,78	1,412	63,92
40	1,00	62,950	67,30	70	1,00	0,9367	58,80
46	100,00	695,500	59,60	76	100	19,8	73,51
46	56,20	471,500	61,19	76	56,2	12,21	74,08
46	31,60	316,300	62,74	76	31,6	7,51	73,95
46	17,80	210,300	64,22	76	17,8	4,623	73,04
46	10,00	138,500	65,66	76	10	2,863	71,14
46	5,62	90,460	67,01	76	5,62	1,795	68,05
46	3,16	58,570	68,25	76	3,16	1,153	63,65
46	1,78	37,600	69,28	76	1,78	0,7711	57,99
46	1,00	23,880	70,06	76	1,00	0,537	52,22
52	100,00	326,300	63,70	82	100	10,58	74,53
52	56,20	215,900	65,21	82	56,2	6,537	74,89
52	31,60	141,600	66,61	82	31,6	3,995	74,30
52	17,80	92,020	67,95	82	17,8	2,452	72,78
52	10,00	59,240	69,17	82	10	1,521	70,12
52	5,62	37,790	70,19	82	5,62	0,9619	66,27
52	3,16	23,900	70,91	82	3,16	0,6278	61,25
52	1,78	15,040	71,12	82	1,78	0,4293	55,41
52	1,00	9,419	70,76	82	1,00	0,3061	49,76
58	100,00	156,900	67,18				
58	56,20	101,400	68,55				
58	31,60	64,910	69,79				
58	17,80	41,250	70,85				
58	10,00	26,030	71,65				
58	5,62	16,290	72,05				
58	3,16	10,150	71,90				
58	1,78	6,332	70,96				
58	1,00	3,957	69,39				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic C

Data:	06/05/2025	Strumento:	MCR 302	Aging:	RTFOT
Unità:	POLITO	Geometria:	PP25	Ripetizione:	2
Operatore:	Teresa DI MARZO	Materiale:	PC5	RdP n°:	3.1/3.1.2.1/44

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	2922,000	50,95	64	100,00	75,23	68,06
34	56,20	2105,000	52,48	64	56,20	48,33	68,85
34	31,60	1500,000	54,06	64	31,60	30,93	69,58
34	17,80	1058,000	55,66	64	17,80	19,74	70,21
34	10,00	737,800	57,22	64	10,00	12,57	70,82
34	5,62	509,700	58,72	64	5,62	7,993	71,38
34	3,16	349,100	60,15	64	3,16	5,099	71,77
34	1,78	237,000	61,47	64	1,78	3,268	71,88
34	1,00	159,800	62,71	64	1,00	2,096	72,13
40	100,00	1406,000	55,42	70	100,00	37,37	71,18
40	56,20	983,700	56,98	70	56,20	23,7	72,36
40	31,60	680,900	58,51	70	31,60	14,91	73,59
40	17,80	466,300	59,97	70	17,80	9,365	74,66
40	10,00	316,000	61,35	70	10,00	5,892	75,53
40	5,62	212,300	62,63	70	5,62	3,728	76,13
40	3,16	141,500	63,80	70	3,16	2,385	76,25
40	1,78	93,750	64,85	70	1,78	1,551	75,68
40	1,00	61,590	65,84	70	1,00	1,028	74,38
46	100,00	662,800	59,59	76	100	19,66	72,76
46	56,20	450,700	61,00	76	56,2	12,42	73,86
46	31,60	303,600	62,31	76	31,6	7,787	75,06
46	17,80	202,600	63,51	76	17,8	4,883	76,07
46	10,00	134,200	64,58	76	10	3,079	76,71
46	5,62	88,310	65,49	76	5,62	1,956	77,00
46	3,16	57,790	66,25	76	3,16	1,257	76,90
46	1,78	37,640	66,74	76	1,78	0,8233	76,14
46	1,00	24,370	67,11	76	1,00	0,5484	75,32
52	100,00	312,800	63,26	82	100	10,49	75,27
52	56,20	207,700	64,45	82	56,2	6,46	77,26
52	31,60	136,900	65,50	82	31,6	3,923	78,70
52	17,80	89,650	66,39	82	17,8	2,377	79,81
52	10,00	58,400	67,11	82	10	1,435	80,55
52	5,62	37,850	67,62	82	5,62	0,8793	81,01
52	3,16	24,450	67,91	82	3,16	0,5473	81,43
52	1,78	15,810	67,82	82	1,78	0,352	81,01
52	1,00	10,230	67,61	82	1,00	0,2337	79,83
58	100,00	150,900	66,10				
58	56,20	98,370	67,06				
58	31,60	63,770	67,86				
58	17,80	41,120	68,57				
58	10,00	26,420	69,16				
58	5,62	16,930	69,62				
58	3,16	10,840	69,98				
58	1,78	6,976	70,02				
58	1,00	4,489	70,24				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic C

Data: 06/05/2025 Strumento: MCR 301 Aging: PAV
Unità: POLITO Geometria: PP08 Ripetizione: 1
Operatore: Teresa DI MARZO Materiale: PC5 RdP n°: 3.1/3.1.2.1/45

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	462	52,90	4	1,00	28100	27,60
34	1,78	643	51,40	4	1,78	33500	26,50
34	3,16	887	49,80	4	3,16	39600	25,50
34	5,62	1210	48,30	4	5,62	46500	24,60
34	10,00	1640	46,80	4	10,00	54300	23,70
34	17,80	2200	45,40	4	17,80	63000	22,80
34	31,60	2930	43,90	4	31,60	72700	22,00
34	56,20	3860	42,60	4	56,20	83400	21,10
34	100,00	5030	41,40	4	100,00	95200	20,30
28	1,00	1120	47,80				
28	1,78	1520	46,30				
28	3,16	2040	44,80				
28	5,62	2720	43,30				
28	10,00	3570	41,80				
28	17,80	4650	40,40				
28	31,60	6000	39,10				
28	56,20	7670	38,00				
28	100,00	9700	37,00				
22	1,00	2800	42,30				
22	1,78	3670	40,80				
22	3,16	4760	39,30				
22	5,62	6100	37,90				
22	10,00	7760	36,60				
22	17,80	9760	35,40				
22	31,60	12200	34,20				
22	56,20	15100	33,20				
22	100,00	18600	32,30				
16	1,00	6510	36,90				
16	1,78	8240	35,50				
16	3,16	10300	34,20				
16	5,62	12800	33,00				
16	10,00	15700	31,90				
16	17,80	19200	30,80				
16	31,60	23300	29,80				
16	56,20	28100	28,90				
16	100,00	33600	28,00				
10	1,00	14000	32,00				
10	1,78	17100	30,80				
10	3,16	20800	29,60				
10	5,62	25100	28,60				
10	10,00	30000	27,60				
10	17,80	35700	26,70				
10	31,60	42200	25,80				
10	56,20	49600	24,90				
10	100,00	58000	24,10				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements

Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic C

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 301
Geometria: PP08
Materiale: PC5

Aging: PAV
Ripetizione: 2
RdP n°: 3.1/3.1.2.1/46

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	291,53	55,90	4	1,00	19292,6	29,20
34	1,78	413,54	54,30	4	1,78	23218,4	28,10
34	3,16	580,95	52,60	4	3,16	27735,4	27,10
34	5,62	808,19	50,90	4	5,62	32898,1	26,10
34	10,00	1112,58	49,30	4	10,00	38774,6	25,20
34	17,80	1515,96	47,70	4	17,80	45445,5	24,30
34	31,60	2044,23	46,10	4	31,60	52961,9	23,40
34	56,20	2729,77	44,60	4	56,20	61390,9	22,60
34	100,00	3606,32	43,30	4	100,00	70819,2	21,80
28	1,00	721,74	50,70				
28	1,78	993,28	49,00				
28	3,16	1351,58	47,30				
28	5,62	1818,39	45,70				
28	10,00	2420,12	44,10				
28	17,80	3187,00	42,50				
28	31,60	4155,20	41,10				
28	56,20	5375,07	39,70				
28	100,00	6907,01	38,40				
22	1,00	1823,91	44,80				
22	1,78	2417,86	43,20				
22	3,16	3170,19	41,60				
22	5,62	4114,21	40,00				
22	10,00	5285,92	38,60				
22	17,80	6731,72	37,30				
22	31,60	8497,22	36,00				
22	56,20	10645,20	34,80				
22	100,00	13294,20	33,70				
16	1,00	4315,57	39,10				
16	1,78	5518,99	37,60				
16	3,16	6993,96	36,10				
16	5,62	8775,38	34,80				
16	10,00	10919,80	33,60				
16	17,80	13474,00	32,50				
16	31,60	16534,30	31,40				
16	56,20	20144,90	30,40				
16	100,00	24388,50	29,40				
10	1,00	9430,11	33,90				
10	1,78	11674,40	32,60				
10	3,16	14334,20	31,40				
10	5,62	17459,90	30,20				
10	10,00	21100,40	29,20				
10	17,80	25357,50	28,20				
10	31,60	30283,90	27,30				
10	56,20	35968,30	26,40				
10	100,00	42502,30	25,50				



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic C

Data: 06/05/2025
Unità: POLITO
Operatore: Teresa DI MARZO

Strumento: MCR 302
Geometria: PP25
Materiale: PC5

Aging: PAV
Ripetizione: 1
RdP n°: 3.1/3.1.2.1/47

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	5494,360	42,77	64	100,00	155,165	68,01
34	56,20	4173,180	44,23	64	56,20	99,7449	69,72
34	31,60	3137,460	45,90	64	31,60	63,4559	71,47
34	17,80	2331,480	47,72	64	17,80	39,9642	73,22
34	10,00	1711,180	49,65	64	10,00	24,8755	74,99
34	5,62	1239,970	51,65	64	5,62	15,2891	76,74
34	3,16	886,959	53,70	64	3,16	9,29535	78,45
34	1,78	626,191	55,75	64	1,78	5,5826	80,08
34	1,00	436,629	57,81	64	1,00	3,31363	81,59
40	100,00	2843,910	47,70	70	100,00	74,6934	71,79
40	56,20	2083,940	49,53	70	56,20	46,9335	73,51
40	31,60	1507,530	51,47	70	31,60	29,1724	75,20
40	17,80	1076,250	53,47	70	17,80	17,9186	76,86
40	10,00	758,500	55,48	70	10,00	10,8887	78,51
40	5,62	527,818	57,50	70	5,62	6,54536	80,09
40	3,16	362,908	59,51	70	3,16	3,88941	81,57
40	1,78	246,668	61,51	70	1,78	2,29215	82,92
40	1,00	165,494	63,53	70	1,00	1,33664	84,11
46	100,00	1381,930	53,28	76	100	37,1072	75,06
46	56,20	975,009	55,28	76	56,2	22,8255	76,66
46	31,60	678,867	57,28	76	31,6	13,8934	78,25
46	17,80	466,887	59,26	76	17,8	8,37046	79,80
46	10,00	317,320	61,22	76	10	4,99088	81,28
46	5,62	213,271	63,15	76	5,62	2,94683	82,64
46	3,16	141,667	65,09	76	3,16	1,72448	83,87
46	1,78	92,960	67,05	76	1,78	1,00176	84,94
46	1,00	60,121	69,04	76	1,00	0,576866	85,86
52	100,00	672,546	58,69	82	100	18,1953	78,09
52	56,20	459,009	60,66	82	56,2	10,9758	79,43
52	31,60	309,265	62,57	82	31,6	6,56047	80,91
52	17,80	205,786	64,46	82	17,8	3,88445	82,27
52	10,00	135,342	66,33	82	10	2,2796	83,52
52	5,62	88,023	68,22	82	5,62	1,32683	84,65
52	3,16	56,603	70,13	82	3,16	0,766229	85,63
52	1,78	35,957	72,05	82	1,78	0,439946	86,41
52	1,00	22,517	73,99	82	1,00	0,250895	87,00
58	100,00	322,385	63,63				
58	56,20	213,004	65,47				
58	31,60	139,182	67,29				
58	17,80	90,006	69,11				
58	10,00	57,574	70,93				
58	5,62	36,377	72,77				
58	3,16	22,676	74,62				
58	1,78	13,971	76,45				
58	1,00	8,496	78,23				



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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 3.1.2.1. - Evaluation of the Complex Modulus and Phase Angle of Bitumen with Plastic C

Data:	06/05/2025	Strumento:	MCR 302	Aging:	PAV
Unità:	POLITO	Geometria:	PP25	Ripetizione:	2
Operatore:	Teresa DI MARZO	Materiale:	PC5	RdP n°:	3.1/3.1.2.1/48

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	4985,880	46,83	64	100,00	155,813	67,39
34	56,20	3983,970	46,19	64	56,20	100,698	69,20
34	31,60	3171,150	45,53	64	31,60	64,3402	70,95
34	17,80	2384,230	47,20	64	17,80	40,5895	72,68
34	10,00	1758,420	49,10	64	10,00	25,3162	74,41
34	5,62	1279,970	51,07	64	5,62	15,6238	76,11
34	3,16	919,723	53,09	64	3,16	9,5166	77,75
34	1,78	652,383	55,13	64	1,78	5,74152	79,27
34	1,00	456,879	57,19	64	1,00	3,4183	80,64
40	100,00	2880,330	47,20	70	100,00	74,5953	71,31
40	56,20	2122,810	49,01	70	56,20	46,946	72,99
40	31,60	1544,670	50,91	70	31,60	29,2429	74,66
40	17,80	1109,220	52,88	70	17,80	18,0335	76,30
40	10,00	786,036	54,89	70	10,00	10,998	77,88
40	5,62	549,647	56,90	70	5,62	6,63432	79,38
40	3,16	379,493	58,90	70	3,16	3,96301	80,73
40	1,78	258,790	60,91	70	1,78	2,3462	81,90
40	1,00	174,031	62,93	70	1,00	1,37895	82,85
46	100,00	1425,320	52,69	76	100	36,8427	74,39
46	56,20	1010,570	54,66	76	56,2	22,7174	76,00
46	31,60	707,028	56,64	76	31,6	13,8724	77,60
46	17,80	488,559	58,61	76	17,8	8,38373	79,10
46	10,00	333,515	60,57	76	10	5,01691	80,47
46	5,62	225,000	62,51	76	5,62	2,97506	81,69
46	3,16	149,987	64,45	76	3,16	1,75006	82,73
46	1,78	98,763	66,39	76	1,78	1,02312	83,52
46	1,00	64,111	68,35	76	1,00	0,593977	84,08
52	100,00	688,055	58,06	82	100	18,0114	77,02
52	56,20	471,608	60,02	82	56,2	10,9116	78,53
52	31,60	319,156	61,95	82	31,6	6,54738	80,06
52	17,80	213,332	63,84	82	17,8	3,89539	81,38
52	10,00	140,891	65,72	82	10	2,29843	82,51
52	5,62	91,982	67,59	82	5,62	1,34674	83,47
52	3,16	59,356	69,47	82	3,16	0,784436	84,19
52	1,78	37,853	71,35	82	1,78	0,45524	84,63
52	1,00	23,787	73,23	82	1,00	0,263269	84,79
58	100,00	327,687	63,08				
58	56,20	217,262	64,93				
58	31,60	142,448	66,74				
58	17,80	92,422	68,55				
58	10,00	59,327	70,36				
58	5,62	37,611	72,17				
58	3,16	23,536	73,97				
58	1,78	14,561	75,72				
58	1,00	8,894	77,41				



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PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.2. - Penetration Test of Neat Bitumen

Data: 06/05/2025 **Strumento:** Matatest S.r.l. **Aging:** Original
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** O **RdP n°:** 3.1/3.1.2.2/1

Temperature	Displacement
[°C]	[dmm]
25	94
25	96
25	97

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.2. - Penetration Test of bitumen with Plastic A

Data: 06/05/2025 **Strumento:** Matatest S.r.l. **Aging:** Original
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PA5 **RdP n°:** 3.1/3.1.2.2/2

Temperature	Displacement
[°C]	[dmm]
25	80
25	82
25	83

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.2. - Penetration Test of bitumen with Plastic B

Data: 06/05/2025 **Strumento:** Matatest S.r.l. **Aging:** Original
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PB5 **RdP n°:** 3.1/3.1.2.2/3

Temperature	Displacement
[°C]	[dmm]
25	81
25	78
25	77

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.2. - Penetration Test of bitumen with Plastic C

Data: 06/05/2025 **Strumento:** Matatest S.r.l. **Aging:** Original
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PC5 **RdP n°:** 3.1/3.1.2.2/4

Temperature	Displacement
[°C]	[dmm]
25	58
25	55
25	59



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PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.3. - Ring and Ball Test for Neat Bitumen

Data: 06/05/2025 **Strumento:** Matatest S.r.l. **Aging:** Original
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** O **RdP n°:** 3.1/3.1.2.3/1

T (left)	T (right)	T (average)
[°C]	[°C]	[°C]
45,2	45,0	45,2

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.3. - Ring and Ball Test for bitumen with Plastic A

Data: 06/05/2025 **Strumento:** Matatest S.r.l. **Aging:** Original
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PA5 **RdP n°:** 3.1/3.1.2.3/2

T (left)	T (right)	T (average)
[°C]	[°C]	[°C]
49,0	47,9	48,6

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.3. - Ring and Ball Test for bitumen with Plastic B

Data: 06/05/2025 **Strumento:** Matatest S.r.l. **Aging:** Original
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PB5 **RdP n°:** 3.1/3.1.2.3/3

T (left)	T (right)	T (average)
[°C]	[°C]	[°C]
50,8	50,2	50,6

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.3. - Ring and Ball Test for bitumen with Plastic C

Data: 06/05/2025 **Strumento:** Matatest S.r.l. **Aging:** Original
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PC5 **RdP n°:** 3.1/3.1.2.3/4

T (left)	T (right)	T (average)
[°C]	[°C]	[°C]
53,0	52,9	52,8



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.4. - Multiple Stress Creep and Recovery Test for Neat Bitumen

Data: 06/05/2025 **Strumento:** MCR 302 **Aging:** RTFOT
Unità: POLITO **Geometria:** PP25 **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** R **RdP n°:** 3.1/3.1.2.4/1

T [°C]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	21,2793	17,3757	0,1936	0,2052	5,9562
52	13,4082	7,7729	0,5724	0,6295	9,9821
58	7,8028	2,5109	1,5577	1,7667	13,4182
64	4,3700	0,6459	3,9013	4,4628	14,3922
70	1,8259	0,0750	9,1579	10,3457	12,9705
76	0,5936	0,0069	19,4842	21,6599	11,1669
82	0,2637	0,0049	38,4296	42,0963	9,5413

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.4. - Multiple Stress Creep and Recovery Test for Neat Bitumen

Data: 06/05/2025 **Strumento:** MCR 302 **Aging:** RTFOT
Unità: POLITO **Geometria:** PP25 **Ripetizione:** 2
Operatore: Teresa DI MARZO **Materiale:** R **RdP n°:** 3.1/3.1.2.4/2

T [°C]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	20,1119	16,7409	0,2017	0,2121	5,1878
52	12,5497	7,2261	0,6046	0,6617	9,4483
58	7,2924	2,2455	1,6513	1,8590	12,5786
64	3,4657	0,5391	4,1999	4,7585	13,3011
70	1,4947	0,0586	9,8735	11,1042	12,4650
76	0,6148	0,0041	21,0813	23,4631	11,2978
82	0,3465	0,0023	41,3567	45,7042	10,5120



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PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.4. - Multiple Stress Creep and Recovery Test for bitumen with Plastic A

Data: 06/05/2025 **Strumento:** MCR 302 **Aging:** RTFOT
Unità: POLITO **Geometria:** PP25 **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PA5_R **RdP n°:** 3.1/3.1.2.4/3

T [°C]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	45,8255	26,1147	0,0746	0,1058	41,8002
52	30,6037	13,8323	0,2597	0,3447	32,6982
58	24,4836	5,0394	0,7542	1,0427	38,2536
64	10,1838	1,4769	2,2315	2,8209	26,4124
70	7,5945	0,3306	5,4091	6,8741	27,0842
76	5,3370	0,0526	12,1256	15,2571	25,8255
82	2,6373	0,0092	24,5559	30,8136	25,4838

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.4. - Multiple Stress Creep and Recovery Test for bitumen with Plastic A

Data: 06/05/2025 **Strumento:** MCR 302 **Aging:** RTFOT
Unità: POLITO **Geometria:** PP25 **Ripetizione:** 2
Operatore: Teresa DI MARZO **Materiale:** PA5_R **RdP n°:** 3.1/3.1.2.4/4

T [°C]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	37,3723	26,5033	0,0923	0,1103	19,5628
52	30,3362	14,2508	0,2716	0,3550	30,7043
58	25,5350	5,2485	0,7658	1,0782	40,7899
64	12,5691	1,5199	2,2465	2,8958	28,9018
70	5,8248	0,3608	5,6917	6,9058	21,3313
76	3,4295	0,0556	12,5384	15,1869	21,1231
82	1,6070	0,0132	25,1911	30,5986	21,4660



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PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.4. - Multiple Stress Creep and Recovery Test for bitumen with Plastic B

Data: 06/05/2025 **Strumento:** MCR 302 **Aging:** RTFOT
Unità: POLITO **Geometria:** PP25 **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PB5_R **RdP n°:** 3.1/3.1.2.4/5

T [°C]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	40,4881	30,4362	0,0732	0,0884	20,7095
52	32,7865	16,7108	0,2130	0,2973	39,5745
58	24,2165	6,3803	0,6259	0,8981	43,4859
64	15,2406	1,8126	1,7346	2,4831	43,1510
70	8,9053	0,3573	4,5123	6,2550	38,6219
76	3,5908	0,0623	11,1840	14,7430	31,8221
82	1,1897	0,0115	26,4766	33,6700	27,1689

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.4. - Multiple Stress Creep and Recovery Test for bitumen with Plastic B

Data: 06/05/2025 **Strumento:** MCR 302 **Aging:** RTFOT
Unità: POLITO **Geometria:** PP25 **Ripetizione:** 2
Operatore: Teresa DI MARZO **Materiale:** PB5_R **RdP n°:** 3.1/3.1.2.4/6

T [°C]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	38,3727	30,1076	0,0689	0,0805	16,7861
52	30,6112	16,9592	0,2056	0,2637	28,2816
58	20,4189	6,3225	0,6345	0,8476	33,5894
64	12,1507	1,7043	1,8075	2,4525	35,6850
70	6,3490	0,2859	4,8103	6,3807	32,6474
76	2,4899	0,0515	11,7318	14,9117	27,1052
82	0,7676	0,0111	26,3624	32,9351	24,9321



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PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.4. - Multiple Stress Creep and Recovery Test for bitumen with Plastic C

Data: 06/05/2025 **Strumento:** MCR 302 **Aging:** RTFOT
Unità: POLITO **Geometria:** PP25 **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PC5_R **RdP n°:** 3.1/3.1.2.4/7

T [°C]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	97,7527	52,1831	0,0008	0,0205	2463,2812
52	92,3516	36,2825	0,0071	0,0715	906,8662
58	67,2727	21,4665	0,0720	0,2254	213,0208
64	49,3213	9,8283	0,2600	0,6765	160,2043
70	36,2363	3,7554	0,7460	1,9634	163,1954
76	19,8824	1,3932	2,7800	4,8434	74,2244
82	12,0411	0,1189	6,2000	10,9188	76,1089

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.4. - Multiple Stress Creep and Recovery Test for bitumen with Plastic C

Data: 06/05/2025 **Strumento:** MCR 302 **Aging:** RTFOT
Unità: POLITO **Geometria:** PP25 **Ripetizione:** 2
Operatore: Teresa DI MARZO **Materiale:** PC5_R **RdP n°:** 3.1/3.1.2.4/8

T [°C]	R0.1 [%]	R3.2 [%]	Jnr0.1 [kPa ⁻¹]	Jnr3.2 [kPa ⁻¹]	Jnrdiff [%]
46	64,5837	43,8286	0,0176	0,0296	67,9332
52	50,8362	31,5448	0,0648	0,0940	45,0810
58	52,0510	17,9683	0,1558	0,3011	93,2827
64	34,2028	7,2690	0,5325	0,9254	73,7905
70	26,3762	2,3997	1,4119	2,5394	79,8560
76	16,8694	0,7978	3,6593	5,9330	62,1358
82	11,2913	0,2261	8,2367	13,2101	60,3811



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PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Neat bitumen

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** P **RdP n°:** 3.1/3.1.2.5/1

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-12	8,0	981	0,30662	258	258	0,000	0,265
-12	15,0	980	0,36524	216	217	0,463	0,289
-12	30,0	979	0,44948	176	176	0,000	0,315
-12	60,0	979	0,56325	140	140	0,000	0,341
-12	120,0	980	0,72137	110	110	0,000	0,367
-12	240,0	981	0,93975	84	84	0,000	0,393

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Neat bitumen

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 2
Operatore: Teresa DI MARZO **Materiale:** P **RdP n°:** 3.1/3.1.2.5/2

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-12	8,0	985	0,31085	255	255	0,000	0,270
-12	15,0	984	0,37049	214	214	0,000	0,290
-12	30,0	981	0,45642	173	174	0,578	0,311
-12	60,0	986	0,56988	140	139	-0,714	0,333
-12	120,0	985	0,72452	110	110	0,000	0,354
-12	240,0	987	0,93568	85	85	0,000	0,376



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PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Neat bitumen

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** P **RdP n°:** 3.1/3.1.2.5/3

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-18	8,0	986	0,16204	491	489	-0,407	0,213
-18	15,0	983	0,18694	424	426	0,472	0,231
-18	30,0	983	0,22054	359	360	0,279	0,251
-18	60,0	984	0,26331	301	301	0,000	0,270
-18	120,0	984	0,31938	248	248	0,000	0,289
-18	240,0	987	0,39626	201	201	0,000	0,309

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Neat bitumen

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 2
Operatore: Teresa DI MARZO **Materiale:** P **RdP n°:** 3.1/3.1.2.5/4

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-18	8,0	990	0,16610	481	180	-0,208	0,208
-18	15,0	989	0,19082	418	419	0,239	0,228
-18	30,0	991	0,22524	355	355	0,000	0,250
-18	60,0	990	0,26990	296	296	0,000	0,273
-18	120,0	990	0,32823	243	243	0,000	0,295
-18	240,0	993	0,40763	196	197	0,510	0,317



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Bitumen with Plastic A

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PA5 **RdP n°:** 3.1/3.1.2.5/5

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-12	8,0	983	0,30358	261	261	0,000	0,256
-12	15,0	983	0,35906	221	221	0,000	0,273
-12	30,0	982	0,43634	181	182	0,552	0,292
-12	60,0	982	0,53750	147	147	0,000	0,311
-12	120,0	982	0,66961	118	118	0,000	0,329
-12	240,0	983	0,85014	93	93	0,107	0,348

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Bitumen with Plastic A

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 2
Operatore: Teresa DI MARZO **Materiale:** PA5 **RdP n°:** 3.1/3.1.2.5/6

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-12	8,0	988	0,30149	264	264	0,000	0,256
-12	15,0	987	0,35681	223	223	0,000	0,275
-12	30,0	988	0,43456	183	183	0,000	0,296
-12	60,0	987	0,53670	148	148	0,000	0,316
-12	120,0	987	0,67201	118	118	0,000	0,337
-12	240,0	988	0,85718	83	93	0,108	0,357



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Bitumen with Plastic A

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PA5 **RdP n°:** 3.1/3.1.2.5/7

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-18	8,0	981	0,15530	509	509	0,000	0,206
-18	15,0	980	0,17792	444	445	0,225	0,223
-18	30,0	980	0,20903	378	378	0,000	0,242
-18	60,0	981	0,24879	318	318	0,000	0,262
-18	120,0	982	0,30042	264	263	-0,379	0,281
-18	240,0	986	0,36951	215	215	0,000	0,300

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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Bitumen with Plastic A

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 2
Operatore: Teresa DI MARZO **Materiale:** PA5 **RdP n°:** 3.1/3.1.2.5/8

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-18	8,0	986	0,16683	477	476	-0,210	0,204
-18	15,0	986	0,19105	416	416	0,000	0,224
-18	30,0	987	0,22472	354	354	0,000	0,245
-18	60,0	984	0,26771	296	297	0,338	0,266
-18	120,0	985	0,32432	245	245	0,000	0,288
-18	240,0	987	0,40016	199	199	0,000	0,309



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Bitumen with Plastic B

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PB5 **RdP n°:** 3.1/3.1.2.5/9

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-12	8,0	988	0,30232	264	263	-0,379	0,260
-12	15,0	989	0,35859	222	222	0,000	0,278
-12	30,0	988	0,43747	182	182	0,000	0,299
-12	60,0	988	0,54152	147	147	0,000	0,319
-12	120,0	988	0,68037	117	117	0,000	0,339
-12	240,0	991	0,86954	92	92	0,000	0,359

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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Bitumen with Plastic B

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 2
Operatore: Teresa DI MARZO **Materiale:** PB5 **RdP n°:** 3.1/3.1.2.5/10

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-12	8,0	997	0,31233	261	261	0,000	0,262
-12	15,0	997	0,38765	220	220	0,000	0,276
-12	30,0	998	0,46657	181	181	0,000	0,300
-12	60,0	998	0,55031	146	146	0,000	0,322
-12	120,0	997	0,67152	118	118	0,000	0,337
-12	240,0	998	0,85856	92	92	0,000	0,350



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Bitumen with Plastic B

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PB5 **RdP n°:** 3.1/3.1.2.5/11

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-18	8,0	986	0,15866	501	501	0,000	0,130
-18	15,0	985	0,18224	436	436	0,000	0,229
-18	30,0	985	0,21463	370	370	0,000	0,247
-18	60,0	985	0,25649	310	310	0,000	0,264
-18	120,0	985	0,30973	256	256	0,000	0,281
-18	240,0	989	0,38010	210	210	0,000	0,299

PROGETTO PRIN 2022

WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Bitumen with Plastic B

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 2
Operatore: Teresa DI MARZO **Materiale:** PB5 **RdP n°:** 3.1/3.1.2.5/12

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-18	8,0	996	0,15297	525	525	0,000	0,209
-18	15,0	996	0,17574	457	457	0,000	0,229
-18	30,0	994	0,20718	387	387	0,000	0,250
-18	60,0	996	0,24806	324	323	-0,309	0,272
-18	120,0	995	0,30163	266	266	0,000	0,293
-18	240,0	997	0,37346	215	215	0,000	0,315



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Bitumen with Plastic C

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PC5 **RdP n°:** .1/3.1.2.5/13

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-6	8,0	992	0,51865	154	154	0,000	0,285
-6	15,0	992	0,62524	128	128	0,000	0,303
-6	30,0	991	0,77649	103	103	0,000	0,324
-6	60,0	990	0,97720	82	82	0,000	0,345
-6	120,0	992	1,24862	64	64	-0,312	0,365
-6	240,0	991	1,62575	49	49	0,204	0,386

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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Bitumen with Plastic C

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 2
Operatore: Teresa DI MARZO **Materiale:** PC5 **RdP n°:** .1/3.1.2.5/14

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-6	8,0	990	0,51353	155	155	0,000	0,284
-6	15,0	990	0,61740	129	129	0,000	0,302
-6	30,0	990	0,76624	104	104	0,000	0,322
-6	60,0	989	0,96439	83	83	0,000	0,342
-6	120,0	989	1,23102	65	65	0,000	0,363
-6	240,0	991	1,59689	50	50	0,000	0,383



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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Bitumen with Plastic C

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 1
Operatore: Teresa DI MARZO **Materiale:** PC5 **RdP n°:** .1/3.1.2.5/15

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-12	8,0	988	0,28752	277	277	0,000	0,244
-12	15,0	987	0,33707	236	236	0,000	0,260
-12	30,0	987	0,40617	196	196	0,000	0,279
-12	60,0	988	0,49546	161	161	0,000	0,297
-12	120,0	987	0,61235	130	130	0,000	0,315
-12	240,0	990	0,76913	104	104	0,000	0,333

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WORK PACKAGE 3 - TASK 3.1 Evaluation of new sustainable materials to be employed as bitumen additives or replacements
Activity 3.1.2.5. - Bending Beam Rheometer Test for Bitumen with Plastic C

Data: 06/05/2025 **Strumento:** BBR **Aging:** PAV
Unità: POLITO **Geometria:** **Ripetizione:** 2
Operatore: Teresa DI MARZO **Materiale:** PC5 **RdP n°:** .1/3.1.2.5/16

T	t (time)	P (Force)	d (deflection)	Measured Stiffness	Estimated Stiffness	Difference	m-value
[°C]	[s]	[mN]	[mm]	[MPa]	[MPa]	[%]	-
-12	8,0	991	0,28880	277	277	0,000	0,246
-12	15,0	992	0,33930	236	236	0,000	0,262
-12	30,0	991	0,40889	195	195	0,000	0,280
-12	60,0	990	0,49964	160	160	0,000	0,298
-12	120,0	991	0,61747	129	129	0,000	0,316
-12	240,0	992	0,77571	103	103	0,000	0,334