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Effect of Fischer–Tropsch wax on the performance of conventional and polymer-modified bitumen binders in warm mix asphalt technology

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ABSTRACT

This study investigates the influence of Fischer–Tropsch synthetic wax (FTW) on the compactability and rheological behaviour of conventional 50/70 and polymer-modified PMB 45/80–55 binders in warm mix asphalt (WMA) technology. The results demonstrate a clear binder-specific and concentration-dependent response, rather than a linear improvement in workability. For the 50/70 binder, dynamic shear rheometer (DSR) analysis in conjunction with Black space diagrams enabled the identification of a critical FTW content of 4%, above which rheological instability and structural disturbances occur. The polymer-modified binder exhibited a synergistic interaction with FTW, whereby a low wax content (2%) partially mitigated the stiffness imparted by the polymer network, while a 3% addition enabled a statistically significant reduction in compaction temperature of approximately 20 °C without degradation of the SBS polymer structure. Low-temperature evaluation using the bending beam rheometer (BBR) revealed that while FTW increases creep stiffness (S), it simultaneously reduces the stress relaxation capacity (m-value), particularly in the conventional binder matrix. In both binders, a pronounced rheological lock-up phenomenon was observed, characterised by a rapid increase in viscosity within the FTW melting range (90–115 °C), which defines a narrow technological window for effective compaction. Although FTW increased the high-temperature performance grade by approximately 20 °C, the BBR results indicate a trade-off between enhanced rutting resistance and increased susceptibility to low-temperature cracking.

Keywords: warm mix asphalt, Fischer–Tropsch wax, rheological behaviour, compactability, polymer-modified bitumen, sustainable infrastructure.

INTRODUCTION

Traditional hot mix asphalt (HMA), produced at temperatures ranging from 160 °C to 180 °C, has long served as the standard in road construction, because it ensures adequate coating of aggregates and satisfactory in-service performance. Although it provides mixtures with satisfactory mechanical performance, the technology is associated with high energy consumption, substantial greenhouse gas emissions, and premature binder aging. All these factors ultimately compromise the durability of the pavement [1, 2]. In the context of increasingly stringent environmental regulations and decarbonisation targets in the transport sector, these drawbacks motivate the development of more sustainable technologies for asphalt pavement construction [3–6].

In response to these environmental and performance challenges, the WMA technology has gained increasing acceptance as a more sustainable alternative. By enabling production and compaction at temperatures 20–50 °C below those required for conventional HMA, WMA offers many advantages: reduced fuel consumption and CO_2 emissions, improved working conditions due to less exposure to fumes, slower aging of the binder, increased compactability, and greater potential for using reclaimed asphalt pavement (RAP) [7–10]. Recent reviews emphasise that, when properly designed, the WMA mixtures can achieve the thermo-mechanical and rheological properties comparable to, or in some cases better than, those of conventional HMA, while delivering measurable environmental and economic benefits in terms of energy consumption, production costs and life-cycle impacts [8, 10, 11]. Laboratory and field investigations summarised in these studies also indicate that, for suitably selected technologies, WMA can provide satisfactory rutting, fatigue and moisture resistance, even in demanding traffic and climatic conditions [12–14].

The global use of WMA varies considerably. The United States accounts for over 30% of total WMA production, while in European countries such as France and Germany, the corresponding share exceeds 15% [15]. In contrast, in Poland the technology remains largely experimental and has yet to achieve widespread adoption [16]. At the same time, many road agencies are developing green road rating systems and sustainability indices that explicitly reward the use of WMA and other low-emission technologies in pavement construction, which further accelerates interest in these solutions [17–19]. In several countries, WMA is also being considered in combination with high RAP contents and other secondary materials to maximise both environmental and resource-efficiency gains [20–23].

Among the various WMA techniques, the most commonly used methods for reducing the viscosity of the mixture and improving its workability are chemical additives, foaming processes, and organic additives, in particular synthetic and natural waxes [24, 25]. Chemical (surfactant-based) additives mainly act by modifying surface tension and adhesion at the binder–aggregate interface, thereby enhancing coating and compaction at reduced temperatures [26, 27]. Foaming techniques, often combined with surfactants, temporarily increase the volume of binder and lower its viscosity, and recent studies have shown that foaming parameters significantly influence the rheological behaviour of the WMA binders over a wide temperature and frequency range [28–30]. The choice of the WMA technology and dosage must therefore be tailored to the specific binder-mixture system, especially when using polymer-modified binders or mixtures with high RAP or rubber contents [31, 32].

Waxes have attracted particular interest because of their dual functionality: they lower binder viscosity during mixing, and upon cooling, they crystallise to increase stiffness and improve rutting resistance [9]. However, excessive wax content can negatively affect performance at low temperatures, which requires careful dosage control. In addition to conventional paraffinic or polyethylene waxes, synthetic waxes have been introduced into the WMA mixtures and have been shown to improve the shear fatigue resistance and stiffness performance of asphalt mixtures subjected to repeated loading [33, 34]. Experimental work on asphalt mixtures containing rubber modifiers and a wax-based additive has further demonstrated that wax-modified systems can enhance fracture resistance and delay crack propagation, as evidenced by larger fracture energy and improved post-peak behaviour in semicircular bending and related tests [34, 35]. An organic viscosity-reducing warm-mix agent used in rubber asphalt has also been reported to improve high-temperature performance and workability, while maintaining satisfactory low-temperature properties [36, 37].

FTW, a synthetic product of gas-to-liquid conversion processes, is characterised by high purity, a narrow melting range, and a fine crystalline structure. Such properties make it well-suited as an additive for WMA. Previous studies have shown that FTW can reduce the production temperature by 20–30 °C, increase rutting resistance, and improve the rheological properties of binders at high temperatures [38, 39]. In more complex systems, FTW-based and other organic warm-mix agents have been successfully applied in rubber-modified asphalt, where viscosity-reducing additives significantly decrease high-temperature viscosity and improve workability while preserving the beneficial properties introduced by crumb rubber [24, 40, 41]. The investigations on warm-mix recycled asphalt binders with high percentages of RAP binder have also indicated that wax-based additives such as Sasobit strongly affect the linear viscoelastic response, sometimes leading to thermorheologically complex behaviour that challenges simple time-temperature superposition [32, 42]. However, its interaction with polymer-modified binders is more complex. Polymer-modified binders may significantly affect the crystallisation process of FTW, which in turn determines its overall effectiveness [43].

The interaction between synthetic waxes and more complex binder matrices, such as high-viscosity polymer-modified binders or systems containing reactive polymers, is particularly complex. Recent studies show that the composition of wax-based warm-mix additives, for instance through the incorporation of ethylene-vinyl acetate (EVA), can be tailored to improve compatibility with bitumen and balance viscosity reduction with favourable high-temperature performance and storage stability [43, 44]. For high-viscosity polymer-modified binders, laboratory tests have demonstrated that FTW can be used not only to lower working temperatures but also to tune the complex shear modulus, phase angle and rutting resistance, though its influence on the polymer network structure and low-temperature relaxation remains strongly binder-dependent [40, 45]. These observations suggest that the results obtained for conventional binders cannot be directly transferred to polymer-modified systems without dedicated experimental verification [43].

Most previous studies have focused either on the rheology of the binder or on the properties of the mixture. Relatively few studies have combined these two aspects in a coordinated analysis [46, 47]. There is still a need for comprehensive research combining the improvement in rheological properties caused by FTW (increase in complex modulus and decrease in phase angle) with the workability of the mixture and its performance in regional climatic and technical conditions characteristic of Central Europe, including Poland [48]. In particular, systematic comparisons of FTW modification in both conventional and polymer-modified binders commonly used in road construction, and the resulting impact on mixture compactability and achievable compaction temperature reduction, remain limited in the available literature. Moreover, many existing studies have been carried out under climatic and technical conditions that differ from those typical of Central and Eastern Europe, which further justifies region-specific investigations [40, 49].

To fill this gap, the present study provides an integrated assessment of the influence of FTW on two representative road binders: a conventional 50/70 bitumen and a polymer-modified PMB 45/80–55. Dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests, Brookfield viscosity measurements, and Marshall and Superpave gyratory compaction analyses were employed to characterise the effect of different FTW contents on high- and low-temperature rheological behaviour, including the identification of critical wax dosages and rheological instability thresholds. By linking binder-level rheological changes with mixture compactability, the study provides quantitative guidance on binder-specific FTW dosage windows and technological temperature ranges. These findings can be directly applied in engineering practice to select appropriate binders and wax contents for WMA wearing courses in Central European climates, to optimise plant production and field compaction temperatures, to design the WMA mixtures with high RAP or rubber contents that still meet performance requirements, and to support the wider implementation of the WMA technology in the countries where its current use is still limited, such as Poland.

MATERIALS AND METHODS

Materials

Bitumen binders

The experimental program used two different types of bituminous binders, selected as representative of materials commonly used in road construction in Poland. Their basic properties, as specified by the manufacturer and verified in standard tests, are summarised in Table 1.

Bitumen 50/70 was used as the reference binder to evaluate the fundamental effects of FTW modification on an unmodified bituminous matrix. PMB 45/80-55 is a polymer-modified binder containing approximately 4–5% styrene-butadiene-styrene (SBS) triblock copolymer. SBS networks increase flexibility, cohesion and resistance to permanent deformation compared to traditional bitumen. This binder was added to investigate synergistic interactions between F–T wax and the existing polymer-modified matrix.

In this study, the synthetic FTW used was VESTOWAX SH 105, manufactured by Evonik Industries AG (Germany). This additive is a linear, semi-crystalline rheological modifier produced via the Fischer–Tropsch process, which involves the catalytic synthesis of syngas into long-chain hydrocarbons. VESTOWAX SH 105 is specifically characterised by high chemical purity, a narrow molecular weight distribution, and a high melting point (typically 105–115 °C), which is consistent with the properties summarised in Table 2. Unlike conventional paraffin waxes, this synthetic FTW contains primarily linear n-alkanes, which promotes the formation of a stable, reinforcing crystalline lattice within the bitumen matrix upon cooling.

Table 1. Basic properties of the bitumen binders used in the study

Properties	Standard	Unit	50/70	PMB 45/80-55
Penetration (at 25 °C)	EN 1426 [50]	0.1 mm	61.7	63.1
Softening point (R&B)	EN 1427 [51]	°C	49.5	65.2
Fraass breaking point	EN 12593 [52]	°C	–15.1	–17.9
Viscosity (at 90 °C)	EN 13302 [53]	Pa·s	11.1	105.9

Table 2. Physicochemical properties of the FTW [54]

Properties	Unit	Value
Melting point	°C	108–114
Density	g/cc	0.940
Molecular weight	g/mol	750

Extended modification range (up to 5%) in the case of conventional 50/70 bitumen was chosen in order to investigate the dose-dependent behaviour and identify the potential saturation point or optimum content for this unmodified binder, whose matrix lacks the structural complexity of polymer-modified binders. The modification process was carried out using a high-shear laboratory mixer.

The base binders (50/70 and PMB 45/80-55) were first heated to 170 °C to achieve a fully liquid state. Then, a defined amount of FTW was gradually added to the binder and mixed at a speed of 1000 rpm for 10 minutes to ensure uniform dispersion of the modifier. The selected mixing time was based on both the authors' laboratory tests and the recommendations presented in previous studies [38].

Mineral-asphalt mixture (MAM)

A dense graded asphalt concrete (AC) mixture with a maximum aggregate size of 11 mm, intended for wearing courses, was designed in compliance with Polish technical requirements [55]. The skeleton aggregate consisted of natural gabbro aggregates from the "Braszowice" mine. The particle size distribution curve of the designed mixture is shown in Figure 1.

The detailed composition of the designed AC11 mixture, optimised for traffic categories KR5–KR6 (representing very heavy to extreme traffic loads), is presented in Table 3. The mix design follows a dense-graded distribution with a binder content of 5.5%.

MAM was designed using the experimental method in accordance with [55]. The design process focused on selecting an aggregate grading curve within the boundary points for AC11 S to ensure a robust mineral skeleton suitable for KR5–KR6 traffic levels. The optimal binder content of 5.5% was determined to achieve the required volumetric properties, specifically target air voids (V_m) and voids filled with binder (VFB), while maintaining high workability for the WMA applications.

The selection of the AC11 mix was justified by its widespread use in Poland. The dense graded aggregate and relatively low binder content in this mix make it particularly sensitive to the changes in binder rheology, which makes it possible to clearly observe the effect of FTW modification on compactability and performance properties. Before

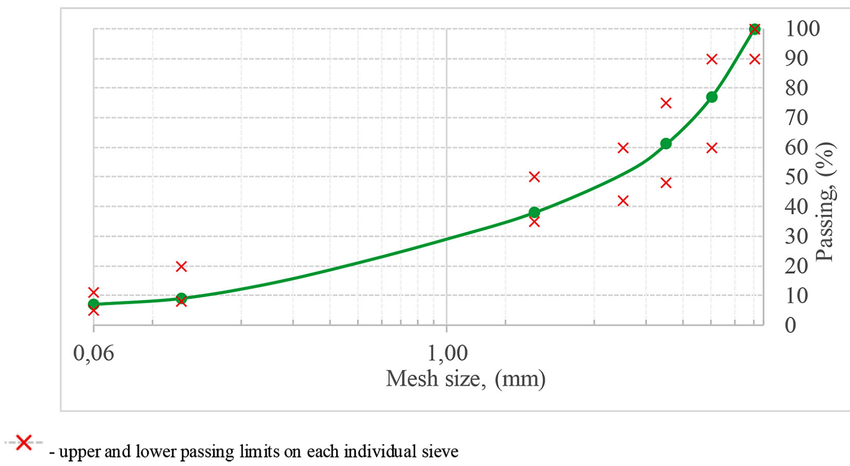


Figure 1. Particle size distribution curve of the designed AC11 mixture

Table 3. Percentage composition and design parameters of the MAM (AC11) for KR5–KR6 traffic

Component	Percentage %
Limestone filler	4.73
Fine aggregate (0/2 mm)	33.08
Coarse aggregate (2/5 mm)	19.04
Coarse aggregate (5/11 mm)	37.65
Total Aggregate	94.50
Bitumen binder (50/70 or PMB 45/80-55)	5.50
Total	100.00

preparing the mixtures, all materials were checked for compliance with the appropriate standards to ensure consistent quality and repeatable results.

Methods

The experimental program involved a comprehensive series of tests to evaluate both binder and mixture properties. For the rheological characterisation (DSR, BBR, and Brookfield viscosity), a total of 108 independent binder trials were conducted (2 base binders × 9 modification levels/temperatures × 3 replicates). The compactability study of MAM included the preparation and testing of 150 specimens (2 binder types × 5 FTW doses × 3 temperatures × 5 replicates for both Marshall and gyratory methods). In total, over 250 individual measurements were performed to provide a robust data set for statistical analysis.

DSR test at high temperature

The rheological properties of binders were determined in accordance with the PN-EN 14770 [56] and AASHTO T 315 [57] guidelines, using a DSR rheometer (Bohlin Instruments Ltd., Cirencester, UK). The device allows for the assessment of the complex shear modulus |G*| and phase angle δ at a specific temperature by applying variable stresses and recording deformations. The measurements were performed in the temperature range of 46–88 °C (every 6 °C) at a constant frequency of ω = 10 rad/s (1.59 Hz).

The samples were thermally stabilised for 10 minutes at the test temperature. The rheometer automatically determined the values of |G*| and δ during the test. On the basis of these parameters, the rutting index (|G*|/sinδ) was calculated in accordance with Superpave specifications to evaluate high-temperature properties (minimum 1.0 kPa for unaged binders). To ensure statistical reliability, each binder variant was tested using three independent specimens ($n = 3$) for every temperature point. The final results for the complex shear modulus |G*| and phase angle (δ) represent the average values from these replicates, with a maximum allowable coefficient of variation below 5%

BBR test at low temperature

The low-temperature properties of the tested binders were evaluated using a Bending Beam Rheometer (Applied Test Systems, Butler, PA, USA). This test was performed according to the EN 14771 standard [58]. Small bitumen beams were prepared with dimensions of 125 × 12.5 × 6.25 mm. Before the BBR testing, all modified binders were subjected to short-term aging using a Rolling Thin Film Oven (RTFOT, Infratest Prüftechnik GmbH, Brackenheim, Germany) and subsequent long-term aging in a Pressure Aging Vessel (PAV, Prentex Alloy Fabricators Inc., Sunnyvale, TX, USA). The test was conducted at temperatures of –10 °C, –16 °C and –22 °C. A constant load of 980 mN was applied to the centre of each beam for 240 seconds. The computer recorded the deflection of the samples at specific time intervals. Two main parameters were evaluated at the 60th second of loading: the creep stiffness (S), which quantifies the resistance of the binder to thermally induced stresses, and the m-value, which represents the stress relaxation capacity of the material. These parameters were used to assess whether FTW incorporation causes excessive embrittlement of the binder at low temperatures.

A minimum of three bitumen beams were prepared and tested for each combination of binder type, modification level, and test temperature (–10 °C, –16 °C, and –22 °C). This approach allowed for the precise determination of the mean creep stiffness (S) and m-value, ensuring that the results were representative of the aged binder's performance.

Brookfield viscosity test

The workability of binders was characterised by measuring dynamic viscosity using a Brookfield viscometer (Viateco Sp. z o.o., Chorzów, Poland). The tests were carried out at three key temperatures: 90 °C, 115 °C, and 135 °C. These temperatures were selected to reflect key stages in bitumen application, from mixing and compaction to service conditions. Viscosity at these points provided insight into the effect of FTW on the flow properties of the binder at elevated and moderate temperatures. Dynamic viscosity measurements were conducted on three separate samples for each binder type at 90 °C, 115 °C, and 135 °C. The use of multiple replicates was essential to capture the rapid changes in rheological behaviour occurring near the FTW melting range.

Compactability of asphalt mixtures

The mixtures were prepared in a multi-stage process. First, the aggregate and filler were weighed according to the mixture recipe and then dried for 8 hours at 195 °C. At the same time, the binders were heated. The dried aggregate was combined with heated bitumen in a heated mixer bowl and mixed until the aggregate particles were completely covered, for a maximum of 4 minutes. Finally, the resulting mixture was conditioned for 2 hours in an oven with air circulation to simulate short-term aging.

Compactability was evaluated using Marshall hammer compaction (Infratest Prüftechnik GmbH, Brackenheim, Germany) and Superpave gyratory compaction (CONTROLS S.p.A., Liscate, Italy). In the Marshall method, specimens were compacted in accordance with PN-EN 12697-30 [59], by applying 75 blows per side. Gyratory compaction was performed following PN-EN 12697-31 [60], with a mould inclination angle of 1.25°, a vertical pressure of 600 kPa, and 200 gyrations, which are commonly adopted to represent field compaction conditions. For each type of binder, compaction was carried out at three temperatures. For 50/70 bitumen, the temperatures were 135 °C, 125 °C, and 115 °C, while for PMB 45/80-55 they were 145 °C, 135 °C, and 125 °C.

Separate series of samples were produced for each combination of temperature and wax content. The compactability was assessed on the basis of the bulk density in a saturated and surface-dry state (SSD method, PN-EN 12697-6 [61] and air void content (PN-EN 12697-8 [62]). The obtained values were compared with reference samples without wax addition.

For the compactability analysis, five replicate specimens ($n = 5$) were prepared for each experimental cell (combination of binder type, wax content, and temperature) to account for the inherent heterogeneity of the AC11 mixture. In total, 75 Marshall specimens and a corresponding set of gyratory compacted samples were evaluated to provide a robust data set for the subsequent ANOVA and Tukey HSD statistical analyses.

Statistical analysis

To ensure the reliability and significance of the observed trends, all experimental measurements were performed on multiple replicates. Rheological tests (DSR, BBR, and Brookfield viscosity) were conducted on three independent samples ($n = 3$) for each binder variant and temperature point. For the compaction analysis (Marshall and gyratory methods) and subsequent air void content determinations, five specimens ($n = 5$) were prepared for each combination of binder type, FTW dosage, and temperature. All results presented in the figures and tables of this study are average values obtained from these multiple replicates, accompanied by their respective standard deviations where applicable.

The statistical basis for the data analysis was established by verifying the fundamental assumptions of parametric tests. The normality of the distribution for each data set was confirmed using the Shapiro–Wilk test, while the homogeneity of variances was assessed using Levene's test. Recognising that individual measurements of heterogeneous materials such as bitumen and MAM do not yield identical values for every sample, these metrics were used to monitor the natural variability of the data. The observed scatter remained within the repeatability limits defined by the respective testing standards (e.g., [56] and [60]). These metrics are reported throughout the results section and, where applicable, are represented as error bars in the figures. The statistical significance of the effect of FTW dosage on the properties of the binder and mixture was assessed using one-way and two-way analysis of variance (ANOVA). In order to identify specific differences between the reference materials and the various modification levels and to statistically justify the determination of the optimal wax content, Tukey's HSD (Honestly Significant Difference) post-hoc test was used at a significance level of $\alpha = 0.05$. This approach allowed for a rigorous determination of whether the observed changes in binder stiffness and mixture compactability were statistically significant or resulted from random measurement fluctuations.

RESEARCH RESULTS AND ANALYSIS

Before performing the comparative analysis, the distribution of all rheological and compactability data sets was verified. The Shapiro–Wilk test confirmed the normality of the distributions ($p >$

0.05), and Levene's test indicated that the variances were homogeneous across the different FTW concentration groups. Consequently, the use of parametric ANOVA and Tukey's HSD post-hoc tests was statistically justified for all evaluated parameters.

Rheological properties of modified binders

Complex shear modulus |G| and phase angle δ*

The viscoelastic response of binders, characterised by |G*| and δ, is shown in Figures 2 and 3 as a function of temperature.

The addition of FTW causes a significant, non-linear transformation of the viscoelastic response in both binders. Prior to the comparative analysis, the prerequisite assumptions for parametric testing were verified; the Shapiro–Wilk test confirmed the normality of the data distribution, and Levene's test indicated homogeneity of variances ($p > 0.05$). A similar increase in stiffness of up to 4% FTW corresponds to the results of the studies on FTW in binders with a high RAP content [63]. Consequently, the observed trends were confirmed by a one-way ANOVA ($p < 0.05$).

In the case of 50/70 bitumen, a gradual increase in stiffness |G*| up to a dose of 4% reflects the formation of a solid wax crystal network in the unmodified matrix. This crystalline saturation at 4% is consistent with recent wax-modified WMA research [64]. Tukey's HSD test showed that 4% is the critical saturation threshold, as a further increase to 5% resulted in a statistically significant decrease in stiffness, suggesting structural destabilisation.

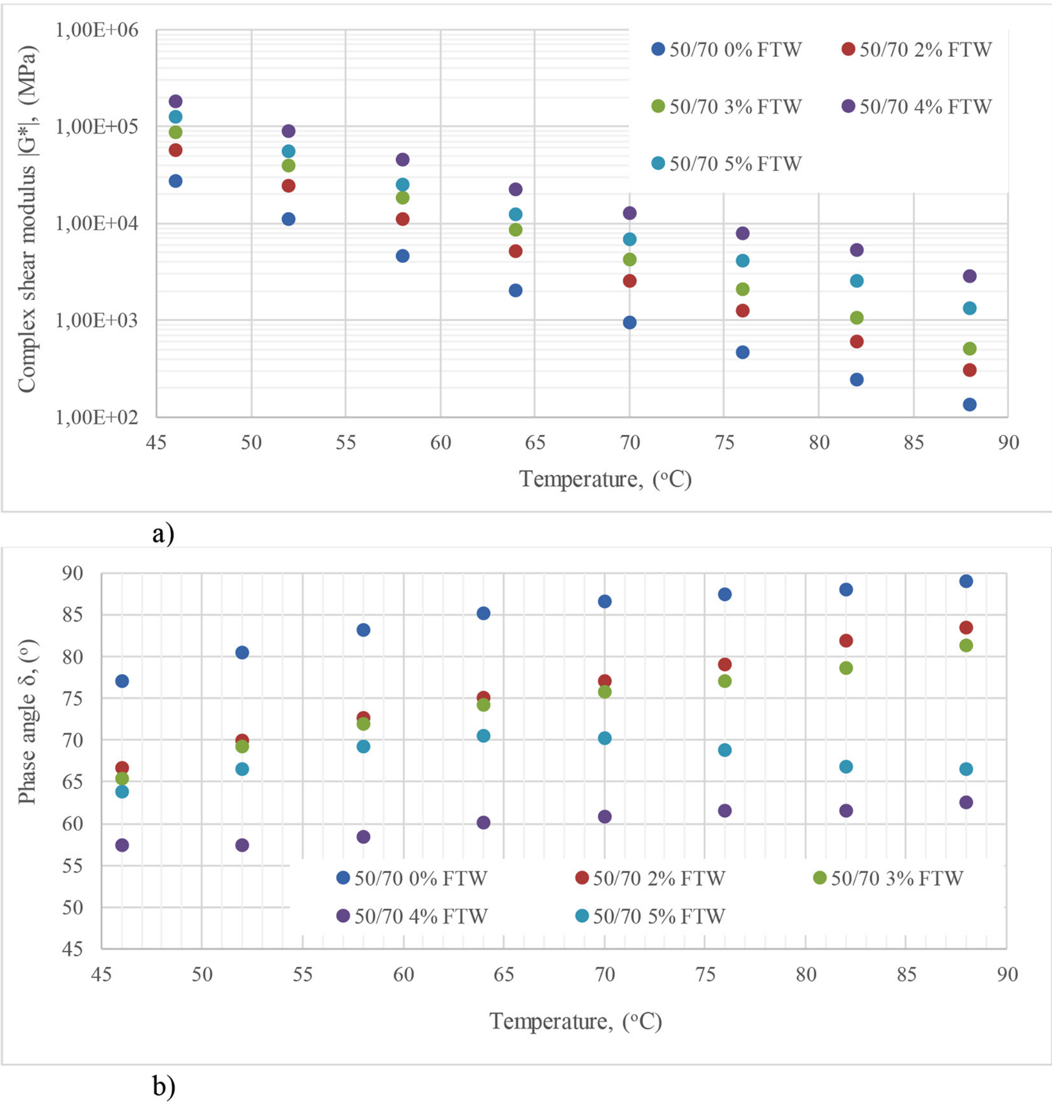
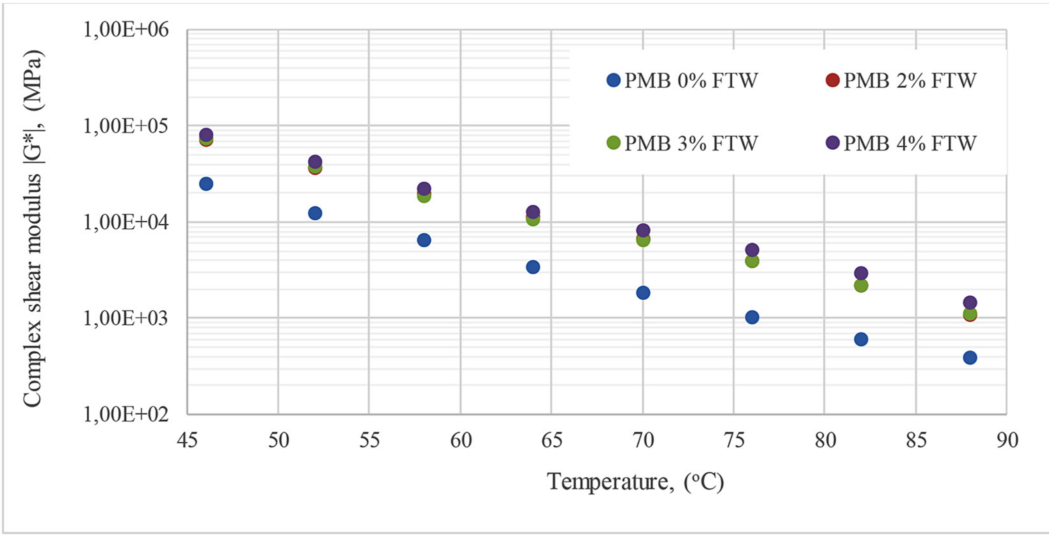


Figure 2. (a) Complex shear modulus (|G*|) and (b) phase angle δ as a function of temperature for 50/70 and FTW-modified binders



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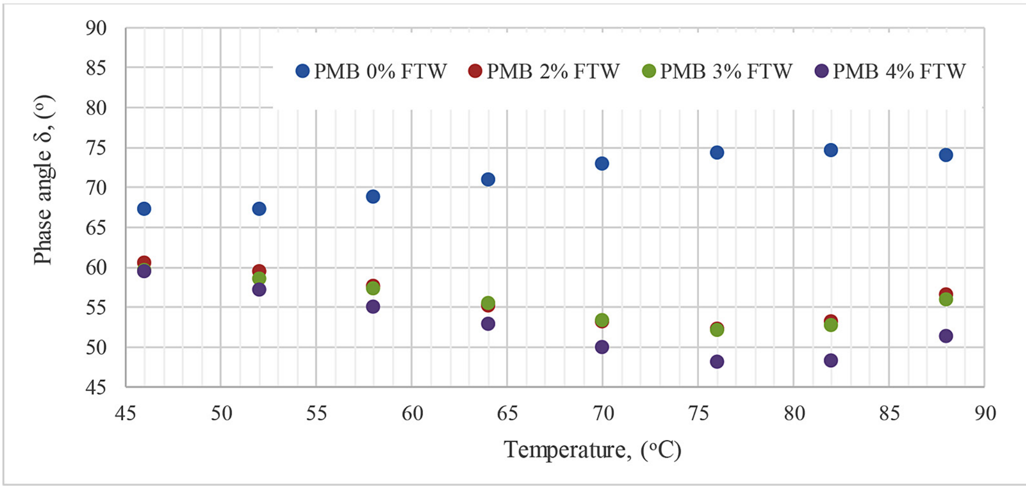

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Figure 3. (a) Complex shear modulus |G*| and b) phase angle δ as a function of temperature for PMB 45/80–55 and FTW-modified binders

Destabilisation above 4–5% reflects recent reports of wax overload in conventional binders [63]. At the same time, the sharp decrease in the phase angle δ indicates a dominant transition from viscous to elastic behaviour, which is confirmed by high repeatability throughout the series.

In contrast, the samples of PMB 45/80–55 bitumen show a clear rheological plateau, where doses of 2% to 4% give a statistically comparable improvement in stiffness and elasticity. This broad synergistic plateau in PMB is consistent with previous studies on polymer-wax hybrid systems [44, 64, 65]. The lack of significant variability ($p > 0.05$) between these modification levels (as indicated by Tukey's post-hoc analysis) suggests a stable synergistic interaction in which the wax reinforces the existing SBS polymer network without reaching an early saturation point. Maintained flexibility at elevated temperatures, particularly at 4% FTW, confirms that the hybrid polymer-wax system provides excellent resilience across the entire operating temperature range, as reported in [65, 66].

Rutting resistance evaluation

The rutting index (|G*|/sinδ) (Figure 4) was calculated based on the data above (Figures 2–3). The Superpave specification sets the minimum value of this index at above 1.0 kPa for unaged binders, above which pavements are considered resistant to permanent deformation.

A two-way ANOVA confirmed that FTW content, temperature, and their interaction significantly improve the rutting index (|G*|/sinδ)

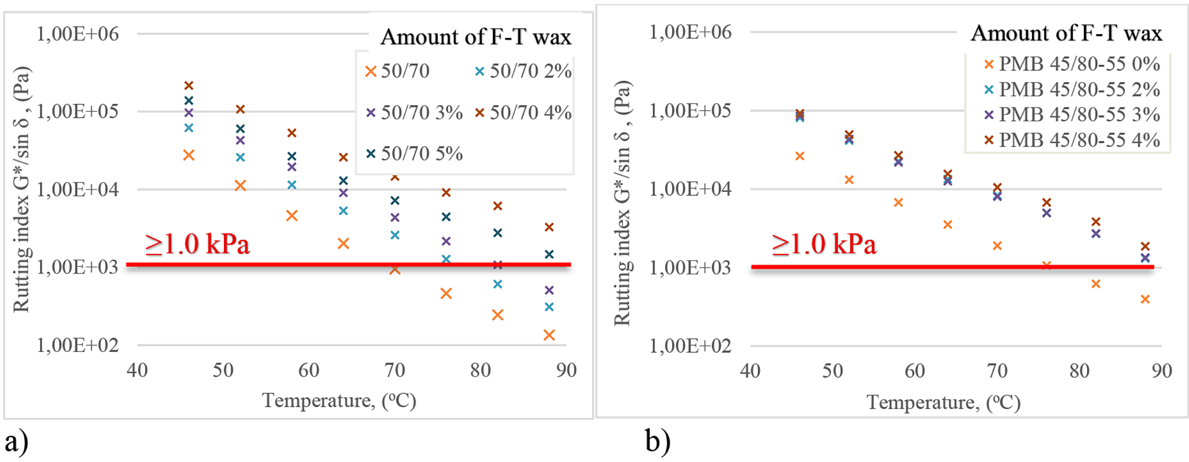


Figure 4. The rutting index |G∗|/sinδ as a function of temperature for: (a) 50/70 bitumen, (b) PMB 45/80–55 bitumen

for both types of binder ($p < 0.001$). These rutting improvements represent standard FTW benefits documented in [67]. Before the analysis, the compliance with parametric assumptions was verified; both the Shapiro–Wilk and Levene's tests confirmed that the data sets for the |G*|/sinδ parameter followed a normal distribution with homogeneous variances ($p > 0.05$). While unmodified 50/70 bitumen does not meet the Superpave requirement of 1.0 kPa above 64 °C, modification with 4% FTW extends this threshold to 88°C, effectively raising the performance class by almost 20 °C, consistent with prior Sasobit/FTW studies reporting PG upgrades of 15–25 °C and rutting parameter increases of 100–300% [32, 38, 68].

For PMB 45/80–55 bitumen, although the reference binder already meets the requirements up to 76 °C, FTW modification ensures compliance across the entire range of 88 °C. Post-hoc analysis showed that a 4% dose is statistically better than 3% at high temperatures, mathematically confirming that this is the optimal concentration for maximising stiffness and providing solid protection against permanent deformation. The high reliability of these conclusions is further supported by the exceptionally low variability observed in all tested series ($SD < 4.2\%$). This low standard deviation (confirming the high repeatability of the measurements) further demonstrates that the improvement in high-temperature performance grade is statistically robust across all modification levels.

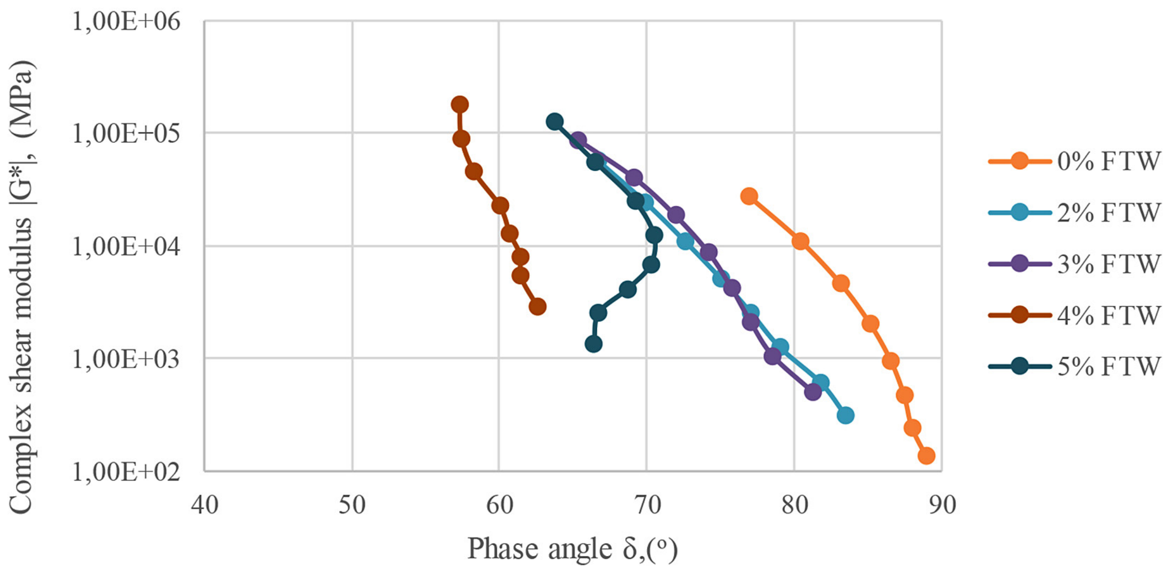


Figure 5. Black diagram: complex shear modulus |G*| as a function of phase angle δ for 50/70 and FTW-modified binders

Black diagram analysis

Black diagrams (shear modulus |G*| as a function of phase angle δ) provide a basic, frequency-independent overview of the rheological properties of bituminous binders. It allows for a direct comparison of the viscoelastic equilibrium of different materials and modification levels, where a shift towards the upper left corner of the diagram (higher |G*| and lower δ) indicates better properties, particularly in terms of elasticity and resistance to permanent deformation. Figures 5 and 6 Black diagrams for 50/70 and PMB 45/80–55 binders modified with different amounts of FTW.

Black diagram analysis reveals a systematic migration of viscoelastic data toward the upper-left quadrant, signifying a fundamental enhancement in both stiffness and elastic recovery for all modified binders [44]. The statistical reliability of these visual shifts was confirmed by verifying the normality of the coordinate distributions ($p > 0.05$). For the 50/70 binder, analysis of the Euclidean distance in the |G*|–sinδ space confirmed statistically significant shifts ($p < 0.05$) for all FTW concentrations, consistent with wax-induced elasticity enhancements in Black diagrams [64]. Post-hoc tests showed that a 4% dose provides the most pronounced change in elasticity. The slight inward shift of the 5% dose curve provides clear statistical evidence of excessive modification, likely due to microstructural destabilisation or overload of the wax crystal network [69].

In PMB bitumen, the close clustering and high overlap of the curves ($R^2 > 0.98$) highlight the robust and predictable synergy between wax and polymer. The lack of statistically significant differences between the 2% and 4% doses ($p > 0.05$) according to Tukey's HSD test highlights the wide range of effective modification, confirming that the rheological balance in polymer-modified systems is much more stable and less sensitive to dosage changes than in traditional bitumen. This high degree of overlap, combined with low standard deviations across the measured phase angles, mathematically confirms the superior structural stability of the hybrid binder system.

Creep stiffness and m-value analysis

The results of the creep stiffness modulus S for the 50/70 and PMB 45/80-55 binders, modified with 0–5% FTW, are shown in Figure 7.

ANOVA results ($p<0.05$) confirm that the FTW dosage determines creep stiffness at low temperatures (S) through fundamentally different rheological mechanisms depending on the binder matrix [38, 40]. Prior to the analysis, the normal distribution of the stiffness data and the equality of variances were confirmed using Shapiro–Wilk and Levene's tests ($p > 0.05$), ensuring the validity of the post-hoc comparisons. In the case of the 50/70 binder, a systematic and statistically significant increase in stiffness ($p < 0.01$) is attributed to the formation of a rigid wax crystal network, which gradually reduces the elasticity of the bitumen [63, 69]. However, a significant reduction in stiffness at a wax content of 5% ($p = 0.038$) indicates a critical saturation threshold above which

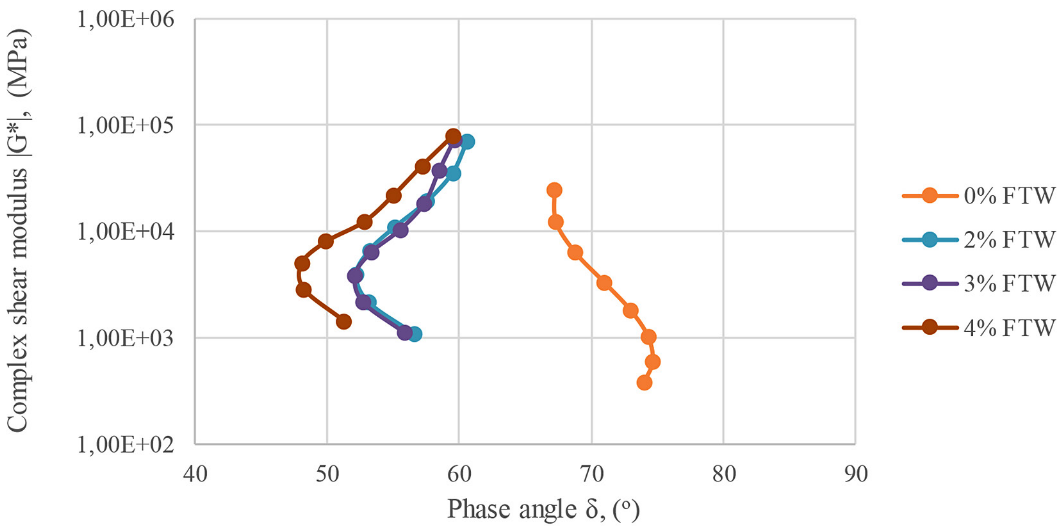
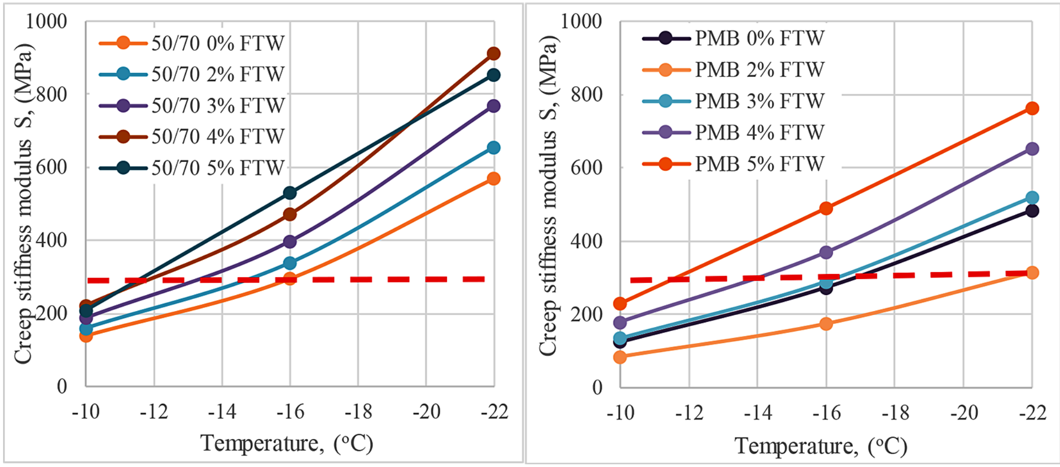


Figure 6. Black diagram: complex shear modulus |G*| as a function of phase angle δ for PMB 45/80–55 and FTW-modified binders



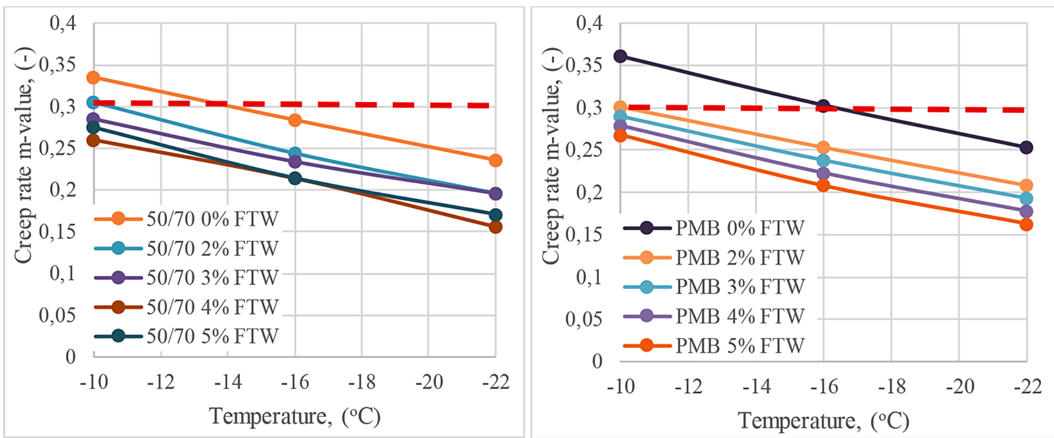
a) b)

Figure 7. Creep stiffness modulus S as a function of temperature for: (a) 50/70, (b) PMB 45/80–55 binders modified with FTW

the unmodified matrix is likely to undergo structural destabilisation [70].

However, PMB binders exhibit nonlinear interaction, characterised by an initial significant decrease in stiffness at 2% FTW ($p < 0.001$). This stable compatibilisation effect (confirmed by an exceptionally low coefficient of variation, $CV < 1.8\%$) suggests that low doses of synthetic wax improve the integration of the SBS polymer-bitumen system before the crystallites begin to act as a reinforcing filler at higher concentrations [71]. Evaluating these results against the 300 MPa breaking point shows that while the 50/70 bitumen exceeds safety thresholds even at 2% modification, the PMB matrix remains statistically safe. Tukey's HSD test confirms that the PMB hybrid system maintains its compliance with low-temperature requirements significantly better than the modified 50/70 binder, confirming the synergistic benefits of combining FTW with polymer-modified binders to maintain durability.

The creep coefficient, represented by the m-value, is a critical parameter determining the ability of bituminous binders to relieve internal stresses caused by thermal shrinkage. A higher m-value indicates a more flexible material capable of dissipating stresses more efficiently, thereby reducing the risk of low-temperature cracking [63, 72]. The m-value results for the tested binders are illustrated in Figure 8. Linear regression analysis shows a highly predictable negative correlation between wax content and m-value ($R^2 = 0.96$ at –10 °C), confirming that the decrease in relaxation capacity is statistically significant



a) b)

Figure 8. Creep rate m-value as a function of temperature for (a) 50/70 and (b) PMB 45/80–55 binders modified with FTW

across the entire temperature range [38, 40]. The validity of this regression model was supported by the normality of residuals, and the significance of the slope was confirmed by ANOVA ($p < 0.05$). Tukey's HSD test confirms that any increase in wax content above 2% significantly reduces the plasticity of the binder, as the rigid crystal network formed by FTW molecules restricts the mobility of bitumen molecular chains [73].

A distinct divergence occurs in the PMB binder at 2% FTW, where creep stiffness (S) improves while the m-value simultaneously deteriorates ($p = 0.012$). This phenomenon indicates that while the wax may act as a compatibiliser to reduce internal stresses, its physical presence as crystallites at sub-zero temperatures creates mechanical obstacles that slow stress relaxation regardless of the overall stiffness [74]. The statistical reliability of this finding is underscored by the high consistency of the data; the CV remained below 2.1% for the m-value and 1.8% for creep stiffness. Such low variability (demonstrating high repeatability despite the natural heterogeneity of the binders) emphasises that the crystalline phase regulates the relaxation response in a predictable manner across both binder types, ultimately determining the fundamental limit of FTW dosage in cold climates [70, 74].

Analysis of dynamic viscosity using Brookfield viscometer

The assessment of the dynamic viscosity of bitumen is essential for understanding its workability and determining the appropriate processing temperatures for asphalt mixtures produced using these binders. The results of viscosity measurements of unmodified and modified FTW binders at three key temperatures (90 °C, 115 °C, and 135 °C) are shown in Figure 9. The melting point of the FTW used is 108–114 °C. This particular property is fundamental to explaining the observed rheological behaviour.

FTW modification exhibits a temperature-dependent dual effect on binder flow properties, as confirmed by two-way ANOVA ($p < 0.001$) [38, 75]. Before performing the analysis, the assumptions of normality and homogeneity of variances were verified ($p > 0.05$ for Shapiro–Wilk and Levene's tests, respectively). At 135°C, the wax acts as a lubricant above its melting point (108–114 °C), providing a statistically significant reduction in viscosity ($p < 0.01$) that facilitates WMA production for both binder types [75, 76]. Conversely, rapid crystallisation at lower temperatures (90–115 °C) triggers a sharp viscosity spike, which is statistically distinct ($p < 0.001$) and particularly pronounced in the PMB series due to strong polymer-wax synergy [77]. Analysis of flow activation energy identifies 4% for 50/70 and 3–4% for PMB as the most stable rheological states, with the 4% dosage offering the optimal balance between high-temperature workability and low-temperature structural reinforcement [78]. The high precision of the viscosity measurements, especially near the FTW melting range where material behaviour is most dynamic, is supported by a *CV* below 3.5% across all measurable samples. This level of variability is notably lower than the 5.0% threshold

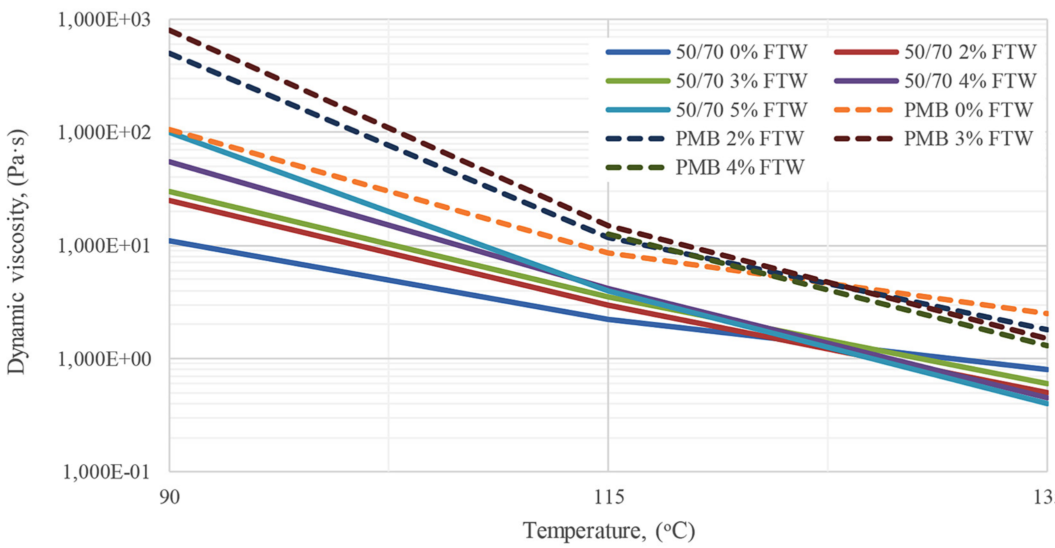


Figure 9. Dynamic viscosity (Pa·s) of unmodified and FTW-modified binders

typically cited in literature as the limit for acceptable repeatability in advanced rheological characterisation of bitumen binders [8]. Furthermore, compared to similar studies on WMA additives where the CV values often range between 4.5% and 7.2% [64], the results obtained in this study demonstrate superior consistency, which validates the robustness of the identified temperature and dosage thresholds.

Compactability of MAM

Marshall compaction method

The compactability of AC11 mixtures was assessed based on the air void content (V_m) in compacted samples at reduced temperatures (115 °C, 125 °C, and 135 °C for 50/70; 125 °C, 135 °C, and 145 °C for PMB 45/80–55) using a Marshall compactor. According to [55], the required V_m range is 2.0–4.0%. The results for mixtures containing 50/70 binder are presented in Figure 10.

A one-way ANOVA analysis confirms that the air void content (V_m) is significantly dependent on the interaction between compaction temperature and FTW dosage [75]. Before the analysis, the fundamental requirements for parametric testing were satisfied, with Shapiro–Wilk and Levene's tests confirming normal distribution and homogeneity of variances ($p > 0.05$) across all mix variants. The statistical reliability of these findings is further supported by the use of five replicates for each combination ($n = 5$), which ensured a stable mean value for the volumetric evaluation. While the reference mix does not meet the specification requirements below 135 °C due to the characteristic increase in viscosity of unmodified bitumen, FTW modification results in a non-linear improvement in workability [79]. Tukey HSD post-hoc tests show that low wax concentrations (2–3%) provide insufficient lubrication to significantly reduce compaction energy, while reaching a specific threshold of 4% allows the temperature to be reduced by 10 °C while maintaining compliance [80]. The most pronounced improvement occurs at a wax content of 5%, which allows the compaction temperature to be reduced by 20 °C [79]. The resulting low void content at higher temperatures suggests a potential risk of over-lubrication [81]. The consistency of the results, evidenced by low standard deviations across the five specimens per series, confirms that the measurements do not yield identical values due to the heterogeneous nature of the mineral-asphalt mixture, yet they remain within the strict repeatability limits of the standard [60]. Ultimately, the statistical divergence between modification levels emphasises that achieving WMA performance is not a gradual process, but requires reaching a critical concentration threshold for effective viscosity reduction [82]. The results for AC11 mixtures containing PMB 45/80–55 binder are shown in Figure 11.

The behaviour of PMB blends reflects a clear synergy between FTW and the SBS polymer matrix, where a two-factor ANOVA identifies temperature, dosage and their interaction as key factors determining air void content. Prior to the analysis, the prerequisite assumptions of normality and homogeneity of variances were verified and satisfied ($p > 0.05$ for Shapiro–Wilk and

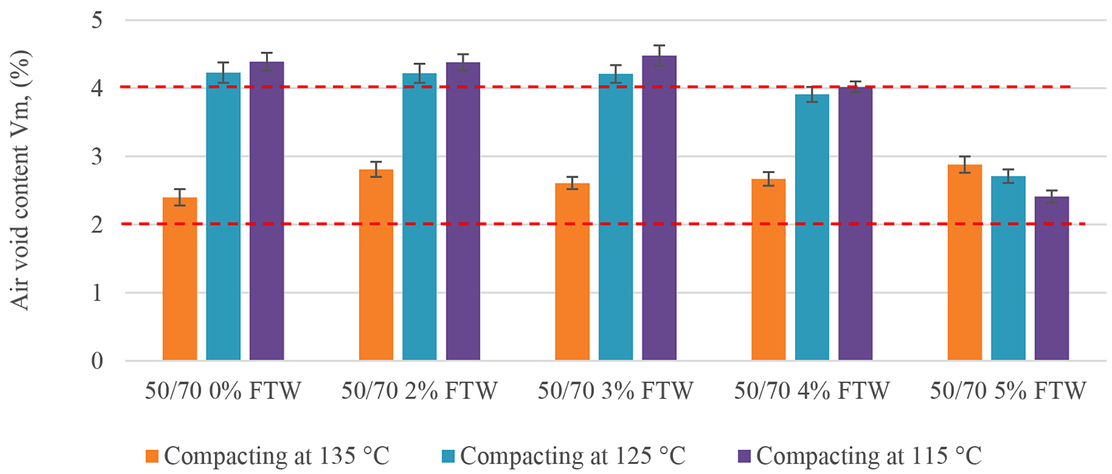


Figure 10. Influence of FTW content and compaction temperature on air void content in AC11 mixtures with 50/70 binder (Marshall method)

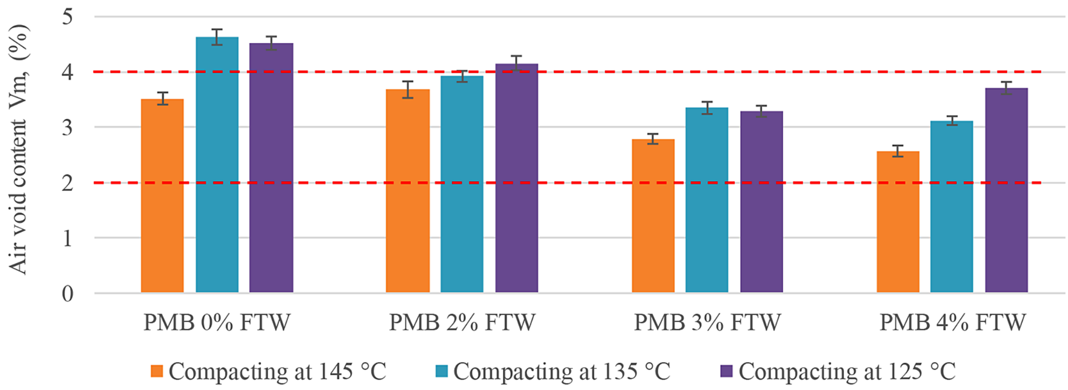


Figure 11. The influence of FTW content and compaction temperature on air void content in AC11 mixtures with PMB 45/80–55 binder (Marshall method)

Levene's tests). While unmodified PMB exhibits a significant reduction in workability below 145 °C due to high viscosity induced by the polymer, the addition of FTW provides a more effective structural effect than that observed with conventional binders, especially at low doses [83]. Tukey's HSD test identifies 3% FTW as the statistically optimal dose, allowing a 20 °C reduction in compaction temperature while maintaining avoid content comparable to that of the reference mixture at standard temperatures [84]. Increasing the amount to 4% causes a statistically significant increase in V_m ($p = 0.041$), suggesting that excess wax may disrupt the SBS network or adversely affect binder crystallisation. The reliability of the observed trends in air void content is confirmed by a low coefficient of variation ($CV < 2.5\%$) over the entire experimental series, indicating uniform compaction energy distribution [85]. Although the individual measurements of the mineral-asphalt samples are not identical due to the inherent heterogeneity of the material, this low *CV* confirms the high repeatability of the results. These statistical indicators are also represented as error bars in Figures 10 and 11, illustrating the high repeatability of the Marshall compaction process.

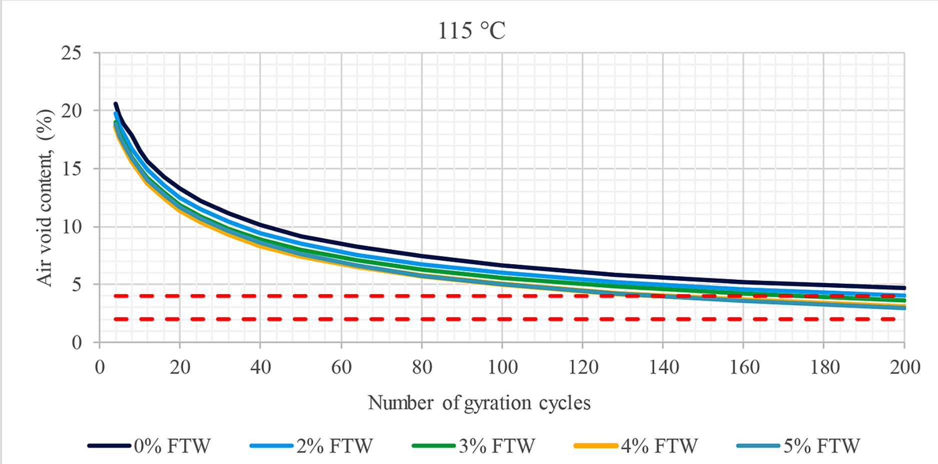
Gyratory compaction method

In order to further verify the compaction properties and more accurately reproduce field conditions, selected mixtures were also compacted using a gyratory compactor. The resulting compaction curves for the AC11 mixtures with 50/70 bitumen are shown in Figure 12.

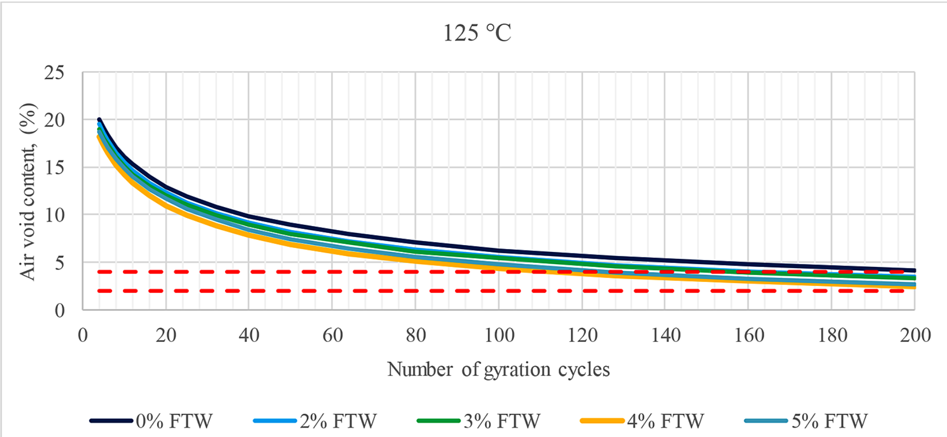
A two-way ANOVA ($p < 0.001$) confirms that the interaction between temperature, gyration count, and wax dosage has a significant effect on the compaction process. Prior to this analysis, the parametric assumptions of normality and homogeneity of variances were verified and satisfied ($p > 0.05$ for Shapiro–Wilk and Levene's tests). At 135 °C, the compaction curves show a non-linear response to workability, where only a 4% dose effectively lubricates the mixture, while other percentages paradoxically increase the air voids relative to the reference value. This indicates that near the melting point of wax, a precise dosage of 4% is critical to achieving a statistically significant improvement in compaction.

As the temperature drops to 125 °C and 115 °C, the benefits of high FTW content become crucial. The mixtures with 4% and 5% wax exhibit significantly steeper compaction slopes, satisfying the density requirements that remain unachievable for the reference binder even after 200 gyrations. In particular, the 5% dosage enables a 20 °C reduction in temperature by reaching the target 4.0% void threshold within 140 gyrations, marking a statistically significant reduction in compaction energy. The high correlation of the non-linear models ($R^2 > 0.98$) and low variability ($CV < 3.1\%$) confirm the validity of these identified dosage and temperature thresholds for conventional binders. While the measurements of individual samples are not identical due to the inherent heterogeneity of the mineral-asphalt mixture, the consistency of the compaction slopes across the five replicates ($n = 5$) confirms the high repeatability of the experimental process

The resulting compaction curves for the AC11 mixtures with PMB 45/80–55 bitumen are shown in Figure 13. The densification behaviour of the PMB mixtures in the gyratory compactor reveals a unique interaction between FTW lubrication and the SBS polymer network, which differs significantly from



a)



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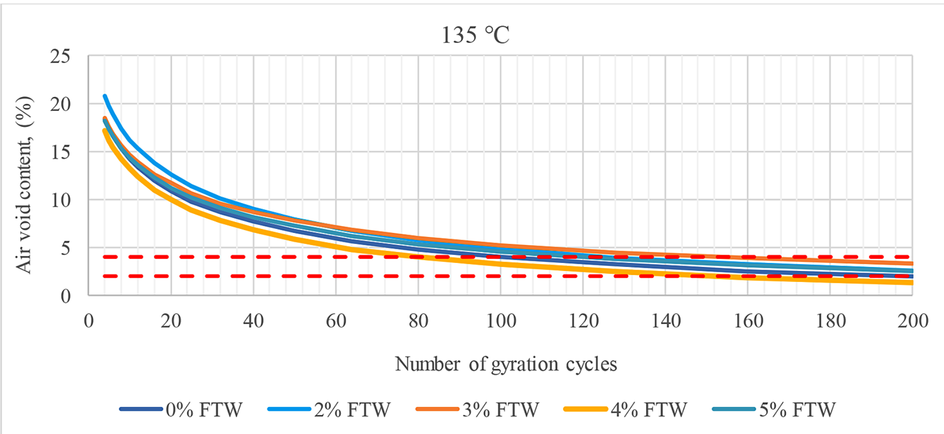
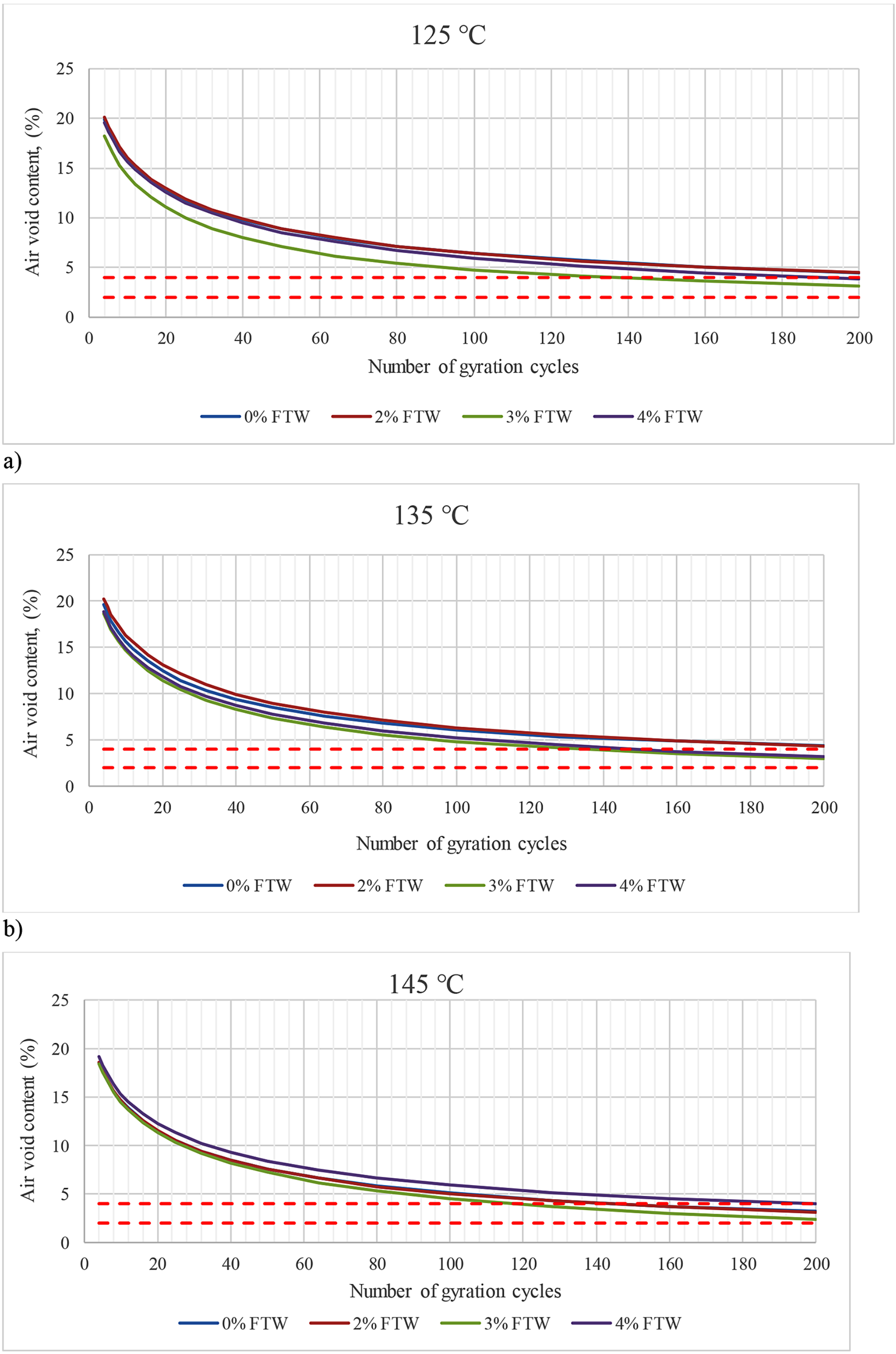


c)

Figure 12. Compaction curves for AC11 mixtures with 50/70 bitumen and variable FTW content at temperatures: (a) 115 °C, (b) 125 °C, and (c) 135 °C

the interaction observed with the 50/70 binder [38, 86]. Although multivariate ANOVA confirms that temperature, dosage, and gyration cycles have a significant effect on void volume (V_m) ($p < 0.001$), the relative benefit of wax is highly sensitive to the compaction temperature range. The normality of the data and homogeneity of variances for these multivariate sets were confirmed ($p > 0.05$), justifying the use of post-hoc comparisons. At the standard temperature of 145 °C, the effect of reducing wax viscosity is less significant, as all mixtures meet the specification limits regardless of dosage [75]. However, as the temperature drops to 135 °C and 125 °C, a 3% FTW dose proves to be a



a)

b)

c)

Figure 13. Compaction curves for the AC11 mixtures with PMB 45/80–55 bitumen and variable FTW content at temperatures: a) 125 °C, b) 135 °C, and c) 145 °C

statistically better modifier, effectively neutralising the high structural viscosity imparted by the polymer matrix [85]. Statistical analysis indicates 3% as the optimal amount for PMB, allowing for a 20°C reduction in temperature while achieving the target density within 140 gyrations – a densification target that the unmodified binder fails to achieve even at the maximum number of gyrations. Importantly, the statistically significant increase in air voids observed when increasing the dose from 3% to 4% ($p = 0.042$) indicates that excess wax may interfere with the integrity of the SBS network or adversely affect crystallisation dynamics [86]. These trends, characterised by high precision ($CV < 2.8\%$), provide clear guidance for maximising workability in polymer- and wax-based hybrid WMA systems. The validity of the identified dosage and temperature thresholds is confirmed by the high correlation of the non-linear models ($R^2 > 0.98$) and low variability among replicates ($CV < 3.1\%$). Although individual measurements vary slightly due to the heterogeneous nature of MAM, these low coefficients of variation, derived from five independent replicates ($n = 5$), confirm that the results are highly repeatable and statistically robust.

CONCLUSIONS

The integrated evaluation of binder rheology and mixture compactability provides the following key findings concerning the application of Fischer–Tropsch synthetic wax (FTW) in warm mix asphalt (WMA) technology for conventional 50/70 and polymer-modified PMB 45/80–55 binders:

1. Low FTW contents (≈2%) exhibit a synergistic plasticising effect in the SBS-modified binder (PMB 45/80–55), temporarily reducing creep stiffness (S) at –16 °C by approximately 15–25% compared to the unmodified PMB. This effect is not observed in the conventional 50/70 binder and is interpreted as improved compatibility and partial disruption of polymer network rigidity prior to dominant wax crystallisation.
2. Workability improvement is strongly binder-dependent and non-linear with respect to FTW dosage. For the conventional 50/70 binder, a critical threshold of 4–5% FTW is required to enable a compaction temperature reduction of ≈20 °C (from 135 °C to ≈115 °C) while achieving air void contents (Vm) within the specification range of 2.0–4.0%. Lower dosages (2–3%) reduce viscosity only marginally (typically < 20–30% at 135 °C) and do not allow comparable temperature reduction.
3. In the polymer-modified binder (PMB 45/80–55), 3% FTW represents the statistically optimal dosage (confirmed by Tukey's HSD post-hoc tests), enabling a compaction temperature decrease of ≈20 °C (from 145 °C to 125 °C) while maintaining equivalent densification behaviour in both Marshall and gyratory compaction methods. This corresponds to a reduction in required compaction effort of approximately 25–40% (fewer gyrations to reach target density). Higher dosages (4–5%) lead to a statistically significant increase in residual air voids ($p < 0.05$), most likely due to interference with the SBS polymer network or altered crystallisation kinetics. A distinct "rheological lock-up" phenomenon occurs in the temperature range 90–115 °C, where dynamic viscosity increases sharply by 180–450% (depending on FTW content and binder type) compared to measurements at 135 °C. This narrow processing window constitutes a critical technological limitation of the FTW-based WMA systems and must be carefully controlled during mixture production and field compaction.
4. FTW modification markedly improves high-temperature performance: for the 50/70 binder, 4% FTW increases the high-temperature PG by ≈18–22 °C, corresponding to an increase in the rutting parameter |G*|/sinδ by 180–320% at 76 °C and over 500% at 88 °C relative to the unmodified binder. The PMB 45/80–55 binder, already characterised by high rutting resistance, maintains compliance with Superpave criteria up to 88 °C across the entire tested FTW range.
5. At low temperatures, FTW addition consistently increases creep stiffness (S) while reducing stress relaxation capacity (m-value). At –16°C, creep stiffness rises by 45–110% in the 50/70 binder and by 20–65% in PMB after 3–5% FTW incorporation, while the m-value decreases by 12–28% (most pronounced at –22 °C). This trade-off between enhanced rutting resistance and increased brittleness at low service temperatures must be carefully considered in regions with cold winters, such as Central and Eastern Europe.

This research complements current knowledge by providing a detailed comparative analysis of FTW modification effects on both conventional and PMB binders within a single, consistent experimental framework. While previous studies often focused on either binder rheology or mixture compaction, this work established a direct statistical link between binder phase transitions and the compaction energy thresholds of the WMA mixtures. Furthermore, the identification of a 'structural destabilisation' point at 5% FTW for 50/70 bitumen versus the 'synergistic plateau' for PMB offers a new practical guideline for dosage optimisation in hybrid binder systems. These findings refine the understanding of wax-polymer interactions, demonstrating that the effectiveness of the WMA additives is fundamentally governed by the initial internal structure of the base bitumen.

The obtained results indicate that FTW can be an effective viscosity-reducing and performance-enhancing additive in the WMA technology, provided that the dosage is precisely tailored to the base binder type (≈4–5% for neat bitumen, ≈3% for SBS-modified binders) and that production/compaction temperatures remain above the critical crystallisation range. The findings offer practical guidance for optimising WMA mix design in Polish and Central European climatic and technical conditions and support further implementation of sustainable asphalt technologies.

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