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Research Paper

Effects of Waste Turmeric Oil on the Rheology and Structural Performance of Modified Bitumen

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ABSTRACT

Flexible pavements face continual degradation due to traffic and environmental stresses. Concurrently, waste materials like Waste Turmeric Oil (WTO) pose sustainability challenges. This study explores the WTO as a bio-modifier for VG30 bitumen, aiming to enhance binder performance while addressing waste disposal concerns. WTO-modified binders (WTOMB) were evaluated through physical tests (penetration, softening point, flash point) and rheological tests using a Brookfield viscometer and Dynamic Shear Rheometer (DSR). Results showed that increasing WTO content raised penetration and reduced softening points, indicating improved flexibility. Viscosity decreased by 20–25% at WTO contents above 3%, enhancing workability and reducing mixing temperatures. Short-term aging was simulated using the Rolling Thin Film Oven (RTFO) test, with all samples showing low mass loss and good thermal stability. DSR-based Performance Grade (PG) and Multiple Stress Creep Recovery (MSCR) tests indicated a significant reduction in non-recoverable creep compliance (J_{nr}) to 1.8 kPa¹ at 3% WTO, identifying it as the optimal dosage for rutting resistance. Although 4% WTO also achieved J_{nr} < 2.0 kPa¹, benefits plateaued. Recovery results suggested that binders with 1–2% WTOMB are suitable for high-traffic conditions. Overall, WTO effectively enhances the performance and sustainability of bitumen binders, offering a cost-efficient and environmentally responsible solution for flexible pavement construction.

1 Introduction

Flexible pavements are widely used in developing countries, such as India, due to their cost-effectiveness and ease of phased construction. However, the increasing demand for durable road infrastructure, capable of withstanding high traffic loads and extreme weather conditions, necessitates the use of high-quality bitumen. Unfortunately, the global supply of crude oil, the primary source of bitumen, is limited, leading to concerns about the long-term availability of conventional binders [1].

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Bitumen aging is a complex phenomenon that significantly affects pavement performance. It involves both physical and chemical changes in the binder, primarily due to the loss of lighter fractions, oxidation, and steric hardening. During asphalt mixing and compaction, the binder is exposed to elevated temperatures, causing the evaporation of volatile components. This is referred to as short-term aging [2]. At this stage, the thin film of bitumen comes into direct contact with atmospheric oxygen, resulting in increased viscosity and stiffness.

Over the pavement's service life, long-term aging occurs due to repeated traffic loading, temperature fluctuations, and environmental exposure. This further stiffens the binder, reducing its ductility and increasing the risk of fatigue cracking and fracture, even though it may slightly reduce rutting [3]. The combined effects of aging render the bitumen brittle, compromising its durability.

As a result, aged pavements are vulnerable to various types of surface distresses, including potholes, rutting, raveling, corrugation, and shoving [4]. To mitigate these issues, the use of additives or modifiers has become an effective strategy to enhance the performance of base binders. Modifiers enhance the binder's consistency, reduce temperature susceptibility, and improve its rheological behavior under various loading and environmental conditions.

Bitumen consistency and temperature susceptibility are evaluated through conventional tests, including penetration, softening point, and viscosity. A binder with high temperature susceptibility may deform at elevated temperatures (rutting) or crack under cold conditions (thermal cracking) [5]. Therefore, it is essential to assess the binder's ability to resist these extremes through performance-based tests such as the Superpave Performance Grade (PG) system and Multiple Stress Creep Recovery (MSCR) test parameters. To ensure long-lasting pavement performance, it is crucial to modify and characterize bitumen binders to enhance their resistance to aging and temperature-induced distress.

2 Literature Review

This section describes several modified bitumen with various modifiers, the shear mixing process, and the physical properties that will be studied. Bitumen can also be modified with various additives. The degree of modification depends on the modifier type, percentage, and the nature of the bitumen. Plastomeric, elastomeric thermoplastic, natural rubber, and crumb rubber are the most utilised modifiers. Additionally, various materials, including waste engine oil, vegetable oils, waste cooking oil, nanomaterials, and pyrolysis oils, have been utilized as modifiers for bitumen.

Arafat et al. [6] highlighted the impact of waste engine oil, vegetable oils, waste cooking oil, nanomaterials, pyrolysis oils, and others on bitumen modification. Their study revealed that incorporating waste engine oil significantly improved the elasticity and flexibility of bitumen binders, reducing the risk of cracking under low-temperature conditions. Additionally, vegetable and pyrolysis oils improved the resistance to permanent deformation, especially in high-temperature loading scenarios. Arafat et al. also reported that optimally dosed nanomaterials provided improved thermal stability and higher fatigue resistance, contributing to an extended pavement lifespan. The study emphasized the importance of balancing the concentration of these modifiers to prevent adverse effects on the binder's properties, such as excessive softening or reduced adhesion to the aggregates. The study revealed improved binder elasticity, reduced temperature susceptibility, and enhanced resistance to rutting with optimized modifier content.

Base and modified binders before and after ageing conditions. He modified the binder with Palm Oil Fuel Ash (POFA), a by-product of palm oil mills. POFA added in Pen bitumen is 80/100 at 2.5%, 5%, 7.5%, and 10% of the total bitumen weight, using a high-shear mixer. Conventional tests were performed. The RTFO and pressure-ageing vessel (PAV) tests were used to determine short- and long-term ageing. Adding POFA increased susceptibility to modified bitumen at high temperatures, especially. It lowered the temperature susceptibility of bitumen for long-term ageing, improving its rutting performance. To regenerate ageing SBS modified bitumen, Z. Feng et al. [7] examined the use of waste engine oil in wet mixing and assessed its physical properties. The results show that waste engine oil significantly regenerates older SBS-modified bitumen; however, applying excessive waste engine oil can alter its physical characteristics. According to the study [8] HDPE and WCO combined improve the properties of the asphalt binder. The findings indicated that the addition of 7.5% HDPE to the binder and replacing 15% of the basic bitumen with WCO yielded successful results. Additionally, the softening point increased while penetration decreased. Therefore, this study demonstrates that waste oils and HDPE can be utilized in asphalt mixtures to enhance surface performance. Subhy [9] reviewed the fundamental analysis methods used in this paper to characterise fatigue and binder-rutting properties, the SHRP rutting parameter, Shenoy rutting parameter, ZSV, and MSCR

are used to evaluate bitumen rutting. Furthermore, this work clearly explains the fundamental ideas underlying dynamic mechanical analysis (DMA) and the DSR.

Musco et al. [10] highlights the potential to reduce the paving industry's carbon footprint by replacing traditional bitumen derived from fossil fuels, which has significant environmental impacts. These are sustainable alternatives to bitumen, derived from biomass such as vegetal and animal wastes and waste cooking oils. They are produced through thermochemical conversion processes, such as pyrolysis, which yield biochar and bio-oils. Bio-binders perform better at low temperatures than traditional bitumen but require improvement for high-temperature performance. Several knowledge gaps, including aging resistance, recyclability, health, safety, and environmental aspects, as well as cost-effectiveness, require further investigation. Depending on the percentage of bitumen replacement, bio binders can be classified into modified bitumen, fluxed bitumen, extended bitumen, and alternative binders. The document details the chemical processes involved in converting biomass into bio-binders, including pyrolysis and hydrothermal liquefaction. The rheological properties of bio binders vary based on the type and amount of biomaterials used. Biochar increases viscosity and stiffness, while biooils can soften the binder. The use of bio-binders can significantly reduce energy consumption and the impact of global warming, making them a more sustainable option for road construction. Further research is needed to optimise production processes, understand the long-term performance, and develop standardised test protocols for bio-binders. The author concludes that while biobinders hold promise for sustainable road construction, further research is needed to fully understand their potential and address existing challenges [1].

The study investigates waste engine oil and recycled engine oil bottoms as partial substitutes for bitumen in road construction, aiming to reduce reliance on natural resources.

Two types of waste oil were utilized: untreated waste engine oil and recycled engine oil bottoms, both sourced from a certified waste treatment company. The modified bitumens exhibited improved properties, including flexibility, stability at high temperatures, and low non-recoverable creep compliance values, indicating potential for effective pavement performance. Incorporating waste materials, such as plastic and crumb rubber, enhances the characteristics of bitumen, resulting in higher softening points and lower penetration values. The research highlights the environmental benefits of using recycled materials, including reduced landfill waste and the conservation of natural resources [11].

The study highlights the renewable and eco-friendly characteristics of biobased rejuvenators and assesses their effectiveness in mitigating the adverse effects of asphalt. It explains the mechanisms of asphalt aging, particularly oxidative aging, which leads to stiffness and fatigue cracking. It provides an extensive overview of biobased rejuvenators, including vegetable oils, waste-derived bioproducts, and biopolymers, highlighting their renewable and environmentally friendly attributes. The study critically analyzes how bio-based rejuvenators enhance the rheological and mechanical properties of aged asphalt, thereby reducing stiffness, improving elasticity, and increasing workability. The environmental benefits of biobased rejuvenators are examined, including reduced greenhouse gas emissions, lower energy consumption, and a smaller overall environmental footprint compared to their conventional counterparts. The author identified compatibility issues, long-term performance, and economic feasibility of biobased rejuvenators. It discusses potential advancements and research pathways to optimize the utilization of bio-based rejuvenators, including customized formulations, advanced characterization techniques, and climate-responsive rejuvenators. The author concludes that biobased rejuvenators offer a sustainable and environmentally friendly solution for asphalt pavement maintenance, with ongoing research needed to address challenges and optimise their use [12].

The study investigates the effects of modifying bitumen with waste vegetable oil and waste agricultural ash for use in flexible pavements. The research aims to improve the performance and stability of bituminous hot mixtures, optimize additive quantities, and create more economical designs. Using the Taguchi method, various percentages of waste vegetable oil (0%, 2%, 4%) and waste agricultural ash (0%, 3%, 6%) were added to pure bitumen. The modified bitumen samples were prepared at different temperatures (170°C, 180°C, 190°C) and mixing times (10, 20, 30 minutes) and tested for penetration, softening point, flash point, and stability. Stability and softening point values decreased with increased oil content, while flash and penetration values increased. Increased ash content resulted in higher stability, flash, and softening point values, as well as lower penetration values. Mixing temperature and time had little effect compared to oil and ash additives. The optimum parameters were 4% oil, 0% ash, a temperature of 170°C, and a mixing time of 10 minutes. The study concludes that waste vegetable oil and agricultural ash can serve as modifiers without altering the bitumen's chemical structure, thereby contributing to waste management and environmental sustainability [13].

The authors investigated the rheological and physical properties of WCO-modified binders under both aged and unaged conditions. The results indicate that the modified binder's softening point decreased and the penetration value increased as the WCO percentage increased [14, 15]. In this paper, the author focuses on applying WEOIL to produce ageing-resistant bitumen and investigates both short-term and long-term aging. This study added WEOIL to a base binder in various percentages from 1% to 5% by bitumen weight. The results show that WEOIL enhances the rheological properties of modified bitumen. The author focused on the potential of strengthening asphalt by mixing waste vegetable oil (WVO) with waste polymers such as LDPE and PVC. The WVO in the base binder increased the penetration value but lowered the viscosity. According to the author's results, this modified bitumen is used in cold climate regions with lower temperature susceptibility [16].

This literature review observes that the various modifiers used to modify the base binder best enhance its properties. Most authors also employed various conventional and advanced tests, such as MSCR, PG, and BBR, to determine the properties of base and modified binders.

3 Methodology

Figure 1 outlines the systematic evaluation of Waste Turmeric Oil (WTO) as a modifier for VG30 bitumen, focusing on its impact on physical and rheological properties.

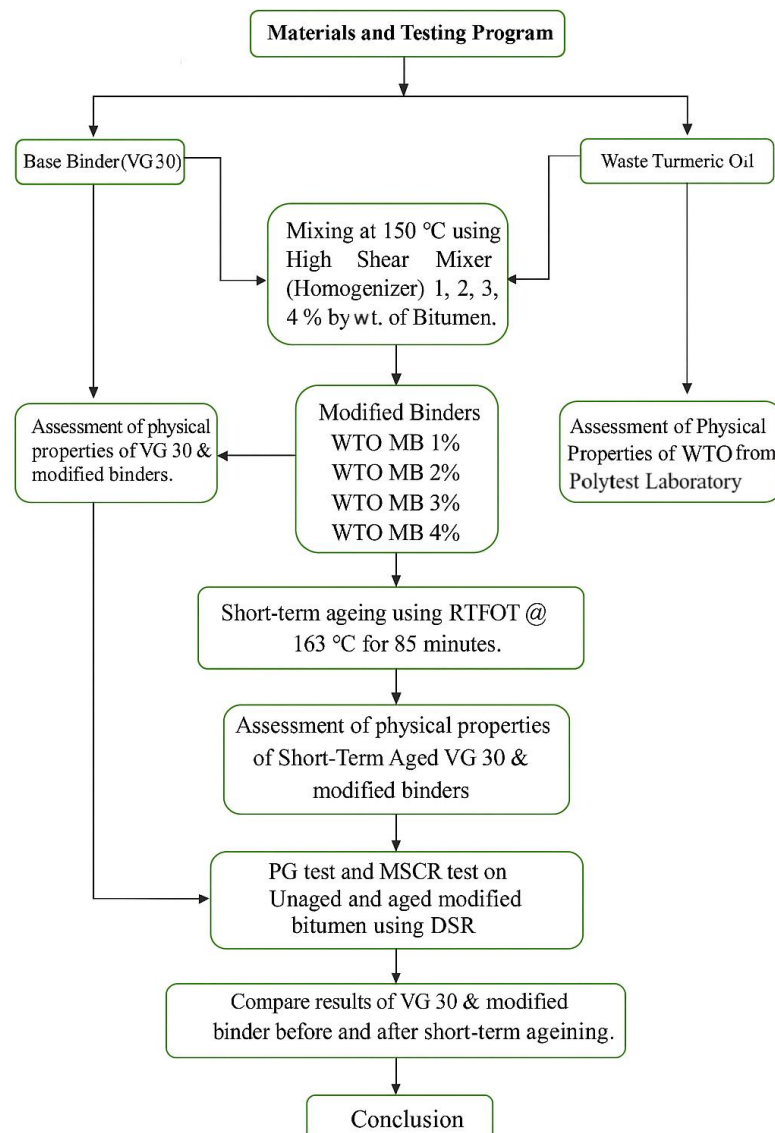


Fig. 1 - Experimental plan

The study begins with the selection and characterization of the WTO (tested at the Politest Laboratory) to ensure its suitability. Modified binders (WTOMB) were prepared by blending VG30 with WTO at concentrations of 1%, 2%, 3%, and 4% (by weight) using a high-shear mixer at 150°C to achieve uniform dispersion. The physical properties, including penetration, softening point, viscosity, and flash point, were assessed for both unaged and RTFO-aged samples to understand their temperature sensitivity and aging behavior. RTFO aging was performed at 163°C for 85 minutes to simulate short-term field conditions, and mass loss was recorded to evaluate thermal stability. Rheological characterization was done using a Dynamic Shear Rheometer (DSR), including Performance Grade (PG) and MSCR tests. Parameters such as complex shear modulus (G^*), phase angle (δ), and non-recoverable creep compliance (J_{nr}) were analyzed to determine rutting resistance and elastic recovery.

Finally, results before and after aging were compared to identify the optimum WTO content, balancing improved performance, sustainability, and cost-effectiveness. The study concludes with practical recommendations for incorporating the WTO in sustainable pavement design.

4 Materials

4.1 Base Binder (VG30)

This study used Viscosity Grade 30 (VG30) bitumen as the base binder. Various physical property tests were conducted on VG30 in the Transportation Engineering Laboratory at the College of Engineering, Pune, India. The results are summarized in Table 1.

Table 1. Properties of Base Binder

Properties	Test method	Specification	Results obtained
Penetration (1/10mm)	IS:1203-2022	50-70	55
Softening point (°C)	IS:1205-2022	47, min	48.7
Viscosity at 60°C (Poise)	IS:1206-2021	2400-3600	2724.47
Ductility (cm)	IS:1208-2022	40, min	70
Flash Point (°C)	IS:1209-2022	220	235

4.2 Waste Turmeric Oil (WTO):

Turmeric is widely used in the pharmaceutical, nutraceutical, cosmetic, and homeopathic industries. It contains curcumin, a key active ingredient valued in skincare products for its antioxidant, anti-inflammatory, and anti-aging properties. Turmeric waste oil (WTO) is a by-product obtained after the extraction of curcumin. Since the COVID-19 pandemic in 2020–21, demand for turmeric has surged, leading to increased production. In 2020–21, turmeric production in India reached approximately 2.73 lakh tons, with a productivity rate of 6,654 kg/ha (2,693 kg/acre). India remains the world's largest producer, consumer, and exporter of curcumin, accounting for over 80% of the global output. As a result, the growing demand has led to increased production and, consequently, a larger quantity of turmeric oil waste. Curcumin-removed turmeric oil (CRTO), commonly referred to as WTO, constitutes approximately 14–15% of the turmeric extraction process. WTO is currently used as an animal feed additive, for coloring applications, and as a component in furnace oil. In this study, the WTO was used as a bio-modifier at concentrations of 1%, 2%, 3%, and 4% by weight of the VG30 base binder. The WTO used was sourced from a major turmeric extract supplier identified through the RAK laboratory in Kozhikode, Kerala. Its chemical properties were analyzed and are presented in Table 2, based on tests conducted at Polytest Laboratories, Pune.

Table 2: Chemical Properties of WTO

Test	Test method	Unit	Results
Density at 15°C	IS1448	kg/m ³	1073.20
Water Content	IS2362	mg/kg	11388.09
Flash Point	IS1448	°C	<40
Kinematic Viscosity	IS 1448	cSt	160.50
Gross Calorific Value	IS1448	cal/g	8310

4.3 Effect of temperature on the yield of WTO

The effect of temperature on direct WTO performance was explored. Although previous research has focused on the production of pyrolysis-derived bioasphalt from waste cooking oil (WCO), which shows a temperature-dependent yield (with higher temperatures initially increasing yield and later decreasing it due to thermal cracking), a similar temperature effect can be hypothesised for WTO. Temperature can influence the viscosity and properties of the WTO when it is added directly as a modifier to the asphalt binder. Higher temperatures may lead to increased oxidation and degradation of WTO, which can affect its high-temperature performance. Therefore, temperature may play a significant role in determining the optimal performance range of WTO-modified binders, particularly in terms of viscosity and stability. Figure 2 illustrates the effect of temperature on the yield of waste turmeric oil (WTO). Similar to pyrolysis-derived bio-asphalt, the yield of WTO initially increases as the temperature rises from 250°C to 300°C, reaching the peak yield of approximately 92.2%. However, as the temperature continues to increase beyond 350°C, the yield gradually decreases, likely due to thermal degradation and cracking of the oil. This decrease in yield, coupled with the increase in viscosity at higher temperatures, may affect the performance of WTO as a binder modifier, particularly under high-temperature conditions. Thus, in your study, this temperature-related behavior of the WTO could be crucial in optimizing binder performance for different climate and traffic conditions.

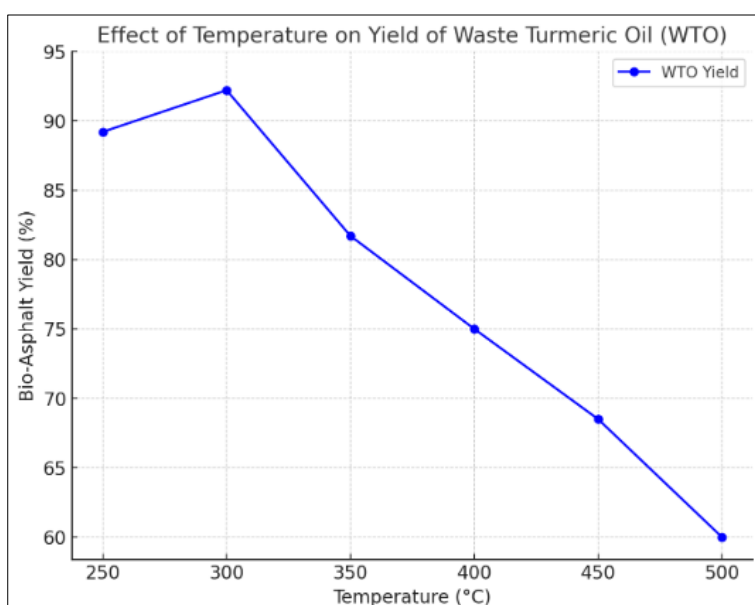


Fig. 2 - Effect of temperature on yield of WTO

4.4 Sample Preparation:

VG30 bitumen was liquefied by heating it in an oven at 150 °C. Four steel containers, each filled with 300 grams of the heated bitumen, were prepared. Turmeric waste oil (WTO) was added to each container based on the weight of the bitumen (w/w) at proportions of 1%, 2%, 3%, and 4%, corresponding to 3 g, 6 g, 9 g, and 12 g, respectively. The modification process was carried out using a high-shear homogenizing mixer. For the first 20 minutes, blending was performed at 5,000 rpm while maintaining a temperature of approximately 150 °C. The mixing speed was then reduced to 3,000 rpm for an additional 5 minutes to ensure uniform dispersion of WTO in the binder. After modification, the resulting binders were referred to as Waste Turmeric Oil Modified Binders (WTOMB).

5 Experimental work:

Several methods are available for examining the properties of bitumen. All of these tests simulate actual field conditions in various ways. The standard tests that were run on it are as follows.

5.1 Physical properties of binders

The physical and rheological characteristics of VG30 and Waste Turmeric Oil Modified Binders (WTOMB) were assessed under unaged and short-term aged conditions. Key parameters, penetration [17], flash point [18], ductility [19], softening point [20], and viscosity [21], were evaluated, as summarized in Table 3. The penetration value of VG30 at 25°C was 54.33 (1/10 mm), increasing with WTO content: 58, 61.3, 64.2, and 74.6 for WTOMB1 to WTOMB4, respectively. This indicates reduced binder stiffness and improved flexibility. However, excessive softening in WTOMB4 could hinder performance under heavy traffic loads. VG30 showed a flash point of 235°C, with WTOMB samples varying between 225°C and 235°C, well within thermally safe limits. The ductility of VG30 was 90 cm (unaged), with a slight decrease upon aging. WTOMB1 and WTOMB2 recorded 95 cm, while WTOMB3 and WTOMB4 reached 100 cm, signifying enhanced tensile resistance and flexibility. Softening points for WTOMB1 to WTOMB4 (unaged) decreased from 45.75°C to 40.95°C compared to 48.7°C for VG30. Aging elevated softening points across all binders, indicating improved temperature susceptibility. VG30's viscosity increased from 2724 Poise (unaged) to 4875 Poise (aged). WTO-modified binders had lower unaged viscosities (2,400 to 1,846 Poise), which increased after aging (3,787–4,445 Poise), supporting better workability and lower mixing and compaction temperatures. In summary, WTO modification improves binder flexibility, thermal aging resistance, and workability, with WTOMB3 showing the most balanced performance. However, higher WTO levels (WTOMB4) may negatively affect high-temperature stability.

Table 3: Physical Properties of Binders

Binders	Tests	Penetration at 25°C (1/10mm)	Flash point (°C)	Ductility (cm)	Softening (°C)	Point	Viscosity at 60°C (Poise)	
		Unaged	Unaged	Aged	Unaged	Aged	Unaged	Aged
	VG30		54.33	235	90	48.7	51.75	2724
WTOMB1		58	225	95	45.75	50.35	2400	4445
WTOMB2		61.3	230	95	44.9	50.35	2350	4110
WTOMB3		64.2	230	100	44.35	49.90	2236	4005
WTOMB4		74.6	235	100	40.95	40.45	1846	3787

5.2 Rheological Properties

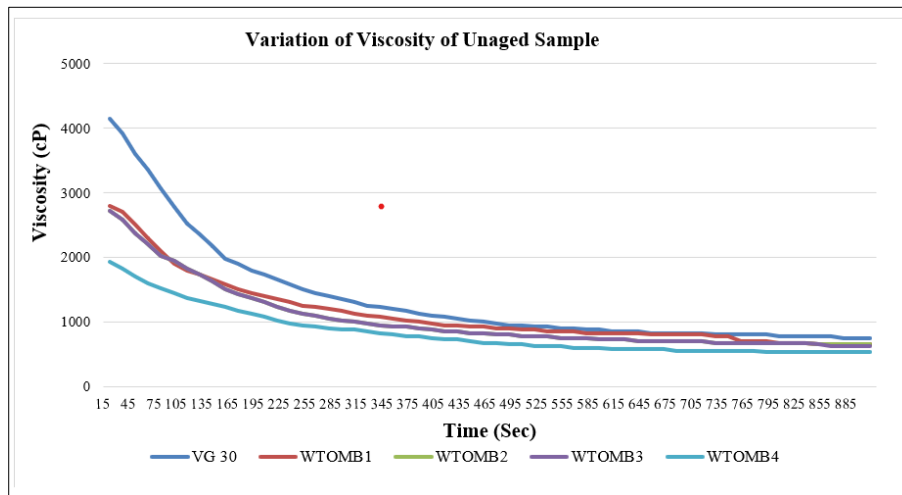
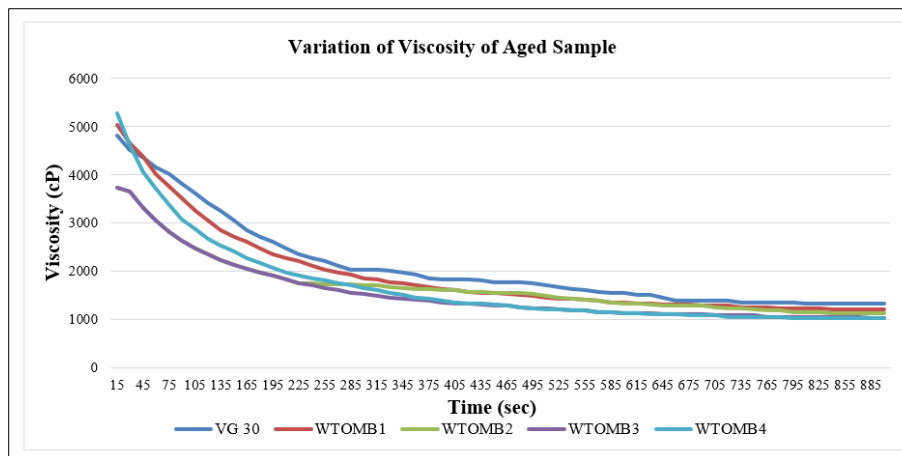
The rheological properties of bitumen, which reflect its stiffness and compliance, are crucial for optimizing its performance in various climatic and loading conditions. These properties are often evaluated through standard tests such as softening point, viscosity at 65°C and 135°C, elastic recovery at 25°C (using a ductilometer), and storage stability assessments based on penetration and softening point values. Flash point and additional tests after Thin Film Oven Aging (RTFOA), including softening point, viscosity, and elastic recovery, are also used to evaluate aging effects on the binder [15, 22].

5.3 Rotational viscosity test

Viscosity testing was conducted using a Brookfield viscometer, following the procedures outlined in ASTM D4402 [23]. The rotational viscosity was measured by determining the torque required to maintain a cylindrical spindle rotating at a constant speed of 20 rpm while immersed in bitumen at a fixed temperature of 135°C. Table 4 presents the viscosity results for both base and modified binders under unaged and aged conditions at 135°C. The decrease in viscosity with increasing WTO content is attributed to the viscoelastic behavior of the base binder, which becomes more flexible with the addition of the modifier [24]. Figure 3 clearly illustrates these changes in both aged and unaged conditions. The results indicate that WTO has a softening effect on VG30 bitumen. Since viscosity directly influences the temperatures required for mixing and compaction, lower viscosity values suggest improved workability and reduced energy consumption during pavement construction. Conversely, higher viscosity values would require elevated temperatures, thereby increasing energy demands during processing.

Table 4: Results of Rotational Viscosity Test at 135 °C

Binder Condition	VG30	WTOMB1%	WTOMB2%	WTOMB3%	WTOMB4%
Unaged	750	665	650	625	525
Aged	1325	1200	1125	1025	1025

**(a)****(b)****Fig. 3 - (a & b) Variation of viscosity vs time**

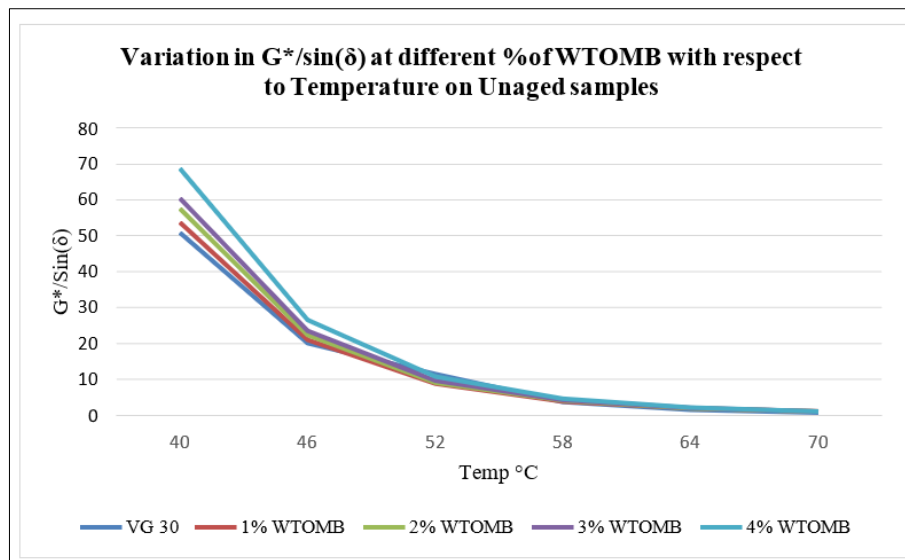
5.4 Performance grade evaluation using DSR

The Dynamic Shear Rheometer (DSR) is used to evaluate the viscosity and elastic behavior of asphalt binders at medium to high service temperatures. This testing method forms the basis of the Superpave Performance Grade (PG) binder specification system. The parameters measured, namely the complex shear modulus (G^*) and phase angle (δ), are used to predict an asphalt binder's resistance to rutting and fatigue cracking [25]. According to current Superpave criteria, at the highest service temperature, the binder must meet the following thresholds for the $G^*/\sin(\delta)$ parameter: Unaged binders must have $G^*/\sin(\delta) \geq 1.0$ kPa, RTFO-aged binders must have $G^*/\sin(\delta) \geq 2.2$ kPa. A higher G^* value indicates increased stiffness and better resistance to permanent deformation, while a lower phase angle (δ) implies a more elastic binder capable of recovering after loading. Table 5 (as per AASHTO M 320 [26]) presents the $G^*/\sin(\delta)$ values for VG30 and WTO-modified binders (WTOMB1–WTOMB4) in both unaged and aged states. The results show that the modified binders exhibit comparable or improved performance to PG 64 binders, particularly in terms of rutting resistance. As the percentage of WTO increases, the complex shear modulus also improves, indicating enhanced stiffness and reduced susceptibility to rutting [27, 28].

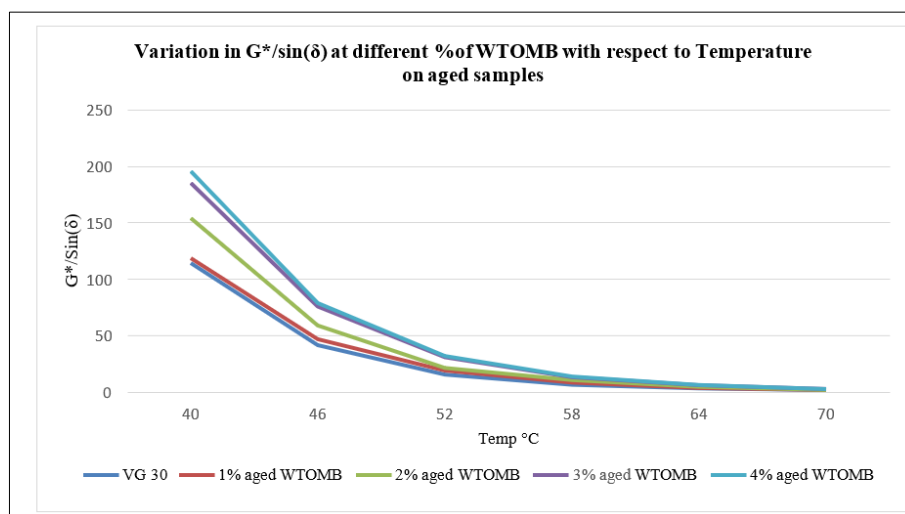
Table 5: Performance grade test for unaged and aged samples

Temp °C	$G^*/\sin(\delta)$ kPa									
	VG 30		WTOMB 1%		WTOMB 2%		WTOMB 3%		WTOMB 4%	
	Unaged	Aged	Unaged	Aged	Unaged	Aged	Unaged	Aged	Unaged	Aged
40	50.71	113.9	53.7	118	57.4	153.68	60.2	185.37	68.5	195.53
46	19.93	41	20.9	46.7	22.1	58.7	23.3	75.2	26.4	78.71
52	11.42	15.1	8.56	19	8.83	21.36	9.42	30.38	10.6	31.66
58	3.61	5.93	3.7	8.06	3.91	10.71	4.04	12.68	4.46	13.19
64	1.48	2.57	1.71	3.59	1.77	4.76	1.83	5.5	2	5.81
70	0.63	1.18	0.84	1.68	0.86	1.82	0.89	2.04	0.95	2.19

Figures 4 (a) and 4(b) graphically illustrate the effect of temperature on $G^*/\sin(\delta)$ for both unaged and aged binders. The trend confirms that modifying the WTO does not degrade the performance of VG30, but somewhat improves its resistance to high-temperature deformation.



(a)



(b)

Fig. 4 - (a & b) Variation in $G^*/\sin(\delta)$ vs temperature

Table 6 presents the failure temperatures and high-performance grades (PG) of VG30 and Waste Turmeric Oil Modified Binders (WTOMB) at varying concentrations. VG30 shows failure temperatures of 64.1°C (unaged) and 67.5°C (aged), corresponding to PG 64. With 1–3% WTOMB, failure temperatures increase slightly, enhancing thermal resistance while maintaining PG 64. At 3% WTOMB, the highest improvement is observed (66.22°C unaged, 69.7°C aged). However, at 4% WTOMB, failure temperatures drop to 63.2°C (unaged) and 64.1°C (aged), indicating reduced performance at higher dosages. Despite variations, all binders fall within the PG 64 category, making them suitable for regions with high temperatures up to 64°C.

Table 6: Performance grade of Binders

Binders	Failure Temp. (°C) Unaged	Failure Temp. (°C) aged	High-Performance Grade
VG 30	64.1	67.5	PG 64
WTOMB 1%	65.3	66.4	PG 64
WTOMB 2%	65.5	67.1	PG 64
WTOMB 3%	66.22	69.7	PG 64
WTOMB 4%	63.2	64.1	PG 64

5.5 Short-term ageing process

The initial oxidation phase, which occurs during mixing and placement (typically within 4–5 hours), plays a crucial role in the short-term aging of asphalt binders and significantly impacts pavement durability, deformation resistance, and long-term performance [29]. During this phase, exposure to high temperatures and oxygen causes the volatilization of lighter components and oxidation of specific chemical fractions, altering the binder's stiffness, viscosity, and susceptibility to cracking and rutting. The Rolling Thin Film Oven (RTFO) test, conducted as per ASTM D2872-22 [30], simulates this aging by subjecting binders to 163°C for 85 minutes in thin-film rotating containers. In this study, WTOMB samples were aged using the RTFO method. Mass loss was measured before and after aging to assess thermal stability. Both VG30 and WTOMB binders exhibited mass loss within the ASTM-specified limit of 1%, indicating adequate resistance to volatilization. WTOMB showed lower volatility than VG30, suggesting improved thermal stability due to the chemical nature of Waste Turmeric Oil (WTO), which may resist oxidation at elevated temperatures [31]. This behavior supports long-term binder performance, especially in hot climates with heavy traffic, and highlights the potential of WTOMB in enhancing mix design strategies and pavement durability.

5.6 MSCR of Binder

Multiple Stress Creep Recovery (MSCR) tests were conducted using a Dynamic Shear Rheometer (DSR) in accordance with the ASTM D7405-08 standard [32]. RTFO-aged binder samples were tested using 25 mm diameter parallel plates at 64°C under stress levels of 0.1 kPa and 3.2 kPa. In each cycle, a one-second creep stress was applied, followed by a nine-second recovery period, and this process was repeated for ten cycles. From this, two key performance indicators were obtained: Non-Recoverable Creep Compliance (Jnr) and Percent Recovery (R%). The Jnr values, as shown in Figure 5, decreased with increasing WTOMB content up to 3%, indicating enhanced rutting resistance. At 3.2 kPa, the Jnr value dropped from 3.5 kPa (VG-30) to 1.8 kPa (3% WTOMB). However, beyond 3%, the Jnr slightly increased, indicating possible over-softening of the binder. A similar trend was observed at 0.1 kPa, suggesting that 3% WTOMB offers the optimal resistance to permanent deformation [33]. The percent recovery (R%) values, shown in Table 6, further validate this trend. VG-30 exhibited 35% recovery at 3.2 kPa and 33% at 0.1 kPa, suggesting suitability for standard to moderate traffic conditions. The 1% and 2% WTOMB binders exceeded the 40% minimum R% threshold specified by AASHTO MP 19 for high-traffic applications [34], with values of 41.5% and 43.8% at 3.2 kPa, respectively. However, R% declined for 3% and 4% WTOMB to 38.2% and 31.7%, indicating a reduction in elastic recovery at higher WTO contents despite improved rutting resistance. Figure 6 illustrates the impact of WTOMB concentration on performance under different traffic conditions. According to the MSCR ranking system defined in AASHTO MP 19 and AASHTO M332 [35], binders with $J_{nr} \leq 0.5$ kPa and $R \geq 40\%$ are suitable for high-traffic loading. Although none of the binders met the strict $J_{nr} \leq 0.5$ kPa requirement, the 1% and 2% WTOMB binders qualify for high-traffic applications based on R%. The 3% WTOMB binder, with excellent

rutting resistance but slightly lower recovery, may be appropriate for moderate to high traffic, while VG-30 and 4% WTOMB are more suited for standard traffic [36]. These findings highlight the trade-off between stiffness and elasticity. 2% WTOMB appears to provide the best balance between rutting resistance and elastic recovery. Further enhancement in recovery at higher dosages could be achieved through dual modification with elastomeric polymers, improving both deformation resistance and binder resilience under heavy traffic loading.

Table 7: Percentage Recovery Values

Binders	3.2 kPa	0.1 kPa
	R%	
VG-30	35	33
1% WTOMB	41.5	52.3
2% WTOMB	43.8	55.7
3% WTOMB	38.2	45.1
4% WTOMB	31.7	40.2

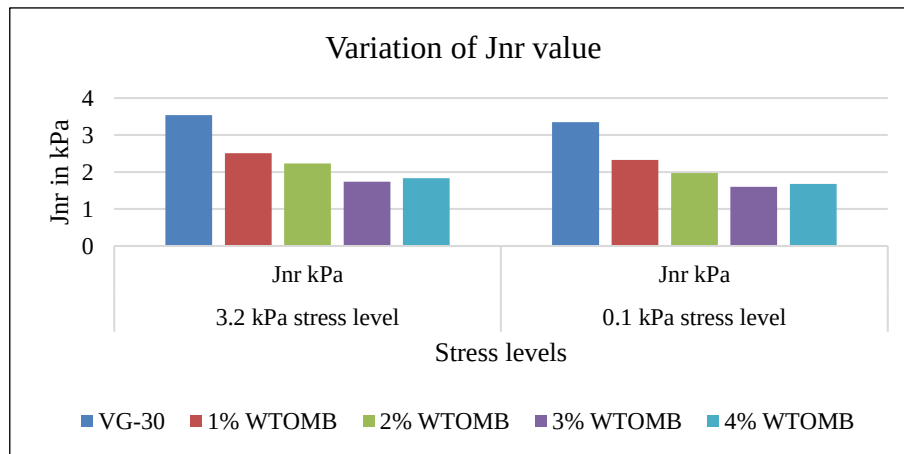


Fig. 5 - Variation of Jnr value at 0.1 and 3.2 kPa

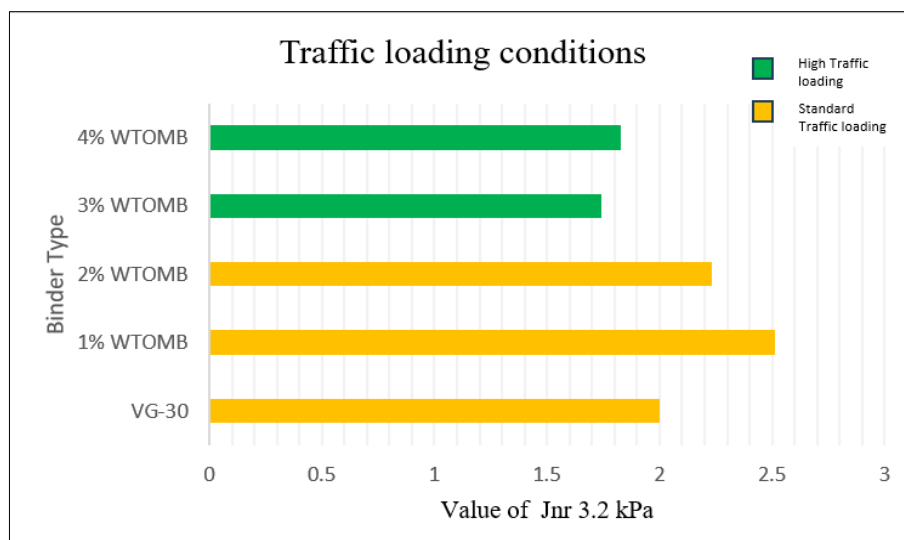


Fig. 6 - Classification of binders based on Jnr 3.2 according to traffic loading conditions

6 Conclusions

This study provides a comprehensive evaluation of the effects of Waste Turmeric Oil (WTO) modification on the physical and rheological properties of VG30 bitumen, emphasizing its potential as a sustainable and performance-enhancing bio-modifier for flexible pavement applications.

The yield of the WTO peaked at approximately 92.2% at 300°C, declining beyond 350°C due to thermal degradation and increased viscosity. This highlights the importance of maintaining optimal processing temperatures to preserve the functional integrity of WTO and ensure consistent binder performance under varying climatic and traffic conditions.

Physical property tests revealed that increasing WTO content led to higher penetration values and lower softening points, indicating reduced binder stiffness and increased temperature susceptibility. A marginal reduction in flash point was observed at higher WTO dosages, underlining the need for safety considerations during handling and storage.

The absolute viscosity of the binder decreased significantly by 20–25% at WTO contents above 3% indicating improved workability and the potential for lower mixing and compaction temperatures. These results align with energy-efficient construction practices and underscore the viability of WTO for promoting sustainable pavement solutions.

Performance Grade (PG) evaluations demonstrated that WTO modification enhanced the complex modulus (G^*) and reduced the phase angle (δ), improving both stiffness and elasticity. The $G/\sin \delta^*$ values increased with the WTO content, confirming enhanced rutting resistance. At a 3% WTO, the non-recoverable creep compliance (J_{nr}) value decreased to 1.8 kPa^{-1} under a stress level of 3.2 kPa, indicating this dosage as optimal. Although the 4% WTO achieved a J_{nr} value below 2.0 kPa^{-1} , further increases in WTO content showed diminishing returns in rutting resistance, likely due to excessive binder softening.

The updated MSCR analysis further supports these findings: 3% WTOMB provided the best balance between rutting resistance and elastic recovery. In comparison, 4% WTOMB was deemed suitable for high traffic conditions, having met the AASHTO M332 criteria. Lower dosages (1–2%) exhibited recovery percentages above 40%, qualifying them for standard traffic conditions. This confirms that the binder's performance is sensitive to the WTO dosage and must be tailored according to the expected traffic loads.

Short-term aging behavior, assessed via the RTFO test, confirmed the thermal stability of WTOMB with mass loss well within ASTM D2872-21 limits, indicating resistance to volatilization and oxidative degradation. Additionally, failure temperature analysis revealed a peak at 3% WTO, which enhanced the aged binder's performance while retaining the PG 64 classification. However, further increases beyond this dosage reduced the binder's thermal resistance.

In summary, the incorporation of 3% Waste Turmeric Oil into VG30 bitumen demonstrated the most favorable balance of physical, rheological, and environmental performance. The study highlights the WTO's potential as an eco-friendly and cost-effective modifier, contributing to waste valorization and enhanced pavement durability. Nonetheless, future research should investigate fatigue life, moisture damage resistance, and field performance to fully validate the long-term viability of WTO-modified binders for sustainable pavement infrastructure.

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