

THERMAL AND RHEOLOGICAL CHARACTERISTICS OF MODIFIED BITUMEN WITH OIL PALM DECANter CAKE

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Abstract

This study evaluates the feasibility of using Oil Palm Decanter Cake (OPDC), a lignocellulosic agricultural residue, as a sustainable modifier for enhancing bitumen performance at elevated temperatures. The study incorporated varying percentages (0% to 20%) of OPDC into palm oil-based polyurethane (PU). It conducted the Simultaneous Thermal Analysis (STA) and Multiple Stress Creep Recovery (MSCR) tests to evaluate the thermal stability and rutting resistance of the modified binders. The results showed that higher OPDC contents enhanced the thermal stability of the binder. The binder with 20% OPDC exhibited a reduced weight loss of 77.54% compared to 80.87% for the control binder due to enhanced char formation. Rheological analysis revealed that 10% OPDC is the optimal percentage for achieving optimal performance, with lower non-recoverable creep compliance (J_{nr}) and enhanced elastic recovery. These enhancements are due to better OPDC interaction and dispersion within the bitumen matrix. Generally, the results confirm that OPDC is an economically viable and environmentally sustainable alternative for enhancing bitumen performance.

Keywords: Creep, MDI, OPDC, Polyurethane, Recovery rate, Rutting, Thermal.

1. Introduction

The chemical composition and structural limitations of conventional bitumen significantly compromised its effectiveness as a binding agent for mixing materials. Over the past decade, water-related damage and traffic loads have been the primary causes of pavement deterioration, including rutting, ravelling, peeling, and cracking. They degrade pavement performance and jeopardize driver safety, threatening the long-term viability and serviceability of highways [1]. Due to these limitations, traditional bitumen is inadequate to meet the demands of modern highway construction. Researchers have investigated the suitability of utilizing various modifiers, including polyurethane (PU), synthetic resins, elastomers, plastomers, crumb rubber, sulphur, paraffins, and metal-organic compounds [2], to enhance bitumen's viscoelasticity and preserve its rheological properties at high temperatures.

The growing emphasis on preserving environmental assets has led to the development of MDI-based prepolymers, which are 'active additives', as alternative petroleum distillates [3]. The incorporation of various polymers, or 'passive additives', revealed limitations across several areas, including compatibility, storage, cost-effectiveness, and the utilization of sustainable resources [4]. Consequently, polyurethane (PU)-based materials are becoming increasingly popular bitumen modifiers due to their distinctive molecular composition. However, there are environmental and safety concerns in the production of commonly used PU prepolymers and PU elastomers [5]. The liquid state of these additives allows their incorporation into bitumen at a low temperature of 90°C [6]. According to Carrera et al. [7], bitumen modification with polyurethane (PU) synthesized from palm kernel oil polyol and methylene diphenyl diisocyanate (MDI) enhanced its performance characteristics. Studies have demonstrated that the interaction between MDI and polyethylene glycol in bitumen significantly enhances complex modulus, thermal stability, and solvent resistance. Apart from their potential as bitumen modifiers, researchers have demonstrated diverse application potentials of Oil Palm Decanter Cake (OPDC) and palm oil-based polyurethane. OPDC is rich in organic matter and nutrients and is widely utilized in agriculture as a biofertilizer and soil conditioner, promoting sustainable waste management in the palm oil industry [8]. It can also be used as a feedstock for biogas production and processed into activated carbon for water and air purification [9]. The palm oil-based polyurethane, derived from renewable resources, is increasingly used to produce eco-friendly foams, coatings, adhesives, and elastomers, offering a biodegradable and sustainable alternative to petroleum-based polymers [10]. These innovations align with green chemistry principles and promote circular economy practices.

In contrast to the commonly used bio-based modifiers, such as bio-oil, biochar, and crumb rubber, the lignocellulosic composition of OPDC, including cellulose, hemicellulose, and lignin, offers distinct advantages in enhancing stiffness, thermal resistance, and char formation during thermal decomposition [11, 12]. Unlike bio-oils, which can reduce stiffness at high contents due to their plasticizing effect, or crumb rubber, which requires high-temperature processing and presents compatibility challenges, OPDC is a low-cost, renewable, and environmentally sustainable alternative [13-15]. Despite these advantages, the utilization of OPDC

in bitumen modification remains largely unexplored, highlighting a clear research gap that this study addresses.

The key focus of this study is Oil Palm Decanter Cake (OPDC) and the incorporation of palm oil-based polyurethane (PU) into the bitumen blend. While PU and other conventional modifiers, including crumb rubber, are widely used to enhance bitumen performance, they often have limitations, including processing complexity, high cost, environmental concerns, and lack of compatibility with the bitumen matrix [11]. For instance, crumb rubber requires high-temperature blending and poses disposal challenges, while synthetic PU is often petroleum-based and less sustainable [12]. In contrast, OPDC is a lignocellulosic biomass by-product of palm oil milling that offers a renewable, low-cost, and environmentally friendly alternative. It is a fibrous, nutrient-rich material characterized by high moisture, biodegradability, and organic content, which enhance stiffness, thermal stability, and rutting resistance, particularly at high temperatures [13]. This study addressed the research gap by conducting a thorough investigation into OPDC applications in road pavements and the viability of combining OPDC with PU as bitumen modifiers.

The PU was synthesized by polymerizing 2,4-diphenylmethane diisocyanate (MDI) with palm kernel oil-based polyol (PKO-p), a polyurethane polyol derived from eco-friendly palm kernel oil [16]. The mixture was continuously stirred in a nitrogen atmosphere at 70–80°C to prevent moisture interference and ensure homogeneity. The stoichiometric NCO:OH ratio of 1.2:1 was maintained at 70–80°C to facilitate complete urethane linkage formation. The mixing was catalysed with 0.1 wt% dibutyltin dilaurate (DBTDL) to accelerate the reaction. The resulting PU prepolymer was cooled and stored in sealed containers before being incorporated into the bitumen. The PU serves as an additive that enhances the bitumen's rheological and mechanical performance by increasing its elasticity and resistance to deformation. Carrera et al. [17] reported that polyurethane-modified emulsions prepared using isocyanate-functionalized polyols exhibit superior rheological properties and higher resistance to permanent deformation than unmodified emulsions, supporting the use of bio-based PU in this study.

Bitumen has viscoelastic properties and exhibits varying behaviour, depending on temperature and the duration of applied load. Thermogravimetric analysis (TGA) is used to measure changes in a material's mass as a function of temperature. It is performed either in an inert nitrogen environment, which inhibits combustion, or in an oxidative air environment. Previous research conducted thermogravimetric analysis in nitrogen environments to investigate bitumen with varying asphaltene concentrations [18]. Researchers observed a correlation between asphaltene content and the bitumen's decomposition temperatures. Higher asphaltene content reduces thermal stability, resulting in a lower char yield [19].

Rutting parameters are rheological measures used to evaluate the permanent deformation of bitumen due to high temperatures or slow-moving loads [20]. The parameter employed by the Strategic Highway Research Program (SHRP) is the creep compliance (J_{nr}), determined using the Multiple Stress Creep Recovery (MSCR) test [21, 22] examined the creep-recovery characteristics of modified bitumen and found that longer creep and recovery phases resulted in lower R values and higher J_{nr} values. This result suggests a gradual decline in bitumen resistance to permanent deformation, increasing the viscous component of its viscoelastic

response. Wasage et al. [23] concurred that using lower-grade bitumen to produce rubber-modified bitumen results in lower accumulated strain, as demonstrated by the MSCR test. This result confirmed that the MSCR test differentiates rutting resistance and exhibits a robust correlation with rutting, unlike the current Superpave binder parameters [24].

The key objectives of this study are to investigate the thermal and rheological characteristics of OPDC-modified bitumen. The bitumen samples are mixed with varying OPDC concentrations of 0%, 5%, 10%, 15%, and 20%, along with PKO-p and 2,4-MDI. The thermal degradation weight loss was measured via TGA. The Temperature Sweep test classified the modified bitumen blends, and rutting resistance was determined via the MSCR test.

2. Experimental Design

2.1. Materials and sample preparation

This study used bitumen with a 60/70 penetration grade as the base binder. The Oil Palm Decanter Cake (OPDC) was supplied by the Sime Darby Oil Palm Mill in Sua Betong, Negeri Sembilan, Malaysia. The OPDC was dried in a 135°C oven for 24 hours to remove moisture and then ground and sieved to obtain a uniform particle size of approximately 300 µm. The OPDC-modified bitumen was incorporated with 20% polyurethane (PU) comprising palm-based polyol (PKO-p) and 2,4-methylene diphenyl diisocyanate (2,4-MDI) at a ratio of 100:60. The OPDC content of 0–20% was selected based on previous studies on biomass-modified bitumen, which reported achieving optimal performance with 5–15% OPDC, and preliminary experimental observations to evaluate the effects of optimum and higher dosages of OPDC on binder behaviour [2, 20].

The polyurethane (PU) must be prepared within three minutes. Therefore, after adding and thoroughly mixing PKO-p, the 2,4-MDI was incorporated immediately to prevent premature curing. It is pivotal to immediately incorporate 2,4-MDI due to the rapid reaction between the hydroxyl groups in the polyol and the isocyanate groups in MDI. MDI-based polyurethane systems are characterized by swift curing and notably short 'pot life' [25]. Polymeric MDI systems generally have a limited workability period of approximately 20 minutes at elevated temperatures, which can be accelerated with catalysts [26]. Rapid mixing and application ensure even distribution, prevent uneven crosslinking, minimize the exposure of free isocyanate to moisture, which can lead to foaming and defects, and mitigate the safety risks associated with uncontrolled exothermic reactions.

The treated OPDC was incorporated into the bitumen at 5%, 10%, 15%, and 20% by weight. A second control binder, comprising bitumen with a 60/70 penetration grade blended with PU and unmodified base binder, was prepared for comparative analysis. The preparation involved heating the base bitumen to 165°C to ensure adequate fluidity for mixing and gradually adding the required amount of OPDC. The binder was blended for 15 minutes at 2,000 rpm in a high-shear mixer, IKA T25 digital ultra-TURRAX, to ensure that the OPDC and PU are uniformly dispersed in the bitumen matrix. The high-shear mixing ensures a homogeneous distribution of OPDC particles, thereby enhancing the interaction among bitumen, polyurethane, and OPDC. Figure 1 presents the general process for preparing OPDC that produces consistent modified bitumen samples.

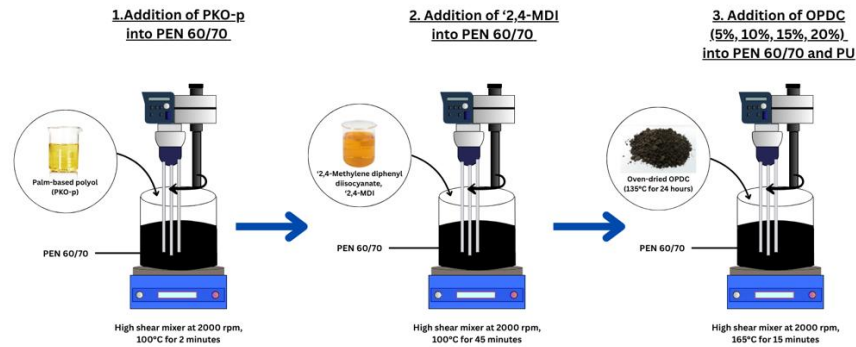


Fig. 1. The preparation process of OPDC modified bitumen.

3. Laboratory Testing

3.1. Simultaneous thermal analysis (STA) test

Many researchers use thermogravimetric analysis (TGA) as a potent method to test the thermal stability of various materials, including bitumen [27]. For this research, Simultaneous Thermal Analysis (STA) was employed as it integrates DTG and TGA measurements into a single operation, thereby reducing time and facilitating easier interpretation of the findings. STA typically denotes the concurrent use of Thermogravimetry (TGA) and Differential Thermal Analysis (DTG) on a single sample within one instrument. The experimental conditions for both TGA and DTG measurements are identical in every aspect, including the atmosphere, gas flow rate, vapour pressure on the sample, heating rate, thermal contact between the sample crucible and sensor, and radiation effects. Moreover, the efficiency of sample analysis is enhanced as each test run yields a greater amount of data [23]. The STA 449 F3 Jupiter equipment was used in this study's thermal tests to examine the modified bitumen's thermal behaviour. Any shifts to the decomposition curves are caused by the bitumen's addition of PU and OPDC.

To further analyse the TGA thermogram, differential thermal analysis (DTA) is employed. DTA is a thermoanalytical technique that shares similarities with differential scanning calorimetry. In Differential Thermal Analysis (DTA), the temperature difference is graphed as a function of time or temperature. This method allows for the detection of any exothermic or endothermic changes occurring within the sample [28].

3.2. Temperature sweep test

The rheological properties of the unaged control and OPDC-modified bitumen binders were evaluated using a Dynamic Shear Rheometer (DHR-2, TA Instruments) in accordance with ASTM D7175 and ASTM D6373. The temperature sweep test was conducted to evaluate the effect of increasing temperature on the viscoelastic behaviour of the binders. This test provides valuable information on the temperature-dependent changes in binder stiffness and elasticity, which are critical indicators of rutting resistance and high-temperature performance. The test was performed using a 25 mm parallel plate geometry with a 1 mm gap. The specimens were tested over the selected temperature range while maintaining a constant oscillation frequency and strain within the linear

viscoelastic region. The complex shear modulus (G^*), phase angle (δ), and rutting parameter ($G^*/\sin\delta$) were recorded to assess the binder stiffness and resistance to permanent deformation at elevated temperatures.

3.3. Multiple Stress creep recovery (MSCR) test

The MSCR test was performed to determine the rutting susceptibility of the bitumen. AASTO TP requires conducting a Multiple Stress Creep Recovery (MSCR) test to determine the rutting susceptibility. In accordance with AASHTO TP70-09, the binder's elastic behaviour was quantified using the recovery percentage (R), while the extent of permanent deformation under repeated loading was assessed using the non-recoverable creep compliance (J_{nr}). This study modified the standard MSCR procedure by increasing the loading cycles at each stress level from 10 to 30. This modification minimizes the influence of transient, non-steady-state responses in every loading stage, consistent with approaches adopted in recent studies [29].

It is worth noting that, because each test condition was measured once, the data variability cannot be represented with error bars. The researchers acknowledge this limitation, and future work should replicate testing to improve statistical reliability and confidence in the results.

4. Results and Discussion

4.1. Simultaneous thermal analysis

Typically, A thermogram analysis curve comprises the thermogravimetric analysis (TGA) and difference thermogravimetric analysis (DTG). The DTG curve represents the rate of weight loss versus time (T), while the thermogravimetric curve illustrates mass reduction against temperature. The latter shows the original sample's composition and its thermal stability [30]. Figures 2 and 3 present the DTG and TGA curves for the 0%, 5%, 10%, 15%, and 20% samples. The thermal analysis revealed that each binder sample undergoes one degradation phase. The thermogram shows that the TGA curve comprises three horizontal sections.

The DTG curve in the study by Murugan et al. [31] shows that the bitumen undergoes three stages of cracking and extraction during the TGA test: (1) the initial sample, (2) sample cracking, and (3) catalytic cracking of the sample. The DTG peaks for OPDC-modified bitumen are 449.1°C, 451.6°C, 450.8°C, 450.0°C, and 449.0°C. The incorporation of OPDC 1 to OPDC 4 reduces weight loss at temperatures between 449.1°C and 450.8°C.

The cracking and extraction of all OPDC-modified bitumen showed that the initial bitumen occurs at approximately 460°C, where bitumen undergoes a carburization reaction and dehydrocondensation of cyclic structures due to its H/C ratio. All bitumen samples began to crack between 470°C and 490°C. The dehydrocondensation in the initial stage forms stronger polynuclear aromatic structures, facilitated by the aromatic compound in the OPDC (Section 3.3). Above 490°C, where the bitumen undergoes catalytic cracking, the TGA shows a linear rate of mass loss with the breaking of weak chemical bonds. Thermogravimetric analysis of cracked bitumen samples revealed that the number of resin-bitumen compounds in crude oil derivatives determines the gas-to-solid product during thermal decomposition. The bulk composition of the cracking products was used to gauge bitumen conversion in cracking. Hydrocarbons undergo intense conversion

above 350°C, converting the bitumen-resin components into light hydrocarbons. As the temperature rises in an inert environment, fractured bitumen loses mass monotonically [31].

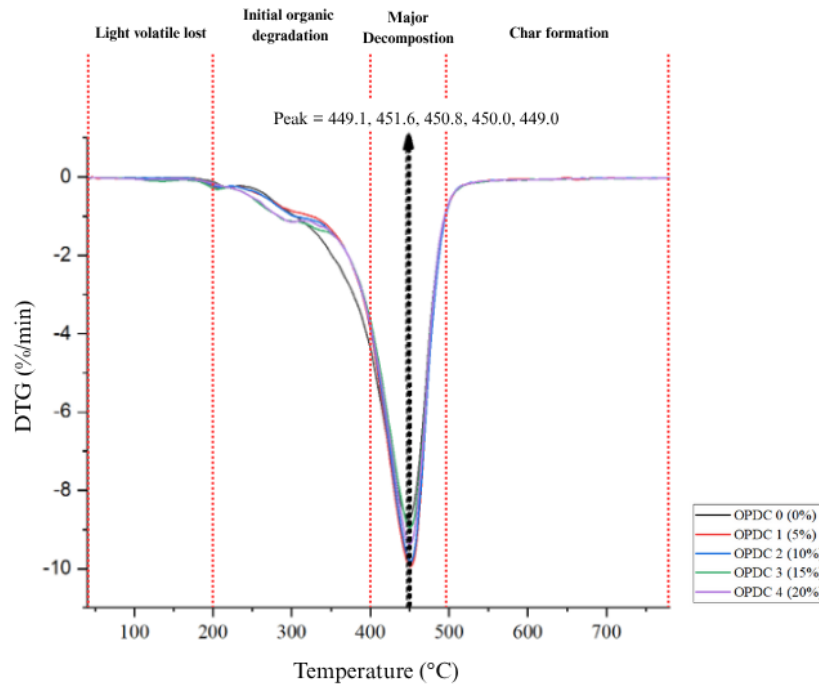


Fig. 2. DTG curves for all OPDC modified bitumen.

A thermal analysis was conducted to investigate the heat-related properties of the modified bitumen. [28] have demonstrated that while unmodified bitumen undergoes thermal degradation in a single phase, the thermal degradation of the modified bitumen is in two distinct stages. The TGA curves in Fig. 3 illustrate a single-stage mass loss, characterized by an initial decomposition temperature (IDT) and a final decomposition temperature (FDT). The IDTs for the 0%, 5%, 10%, 15% and 20% OPDC are 98.87°C, 99.14°C, 99.08°C, 97.15°C, and 96.62°C, respectively. For FDT, the temperatures are 17.89°C, 18.87°C, 18.30°C, 19.89°C, and 19.08°C, respectively. The increase in mass loss occurs between 250°C and 450°C. The stage of slow composition, which occurs after 450°C, is characterized by the release of volatile organic molecules and the combustion of fixed carbon, both of which indicate the end of mass loss. OPDC 0 (0%), incorporated with only PU, exhibits the highest mass loss of 80.87%, whereas OPDC 4 (20%) undergoes the least mass loss of 77.54%.

The reduced weight loss with higher OPDC contents can be attributed to its lignocellulosic component, particularly lignin, which promotes char formation during thermal decomposition. The decomposition of hemicellulose and cellulose occurs at lower temperatures than lignin decomposition, which occurs over a wide temperature range, promoting the formation of thermally stable carbonaceous residues [17, 18]. The char layer serves as a physical barrier that slows down the

release of volatile compounds and the thermal degradation. Additionally, the porous structure of OPDC particles facilitates the adsorption of lighter maltene fractions, further limiting mass loss [19]. Together, these mechanisms contribute to the modified binder's enhanced thermal stability. This result is consistent with the outcomes of previous studies on biomass-modified bitumen, where increased char formation enhances thermal stability and reduces volatilization [18, 19].

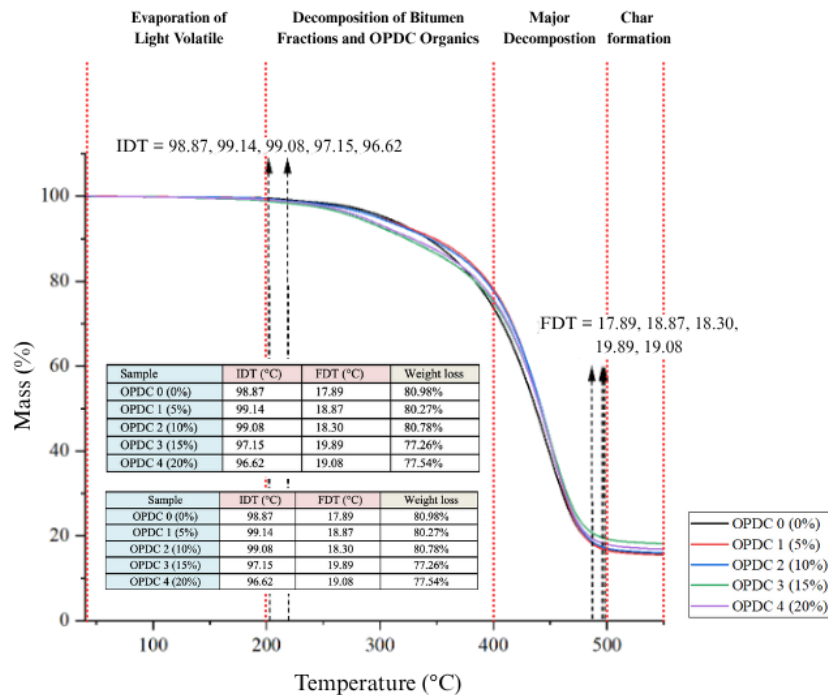


Fig. 3. TGA curves for all OPDC modified bitumen.

4.2. Rutting resistance analysis

The Superpave requires using the rutting parameter ($G^*/\sin\delta$) to evaluate bitumen's ability to resist permanent deformation. Greater $G^*/\sin\delta$ values indicate enhanced resilience against permanent deformation. The PG temperature depends on the rutting parameters of OPDC 0 (0%), OPDC 1 (5%), OPDC 2 (10%), OPDC 3 (15%), and OPDC 4 (20%). $G^*/\sin\delta$ is used to analyse experiment data and evaluate high-temperature performance. Figure 4 shows the rutting parameters of OPDC-modified bitumen at varying temperatures.

The temperature sweep test showed that, based on the Superpave standards, the bitumen performance grading temperatures for OPDC 0 (0%), OPDC 1 (5%), OPDC 2 (10%), OPDC 3 (15%), and OPDC 4 (20%) are PG 76, PG 76, PG 76, PG 76, and PG 70, respectively, and the control bitumen is PG 64.

Figure 4 shows that the $G^*/\sin\delta$ of the OPDC-modified bitumen decreased with higher temperatures. The decreasing $G^*/\sin\delta$ values indicate reduced bitumen stiffness and, therefore, lower rutting resistance. This trend is expected because the

residual oil in the OPDC produced a more elastic bitumen behaviour. This behaviour is evident from the reduced performance grade from OPDC 3 (15%) to OPDC 4 (20%). Yang et al. [20] observed the same behaviour as the bio-oil derived from bamboo charcoal production through the heavy fraction. Rutting performance decreased with higher bio-oil concentrations. In conclusion, the optimal OPDC concentration is between 5% and 10%.

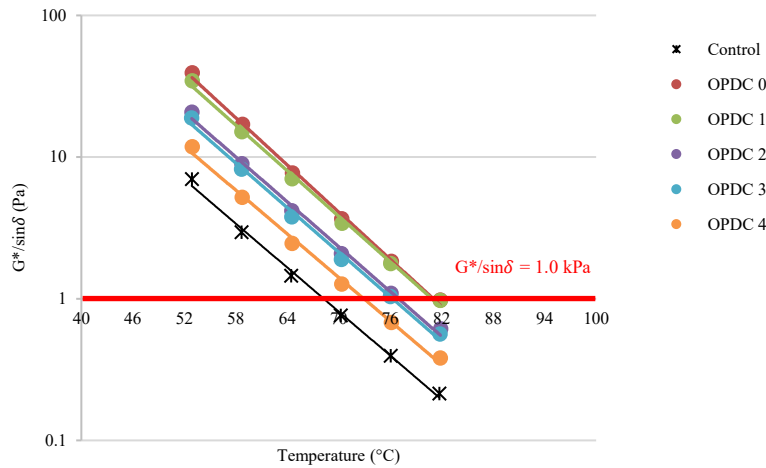


Fig. 4. Rutting parameters of OPDC modified bitumen at different temperatures.

4.3. Multiple stress recovery analysis

Figures 5 and 6 present the MSCR test results for the OPDC-modified bitumen at shear stress of 0.1 and 3.2 kPa, respectively. The results also show the one-second creep phase and a nine-second recovery phase.

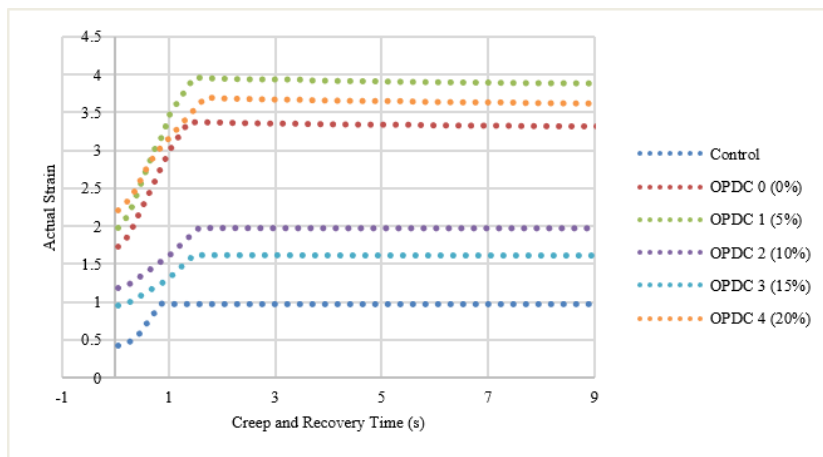


Fig. 5. MSCR results tested at 0.1 kPa.

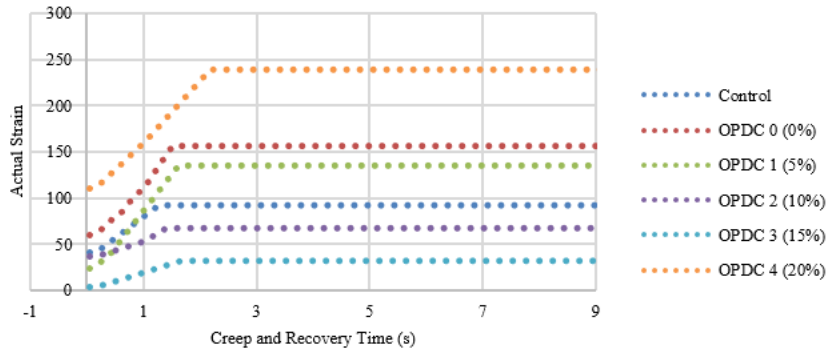


Fig. 6. MSCR results tested at 3.2 kPa.

The strain magnitude increases at a longer 0.1 kPa stress load during the creep phase. The initial rapid strain decrease is followed by a gradually slowing recovery rate, which characterizes the viscoelastic properties of the OPDC-modified bitumen. The elastic strain did not occur instantaneously upon the removal of the creep load, as illustrated by the declining graph for all modified bitumen samples, indicating a recovery phase.

At 3.2 kPa, the strain increases with longer loading duration in the creep phase. The recovery rate diminishes gradually during the recovery phase. This behaviour demonstrates the viscoelastic-plastic characteristics of the OPDC-modified bitumen. The elastic strain upon the removal of the creep load is similar to that shown in Fig. 6. The graph exhibits a consistent trend across all OPDC-modified bitumen samples. Consequently, the specimen is expected to show a significantly lower percentage of strain recovery at a 3.2 kPa creep loading relative to 0.1 kPa. This result suggests that the maximum strain influences the recovery percentage at a minimal applied creep load.

Direct assessment of creep compliance and recovery rate from the graphs is questionable. Therefore, it is essential to determine the non-recoverable compliance R (%) and the J_{nr} differences, which are indicators of high-temperature stability and elasticity, as recommended by FHWA.

Figure 7 shows the non-recoverable compliance, J_{nr} , of the control and OPDC-modified bitumen. Higher creep loading should produce higher values, primarily due to greater permanent deformation and lower recovery percentages [26]. The 0.83 J_{nr} value for a 60/70 penetration grade bitumen at 0.1 kPa decreased to 0.34 at 3.2 kPa. All OPDC-modified bitumen have lower strain levels than the control bitumen at 0.1 kPa and 3.2 kPa. At a creep loading of 0.1 kPa, the J_{nr} values of OPDC 0, OPDC 1, OPDC 2, OPDC 3, and OPDC 4 are 0.200, 0.214, 0.070, 0.068, and 0.181, respectively. OPDC 1 has the highest creep compliance. At 3.2 kPa, the J_{nr} values for OPDC 0, OPDC 1, OPDC 2, OPDC 3, and OPDC 4 are 0.273, 0.349, 0.081, 0.083, and 0.246, respectively. Except for OPDC 1, the OPDC-modified bitumen exhibits lower J_{nr} values than the control bitumen, with the J_{nr} values increasing from OPDC 2 to OPDC 4.

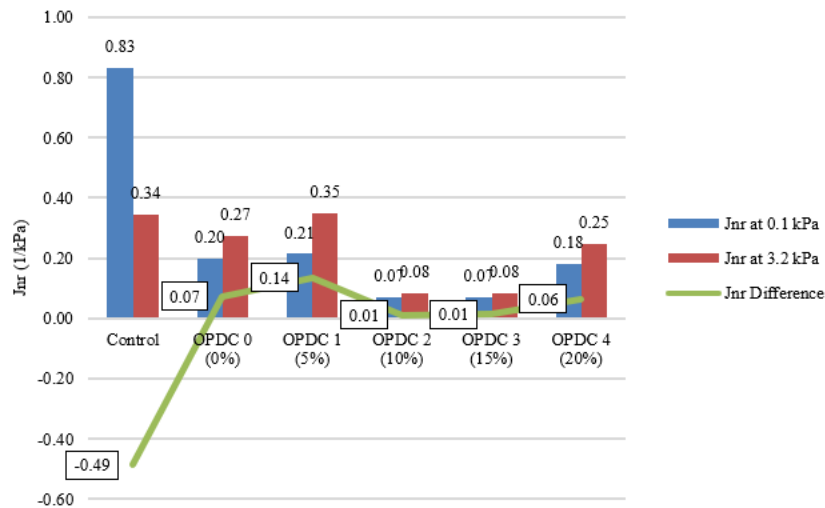


Fig. 7. The non-recoverable compliance (J_{nr}), percentage recovery (%) and non-recoverable compliance (J_{nr}) difference tested at 0.1 kPa and 3.2 kPa.

The significantly lower J_{nr} value for OPDC1 (5%) than OPDC2 (10%) indicates the formation of an optimal internal structure in the bitumen matrix. At this dosage, the well-dispersed OPDC particles enhance the interaction between the polyurethane and the bitumen matrix, improving elastic recovery and resistance to permanent deformation [22]. However, beyond 10% OPDC content, the gradually increasing J_{nr} values suggest reduced efficiency due to particle agglomeration and poor dispersion of OPDC particles. Excessive OPDC contents may disrupt the continuity of the binder matrix, resulting in diminished reinforcement effects [23]. This finding indicates that 10% OPDC is the optimal balance between reinforcement and dispersion within the modified bitumen system.

The MSCR specification has an additional requirement for the J_{nr} difference, where the J_{nr} difference between the higher stress level (3.2 kPa) and the lowest stress level (0.1 kPa) must not exceed 0.75. At high stress levels, stress-sensitive binders may yield and exhibit reduced structural integrity. It is also to avoid the loss of binder strength in the pavement [32]. Therefore, as shown in Figure 7, the control binder is the only bitumen that does not meet this requirement, confirming that OPDC increases bitumen stress sensitivity.

Figure 8 shows that increasing the load from 0.1 kPa to 3.2 kPa resulted in a lower R (%) value. At 0.1 kPa, OPDC 4 has the highest recovery rate of 4.69%, while the recovery rates for OPDC 0, OPDC 1, OPDC 2, and OPDC 3 are 2.27%, 2.91%, 0.82%, and 1.15%, respectively. The recovery rates for all OPDC-modified bitumen are superior to those of the control bitumen. At 3.2 kPa, the control bitumen, OPDC 0, and OPDC 1 failed to recover despite increasing J_{nr} values. The recovery rates for OPDC 2, OPDC 3, and OPDC 4 are 0.026%, 0.029%, and 0.005%, respectively. Negative R values indicate no binder recovery after the load application, thus confirming the greater benefit of incorporating OPDC at higher loading levels.

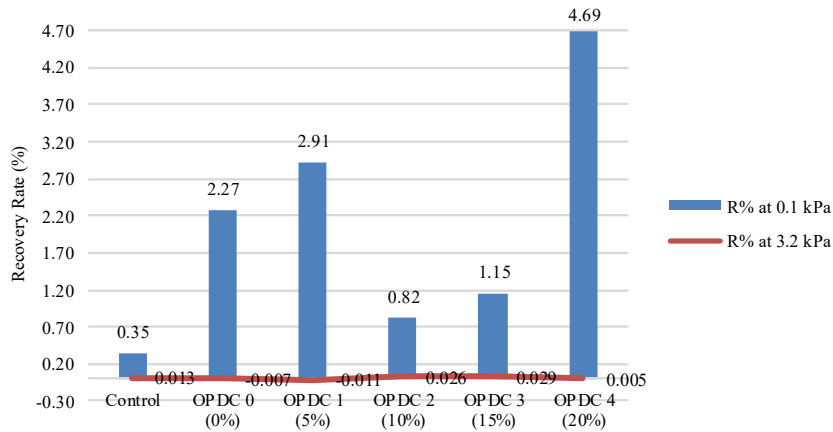


Fig. 8. The recovery rates (%) at stress level of 0.1 kPa and 3.2 kPa

Generally, higher temperatures and stress levels resulted in less recovery and vice versa. However, there is no consistent pattern for the rate of strain recovery and the degree of recovery. At a given temperature and applied stress, the unaged bitumen exhibited an inverse relationship between the rate of strain recovery and the recovered strain. It is worth noting that higher recovery rates do not necessarily correspond with lower non-recovery compliance [32]. Hence, the OPDC-modified bitumen is not expected to exhibit any trend in non-recoverable compliance J_{nr} and the percentage of recovery (R). Nevertheless, among the key factors to consider when choosing the appropriate bitumen are the non-recoverable compliance and the recovery rate. It is apparent that OPDC 2 is the optimal OPDC-modified bitumen for high-temperature performance due to its creep compliance and recovery under both stress levels. Previous research reported similar improvements in rutting resistance in polyurethane- and bio-based binders, where enhanced elastic networks reduced permanent deformation [22].

5. Conclusions

This study investigated the feasibility of using varying percentages of palm oil waste, Oil Palm Decanter Cake (OPDC), and polyurethane (PU) as bitumen modifiers. It focused on their impact on thermal and rheological properties. The following conclusions are drawn based on the evaluation of thermal stability and rheological performance.

The Simultaneous Thermal Analysis (STA) and Thermogravimetric Analysis (TGA) revealed that OPDC reduced weight loss between 449.1°C and 450.8°C, suggesting enhanced thermal stability of the binder. The results from Derivative Thermogravimetry (DTG) corroborated this observation, with reduced mass loss from 80.87% for OPDC 0 (0%) to 77.54% for OPDC 4 (20%). These results indicate that higher OPDC contents reduced the decomposition rate, likely due to the reinforcing effect of fibrous or carbonaceous components in OPDC, which enhances thermal resistance. Nonetheless, all samples exhibited relatively high weight loss, indicating that, although OPDC improves thermal stability, the bitumen system remains thermally sensitive at extreme temperatures.

The temperature sweep test in rheological analysis showed that adding 5–10% OPDC significantly enhanced the binder's rutting resistance, indicating enhanced stiffness and load-bearing capacity at elevated service temperatures. This result is supported by the Multiple Stress Creep Recovery (MSCR) test, which showed a recovery phase for all OPDC-modified binders at 0.1 kPa stress, although binder performance at 3.2 kPa stress was variable. Notably, OPDC 2 (10%) exhibited optimal performance with the lowest non-recoverable compliance (J_{nr}) values of 0.070 at 0.1 kPa and 0.081 at 3.2 kPa and corresponding recovery (R) percentages of 0.819% and 0.026%. These values indicate that OPDC 2 imparts optimal stress resistance and elasticity, which are crucial for minimizing permanent deformation under repeated traffic loading. Additionally, the MSCR data suggested that OPDC-modified bitumen may have a stress sensitivity threshold below 3.2 kPa, beyond which the binder begins to yield, underscoring the importance of regulating traffic loading in practical applications.

In conclusion, 10% OPDC (OPDC 2) is the optimal concentration for enhancing thermal stability and rheological performance. It improved binder durability, rutting resistance, and suitability for high-temperature paving applications. The study outcomes support the feasibility of using OPDC as a sustainable, cost-effective bitumen modifier that enhances pavement performance and waste valorisation in the palm oil industry.

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