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ORIGINAL RESEARCH PAPER

Rheological Properties and Rutting Performance of Waste-incorporated Hybrid Asphalt Binders

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Abstract

Intense efforts have been focused on formulating excellent asphalt mixtures to achieve desirable properties in line with the growing numbers of traffic loads and harsh environmental factors. Nevertheless, the complex rheological behaviour of modified asphalt binders makes it challenging to predict their consistent performance, especially when incorporated with waste materials. In view of the promising use of valuable waste materials in asphalt mixtures, this study examined the rheological characteristics and rutting performance of hybrid asphalt binders incorporated with Palm Oil Fuel Ash (POFA), garnet waste, and sawdust as asphalt modifiers. A Dynamic Shear Rheometer (DSR) with frequency sweep test was used to compare the performance of individual-modified asphalt binders comprising 3% of POFA, garnet waste, and sawdust, respectively, and 0%, 3%, 6%, and 9% hybrid content combining the three waste materials in unaged hybrid asphalt binders and Rolling Thin Film Oven (RTFO) hybrid asphalt binders. The Multiple Stress Creep Recovery (MSCR) test was utilised to assess the creep and recovery properties of the asphalt mixtures, while the complex shear modulus (G*) and phase angle (δ) master curves were constructed to evaluate the viscoelastic performance of the asphalt mixtures. Comparatively, the creep recovery rate of the 6% unaged hybrid asphalt binder was substantially higher compared to its 3% and 9% unaged hybrid asphalt binder. According to the master curve analysis, the improved performance of the 6% RTFO hybrid asphalt binder is evident in the low frequency, which corresponds to the extremely high-temperature conditions. In summary, the addition of 6% hybrid content in the short-term aged RFTO hybrid asphalt binders achieved high creep recovery and high-temperature susceptibility and is considered the optimum asphalt mixture to achieve sustainable and high-performance asphalt pavements.

Keywords Hybrid asphalt binder · POFA · Garnet waste · Sawdust · Rheological properties · Rutting performance

1 Introduction

The modification of asphalt binders has become a crucial research area due to the growing need to enhance the performance of pavement materials under increasing traffic loads and extreme weather conditions. Traditional asphalt binders often suffer from limitations such as susceptibility to permanent deformation, rutting, temperature-induced cracking, and fatigue [1, 2]. To overcome these issues, various modifiers like agro-industrial wastes, polymers and industrial by-products have been introduced [3–5]. In recent years, the use of waste materials for asphalt modification has gained significant attention due to the potential for reducing costs and environmental impacts. By incorporating waste materials, agricultural wastes such as palm oil fuel ash (POFA) and sawdust, along with industrial by-products like garnet

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waste, researchers aim to improve both the mechanical and rheological properties of asphalt, while addressing the global issue of waste management. Since each modifier has particular benefits and disadvantages, the effectiveness of these modifiers in enhancing the binder properties while maintaining other critical characteristics must be evaluated.

Rheological properties, including complex modulus (G*) and phase angle (δ), are essential indicators of the viscoelastic behavior of asphalt binders. Numerous studies have demonstrated that the incorporation of waste materials can significantly alter these properties. POFA, being rich in silica content, has been shown to enhance the elastic response of binders by forming strong silicon-oxygen networks that contribute to higher G* and lower δ values, indicating improved stiffness and reduced susceptibility to permanent deformation at high temperatures [6]. Garnet waste, characterized by its high specific gravity and angular particle morphology, has similarly exhibited the ability to increase G*, thereby reinforcing the binder structure and enhancing resistance to rutting [7]. Conversely, sawdust, due to its fibrous and porous nature, can initially absorb part of the binder, potentially softening the mixture [8]. However, when chemically treated, it has been reported to increase elasticity and reduce phase angle values, contributing to a more recoverable and flexible binder under cyclic loading [9]. Despite these promising findings, the synergistic effects of combining these materials in a hybrid system remain underexplored, particularly in relation to their impact on the binder's rheological response. This study addresses this gap by investigating the integrated effect of POFA, garnet waste, and sawdust on the viscoelastic performance of modified asphalt binders using dynamic shear rheometer (DSR) testing.

A recent study by [10] focused on the rheological performance of asphalt binders modified with palm oil waste and demonstrated that Palm Oil Clinker Fuel (POCF) modified binders exhibit improved rheological and ageing properties [11]. also explored the utilisation of Waste Rubber (WR) powder and Styrene-Butadiene-Styrene (SBS) as modifiers in asphalt binders by performing the MSCR tests to assess their impact. In another study [12], assessed the complicated viscosity and examined the high-temperature performance, temperature susceptibility, and anti-ageing properties of Polyphosphoric Acid (PPA)-SBS and PPA-CR (crumb rubber) modified asphalts. Apart from that [13], contributed insights into rheological characterisation by correlating asphalt binder properties with the recovery phenomenon and predicted permanent deformation in asphalt mixtures. Besides [14], investigated the crosslinking mechanism in rubberised asphalt binders and highlighted the effect of SBS polymer and type-II crosslinking reaction on the rheological properties of the modified asphalt [15]. also investigated lignin as a substitute for bitumen, reporting improved asphalt mixture performance with promising results. In short, these diverse studies contribute valuable insights into the modification and optimisation of asphalt binders, addressing sustainability, waste utilisation, and performance enhancement using various materials and methodologies.

To date, several studies have investigated on Dynamic Shear Rheometer (DSR) [16]. observed different reaction mechanisms throughout thermal and photochemical ageing processes, concentrating on the DSR to study the rheological parameters. The research highlighted the need to consider moisture and Ultraviolet (UV) radiation when conducting laboratory ageing experiments due to their significant impact on pavement lifespan and performance. For example [17], conducted a comprehensive study using DSR and modelling methods to determine the rheological properties of bio-asphalt binders. The research utilised Crude Palm Oil (CPO) as a bio-oil extender, which showed good agreement between the predicted and experimental results. The complex modulus of the bio-asphalt with 5% CPO was similar to that of the base asphalt binder. Short- and long-term ageing processes are a crucial component in assessing the performance of modified asphalt binders. In short-term ageing, elevated temperatures and exposure to oxygen lead to oxidative hardening, resulting in increased stiffness and reduced ductility. On the other hand, long-term ageing involves prolonged exposure to environmental factors, causing a loss of volatility and increased brittleness. Previously [18], investigated the long-term ageing effects on the charcoal-coconut shell ash asphalt mixture, revealing the evolution of rheological properties and the loss of resilience over extended periods. A more recent study by [19] explored the short-term ageing of SBS-modified binders and highlighted the changes in rheological properties and chemical composition due to oxidative ageing. Both studies highlighted the critical need to account for both short-term and long-term aging processes when evaluating the performance of modified asphalt binders, offering essential insights into how they behave under different environmental conditions. Additionally, moisture susceptibility was examined using the Moisture-Induced Shear Thinning Index (MISTI) to determine whether the additives used adversely affected the binder's moisture resistance [20].

Rutting is one of the most prevalent distresses affecting flexible pavements. It results from repeated traffic loading, particularly in regions with high temperatures. Previous studies have investigated the effects of various modifiers on rutting resistance [21–23]. According to [24], proposed using marble dust as a sustainable filler in asphalt mixtures and reported enhanced stability and reduced rutting in the performance tests. In another study [25], assessed the effect of adding Peanut Husk Ash (PHA) to asphalt binders

Table 1 Basic performance of asphalt 60/70 PEN used in the test

Parameters	Results	Requirements
Penetration (dmm)	70	60–70
Softening point (°C)	47.6	49–56
Ductility (cm)	> 100	≥ 100
Viscosity at 135 °C (Pa.s)	0.5	< 3

Table 2 Physical indicators of the waste materials

Hybrid materials	Density (g/cm^3)	Specific gravity	Moisture content (%)
POFA	2.51	2.51	6.1
Garnet waste	2.96	2.97	0.4
Sawdust	1.23	0.26	5.02

and recorded that PHA enhanced resistance to rutting and reduced waste materials. Conversely, fatigue occurs when the pavement repeatedly deforms under stress, causing longitudinal fractures in the wheel path that eventually develop into alligator cracking. Previously [26], revealed that the addition of 8% Oily Sludge (OS) as a bitumen modifier improved fatigue resistance while maintaining performance grade. The pavement contraction at low temperatures causes thermal cracking, and it manifests as relatively uniform-spaced cracks that run counterclockwise to the centreline. To some extent, these failures can be directly attributed to the complex viscoelastic behaviour of asphalts [27]. These studies underline the importance of selecting appropriate modifiers that not only enhance rheological properties but also provide superior rutting performance.

The Multiple Stress Creep Recovery (MSCR) test is commonly employed to evaluate the rheological properties of asphalt binders, especially their rutting resistance [21, 28, 29]. Many past research used the multiple stress creep recovery test to evaluate the performance of polymer-modified binder, which indicates a stronger correlation with the rutting potential of asphalt than other characteristics [13, 30, 31]. The MSCR test offers valuable information about the properties of asphalt binders in terms of elastic response, rutting behaviour, and performance at high temperatures [32]. Previously [33], investigated the MSCR of Palm Oil Fuel Ash (POFA)-modified nanoclay asphalt binders, revealing improved rutting resistance and stiffness due to the synergistic effect of the nanomaterial reinforcement and the pozzolanic properties of POFA. Additionally [34], utilised the MSCR test and demonstrated enhanced fatigue resistance and reduced rutting susceptibility of asphalt binders incorporated with carbon nanotubes and POFA. These studies highlight the significance of the MSCR test in assessing the rheological properties of asphalt binders modified with nanomaterials and POFA, contributing valuable insights into their potential for sustainable and high-performance applications.

Despite the promising results obtained from previous studies, there remains a knowledge gap in understanding the combined effect of multiple waste materials, or "hybrid" modifiers, on both the rheological and rutting performance of asphalt binders. Most studies have focused on single waste material modifiers, overlooking the potential synergistic effects of hybrid combinations. This research aims to address this gap by investigating the rheological and rutting performance of hybrid asphalt binders modified with a combination of waste materials. By doing so, this study contributes to the ongoing efforts to develop more sustainable and high-performing asphalt pavements, while also providing new insights into the optimization of binder modification techniques. Additionally, it provides a workable solution for treating POFA, garnet waste, and sawdust, which are common waste materials in the industrial and agricultural sectors.

2 Materials and Methods

2.1 Materials

This study utilised asphalt 60/70 PEN (grade penetration). The basic performance indicators were measured according to the testing procedures for the asphalt mixtures for highway engineering. Table 1 presents the results of the basic performance of asphalt 60/70 PEN, along with their corresponding requirements. The penetration level was within the acceptable range of 60–70 dmm, indicating compliance, while the ductility result exceeded the requirement of ≥ 100 cm, indicating good ductile properties. Additionally, the viscosity at 135 °C was comfortably below the specified maximum of 3 Pa.s, which could be advantageous for certain applications. On a negative note, the softening point, at 47.6 °C, was slightly below the target range of 49–56 °C, suggesting that the material may be slightly softer than intended. Overall, the material generally complies with the standard requirements to perform this test.

This study focused on the utilisation of three distinct waste materials, as outlined in Table 2, to modify the physical properties of the asphalt binder. POFA and sawdust, categorised as agricultural wastes, were collected from a palm oil plantation in Kuantan, Pahang, Malaysia and a woodworking factory in Terengganu, Malaysia respectively. Meanwhile, garnet waste is a type of industrial waste sourced from a blasting pipe process in Terengganu, Malaysia. All collected samples were first crushed using the Los Angeles abrasion machine to break them into finer particles, then dry-sieved through a 25 µm sieve to obtain a uniform particle size. Notably, POFA exhibits fine particle size and a dark grey colour (Fig. 1a(a)), while garnet waste

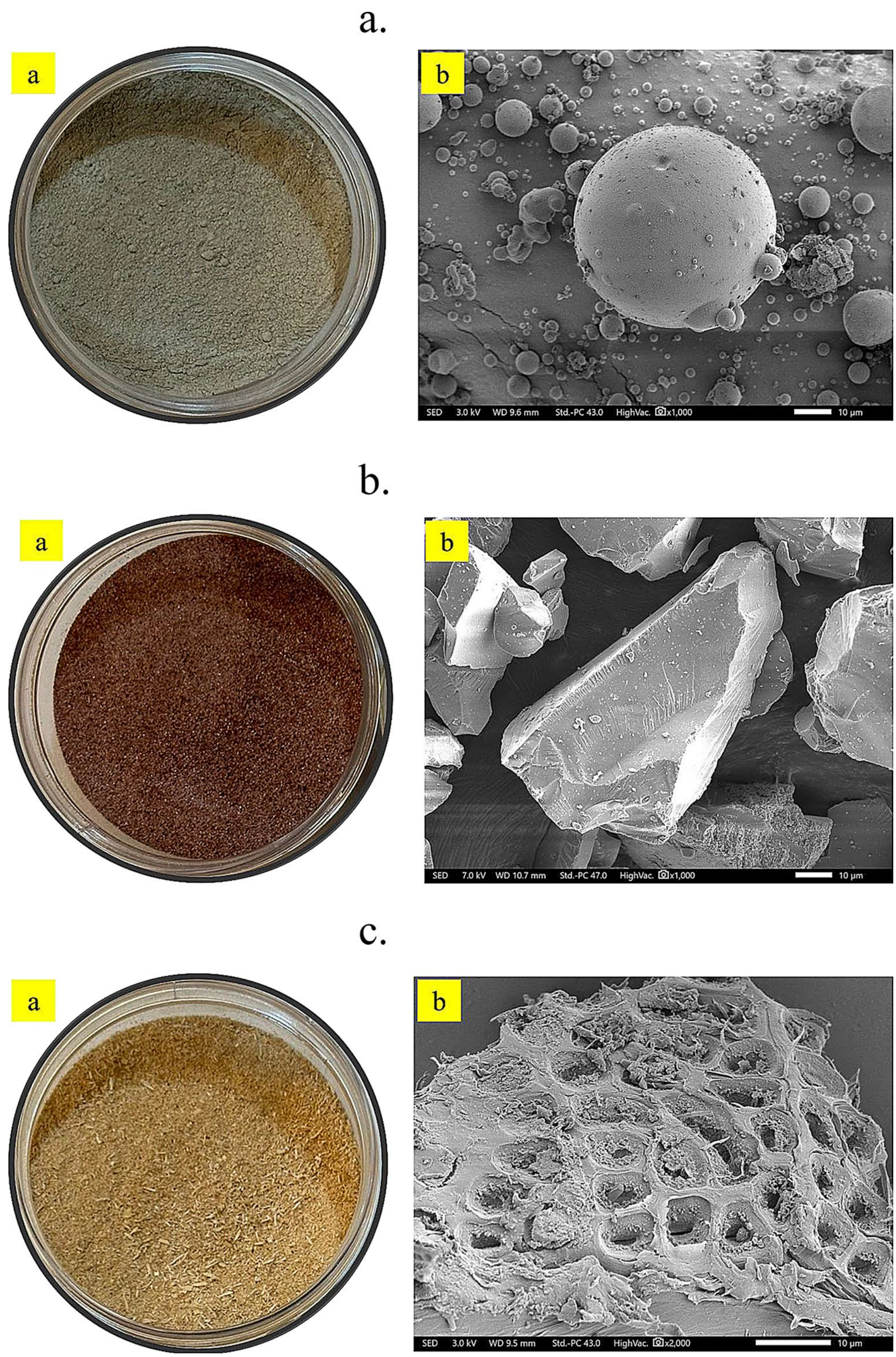

Fig. 1 **a**. Hybrid materials POFA in (a) raw form and (b) SEM images. **b**. Hybrid materials garnet waste in (a) raw form and (b) SEM images. **c.** Hybrid materials sawdust in (a) raw form and (b) SEM images

appears reddish grey (Fig. 1b(a)), and sawdust is characterised by its light brown colour (Fig. 1c(a)). Figures 1a(a), 1b(a), and 1c(a) shows the raw forms of the original waste hybrid materials used in this study. POFA exhibits a density and specific gravity of 2.51, while its moisture content is at 6.1%. Garnet waste boasts a higher density and specific gravity of 2.96 and 2.97, respectively, but a notably low moisture content of 0.4%. Conversely, sawdust displays a substantially lower density of 1.23 and a specific gravity of 0.26, with a considerably high moisture content of 5.02%. The modifiers used were to enhance the physical properties of asphalt by improving its stiffness, tensile strength, and resistance to deformation, contributing to a more durable and sustainable pavement structure.

Utilizing agricultural and industrial wastes such as sawdust, POFA, and garnet in asphalt mixtures offers significant cost savings, with studies indicating up to 30–50% reduction in material costs compared to conventional modifiers like SBS, primarily due to the local availability and low or zero acquisition costs of these wastes. Additionally, life cycle assessment (LCA) studies have shown that incorporating such waste materials can reduce the carbon footprint of asphalt production by 20–40%, as it minimizes the demand for virgin resources and lowers energy consumption associated with raw material processing.

2.2 Preparation of Individual-Modified and Hybrid Asphalt Binders

All three waste materials were first dried at 100 °C and sieved to obtain a uniform particle size of 25 µm. For this study, three main types of modified asphalt binders were prepared: individual-modified, unaged hybrid, and Rolling Thin Film Oven (RTFO) hybrid, as shown in Fig. 2a, b, and c, respectively. From Fig. 2a, every individual waste was chosen 3% contents by weight of asphalt and blending with conventional 60/70 PEN asphalt using high shear mixer. The blending process for the individual waste-modified using a high shear mixer at 1500 rpm and 160 °C for 1 h to achieve a homogenous asphalt blend [35]. The individual-modified asphalt binders comprised 3% of POFA-modified asphalt, 3% of garnet waste-modified asphalt, and 3% of sawdust-modified asphalt, respectively.

Furthermore, the unaged hybrid asphalt binders were prepared by mixing the three wastes at varying levels of 0%, 3%, 6%, and 9% (Fig. 2b). The unaged hybrid asphalt binders were produced via a wet blending process. Table 3 depicts the sample proportion of individual-modified asphalt binders and hybrid asphalt binders. The prefer proportion of the waste materials were based on the previous study using optimal individual waste [10, 36, 37]. The hybrid asphalt mixtures in Table 3 are composed of equal proportions of three waste materials: POFA, garnet waste, and sawdust, added by weight of the original asphalt binder. For the 3% hybrid asphalt mixture, the composition includes 3% POFA, 3% garnet waste, and 3% sawdust. Similarly, the 6% and 9% hybrid asphalt binders consist of 6% and 9% of each waste material respectively, ensuring a balanced integration of the waste materials in the asphalt mixture.

Since this study only focused on the effect of the short-term ageing process, the prepared unaged hybrid asphalt binders were subjected to the RTFO test, which simulates the short-term ageing process by heating the sample in an oven at 163 °C for 85 min (Fig. 2c). This test was performed according to the ASTM D2872 standard. Eight RTFO bottles were filled with 35 g of asphalt before the oven heating procedure. The carriage was rotated at 15 rpm with an airflow of 4000 mL/min into each bottle. The mass loss before and after the ageing conditions of the hybrid asphalt were recorded. The residual hybrid asphalt from the bottles was then transferred into another container for the DSR test.

3 Experimental Methods

3.1 Microscopic Test

3.1.1 X-Ray Fluorescence (XRF)

The XRF used to evaluate the elemental composition of hybrid materials and also used to identify and quantify the elements present in a sample by measuring the fluorescent X-ray emitted from a hybrid material when it is excited by a primary X-ray source The XRF test was conducted using Epsilon 1 PANalytical instrument. These samples were prepared into circular pellets using a hydraulic press for 10 s while applying a load of 20 t with each sample comprised 10 g of waste material in the form of dry powder, and the XRF analysis was conducted and analysed following the British Standard European Standard International Organization for Standardization (BS EN ISO 12677). Moreover, a custom-made X-ray tube with a silver (Ag) anode source (functioning at 50 kV) was used. Lastly, the samples and their corresponding elements were identified based on the unique XRF emitted by the sample when exposed to X-rays.

3.1.2 Scanning Emission Microscopy (SEM)

SEM used to examine the microstructure of hybrid materials. JSM IT-200 instrument was used to analyse the morphology, chemical composition, crystalline structure, and orientation of the samples. The instrument involved a concentrated high-energy electron beam, which caused the surfaces of the materials to generate numerous signals. Furthermore, the height offset was calibrated to handle tall samples before the sample loading process. Each of these samples necessitated a maximum diameter of 150 mm and a height of 48 mm. The procedure of evacuating the chamber was initiated after acquiring the holder graphics. This process entailed completing the designated observation area, condition settings, and image adjustments. The ranged from × 5 to × 300,000 of image magnification, depending on the accelerating voltage from 0.5 kV to 30 kV. Consequently, the SEM results were obtained for the individual waste materials and 0%, 3%, 6%, and 9% of hybrid asphalt binder mixtures.

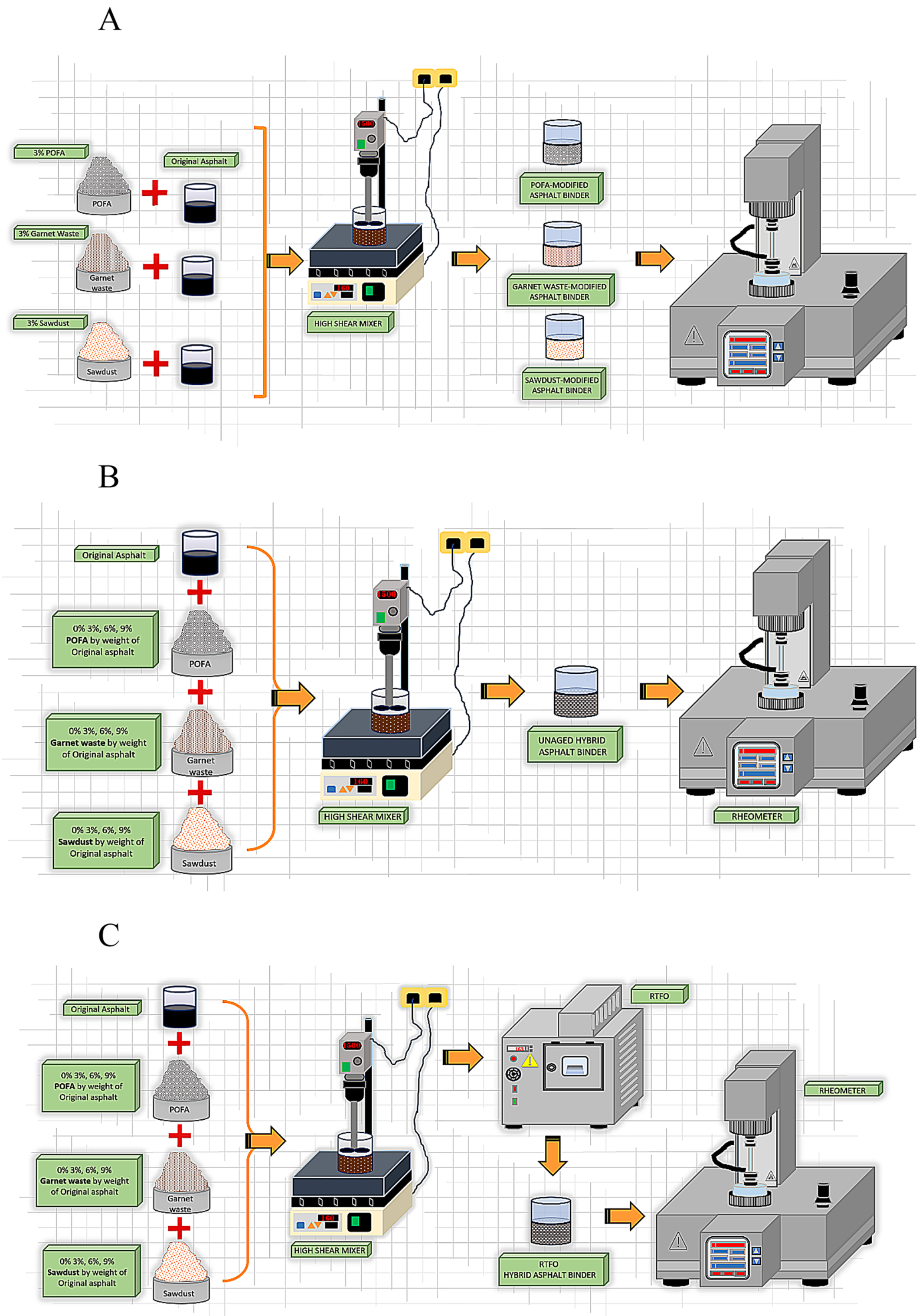

Fig. 2 **a**. Blending process of individual-modified asphalt binders for the DSR test. **b**. Blending process of unaged hybrid asphalt binders for the DSR test. **c**. Blending process of RTFO hybrid asphalt binders for the DSR test

Table 3 Proportion of samples

Waste materials	POFA	Garnet waste	Saw-dust
	Individual-modified asphalt binders		
POFA-modified asphalt binders	3%	-	-
Garnet waste-modified asphalt binders	-	3%	
Sawdust-modified asphalt binders	-	-	3%
	Hybrid asphalt binders		
0% Hybrid asphalt binders	0%	0%	0%
3% Hybrid asphalt binders	3%	3%	3%
6% Hybrid asphalt binders	6%	6%	6%
9% Hybrid asphalt binders	9%	9%	9%

3.1.3 Atomic Force Microscopy (AFM)

The surface topography image was acquired through interaction measurement between a sharp tip and the scanned surface of the cantilever. This technique was performed with the tapping mode in the JPK Nanowizard tool, which provided safeguards against potential harm to the sample. A rectangular silicon tip was utilised in the tapping mode at 27 °C. This study employed a cantilever with a spring constant of 40 N/m, a thickness of 4 µm, a length of 125 µm, and a width of 30 µm with every sample scan involved a scan size of 20 µm × 20 µm.

3.2 Dynamic Shear Rheometer (DSR) Test

The DSR test was employed to understand the rheological characteristics of the individual and hybrid asphalt binders by measuring the strain resulting from applying oscillatory shear stress on the samples. The test was assessed using a Rheometer MCR 302e instrument, as depicted in Fig. 3a. The tool used active thermal management of the motor and bearing at high torques up to 230 mNm. Figure 3b shows the hybrid asphalt binder sample placed on the fixed plate and controlled by the oscillating plate for the temperature sensor before the trimming process. The samples were trimmed slightly larger gap than the test gap to create a bulge after trimming.

The American association of state highway and transportation officials (AASTHO T315) specifies the standard protocols and evaluation standards for the DSR test. This standard offers a solid structure to guarantee that the DSR tests are performed and interpreted uniformly across various labs and research environments. The following sections describe the frequency sweep test and MSCR test to analyse the prepared modified asphalt binders.

3.2.1 Frequency Sweep Test

The hybrid asphalt binder underwent a 0.1–100 rad/s frequency sweep test, with a temperature range from 10 °C to 70 °C at a 10 °C increment. Two vital parameters that characterise the viscoelastic properties of the asphalt samples, namely the phase angle, δ, and complex shear modulus, G*, were then calculated. The William Landel Ferry (WLF) Eq. (1) was used to shift the observed G* and δ into the master curve against the decreasing frequency in accordance with the time-temperature superposition theory.

$$\log(a_T) = \frac{-C_1(T - T_0)}{(C_2 + T - T_0)} \quad (1)$$

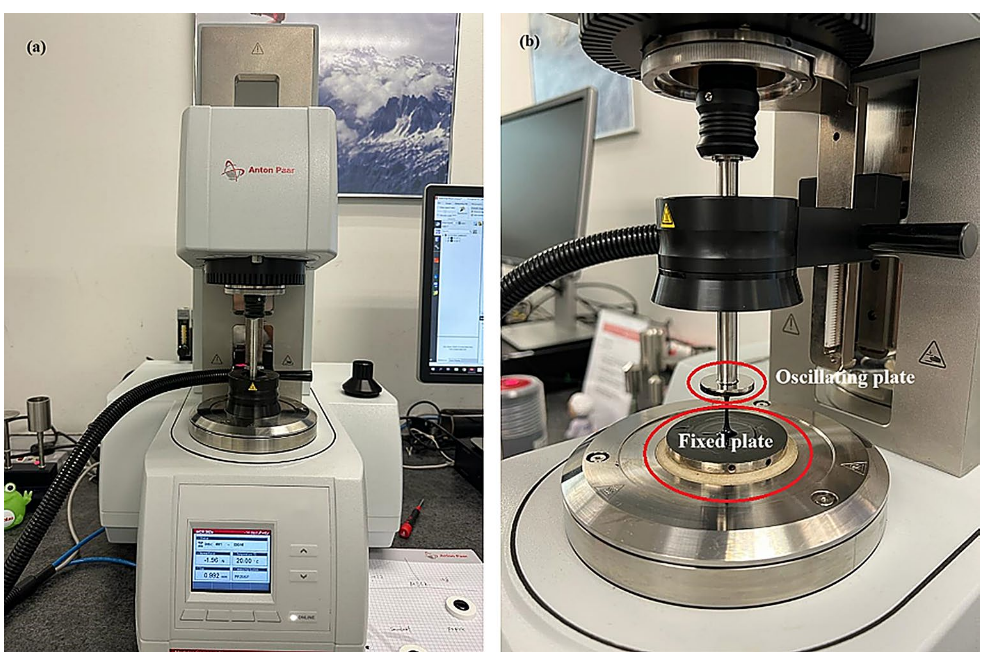

Fig. 3 (**a**) Rheometer MCR 302e. (**b**) Loaded hybrid asphalt binder sample

where αT refers to superposition parameter, C_1 denotes Constant 1, T represents temperature, C_2 is empirical constants, and T_0 is the reference temperature.

3.2.2 Multiple Stress Creep Recovery (MSCR) Test

The MSCR test was conducted to determine the influence of waste materials on the performance of the individual-modified and hybrid asphalt binders at high temperatures before and after the short-term ageing according to the AASHTO T350 standard. The test involved the individual-modified (POFA, garnet waste, and sawdust) asphalt binders at 3% and unaged and RTFO hybrid asphalt binders at 0%, 3%, 6%, and 9%. The test temperatures were set at 40 °C, 50 °C, 60 °C, 70 °C, and 80 °C, which reflect the normal temperature range of the pavement surface layer in Malaysia. Firstly, the short-term ageing of the asphalt sample was simulated using the RTFO test at 163 °C for 85 min. Subsequently, the RTFO sample (dimension: 8 mm diameter, 2 mm gap) was subjected to stress loads of 0.1 kPa and 3.2 kPa for 1 s, followed by a rest period of 9 s at 64 °C for a total of 10 cycles. The recovery percentage (R%), non-recoverable creep compliance (J_{nr}), and the percentage difference in non-recoverable creep compliance (J_{nrdiff}) were determined from the MSCR results. Equations (2) and (3) describe the R% and J_{nr}:

$$R = \frac{\epsilon p - \epsilon u}{\epsilon p} x\ 100\% \tag{2}$$

$$J_{nr} = \frac{\epsilon u}{\sigma} \tag{3}$$

where εp stands for the maximum strain, εu refers to the uncovered strain, and σ describes stress level. The stress sensitivity parameters at 0.1 kPa ($R_{0.1}$) and 3.2 kPa ($R_{3.2}$) were expressed as R_{diff} and J_{nrdiff} and were determined using Eqs. (4) and (5), respectively:

$$R_{diff} = \frac{R_{0.1} - R_{3.2}}{R_{0.1}} x\ 100\% \tag{4}$$

$$J_{nrdiff} = \frac{j_{nr3.2} - J_{nr0.1}}{J_{nr3.2}} x\ 100\% \tag{5}$$

Figure 4 illustrates the overall flow of the experimental design to achieve the above objectives of this study.

4 Results and Discussion

Significant differences were observed in terms of the performance between the individual-modified asphalt binders (POFA, garnet waste, and sawdust), unaged hybrid asphalt binders, and RTFO hybrid asphalt binders. The results of microscopic analysis using XRF, SEM and AFM were presented in Table 4; Figs. 5 and 6. Furthermore, Figs. 7, 8 and 9 present the detailed rheological performance of the various asphalt samples under the temperature sweep evaluation, while Figs. 10, 11, 12, 13 and 14 discuss the MSCR results while comparing them to the engineering properties.

4.1 Microscopic Analysis

4.1.1 XRF Analysis

The XRF analysis in Table 4 indicates the chemical composition of each waste, which consists of various oxides (SiO_2, Fe_2O_3, CaO, Al_2O_3, K_2O, MgO, P_2O_5, and SO_3) as a percentage of the total composition [38]. Of particular note are

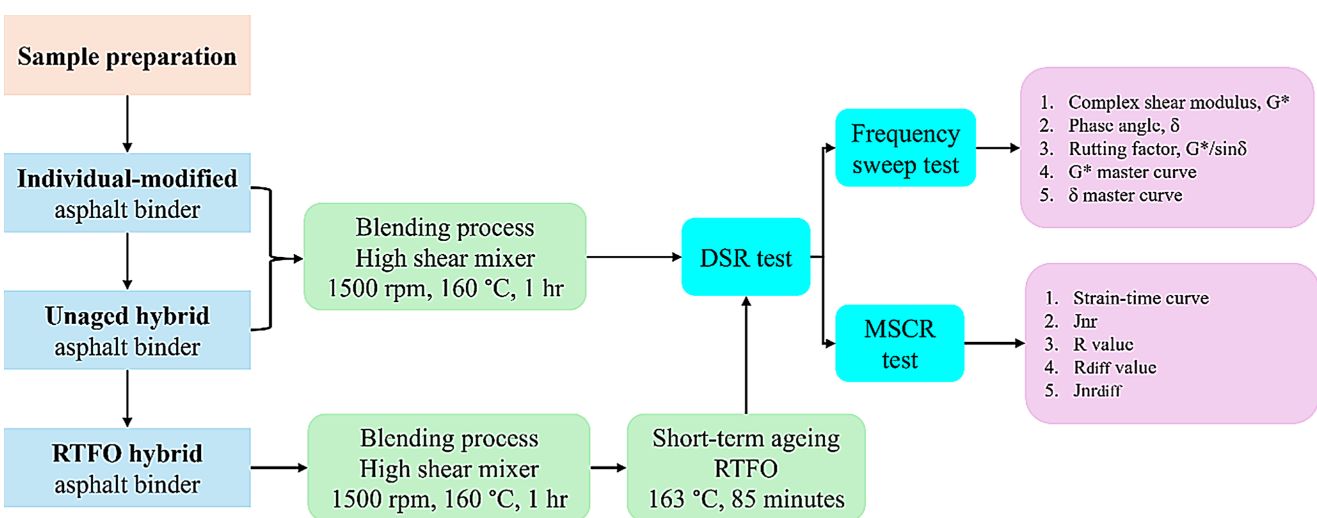

Fig. 4 The overall experimental design of this study

Table 4 Chemical compositions of hybrid materials

Chemical compounds	POFA (%)	Garnet waste (%)	Sawdust (%)
Silicon dioxide (SiO_2)	62.81	27.13	4.61
Iron oxide (Fe_2O_3)	4.77	44.97	3.08
Calcium oxide (CaO)	2.99	1.89	69.65
Aluminium oxide (Al_2O_3)	23.92	17.73	0.00
Potassium oxide (K_2O)	1.80	0.01	6.83
Magnesium oxide (MgO)	0.69	4.90	0.00
Phosphorus pentoxide (P_2O_5)	0.79	0.41	2.96
Sulphur trioxide (SO_3)	0.23	0.06	1.64
Loss of ignition (LOI)	2.00	2.90	11.23

the highest oxide compositions, with POFA having the highest SiO_2 content at 62.81%, while garnet waste contains the highest Fe_2O_3 content at 44.97%, and sawdust boasting the highest CaO content at 69.65%. These compositional differences highlight the potential use of the hybrid asphalt binder for diverse applications.

4.1.2 SEM Analysis

Figure 5 depicts the morphological images of 0%, 3%, 6%, and 9% hybrid asphalt binder. Meanwhile, in previous Sect. [2.1 Materials], Figs. 1a(b), b(b), and c(b) were the individual SEM images in magnification of 10 µm. Compared to the hybrid asphalt binder, the surface of the aggregates exhibited noticeable voids and gaps. Improper bonding between the particles because of the irregular surface textures was also presented due to the inadequate coating application and the prominent unevenness of the surface. Given that no discernible gaps between the aggregates were recorded after the modification process, the voids generated smaller sizes and produced a compact surface. Consequently, the 6% hybrid asphalt binder demonstrated improved material bonding of the POFA, garnet waste, and sawdust components compared to the control sample. A significant surface exposure was also presented due to the extensive surface area of this binder. The particles in the 6% hybrid asphalt binder were uniformly distributed, establishing a cohesive bond among the constituents. This finding improved the bonding characteristics of the 6% hybrid asphalt binder mixture. It can be concluded; the enhanced bonding of the 6% hybrid asphalt binder produced a gap-filling and homogeneous coating which presented greater strength of the hybrid asphalt binder.

The SEM images of the individual waste materials POFA, garnet waste, and sawdust highlight distinct structural characteristics that influence the overall performance of the modified asphalt binder. POFA, with its bonded cloud of smoke and porous surface, enhances the binder's absorption and distribution properties, improving the interaction between the waste material and asphalt matrix. Garnet waste and sawdust, with their irregular shapes and rough surfaces, contribute to better mechanical interlocking within the binder, increasing its stiffness and resistance to deformation.

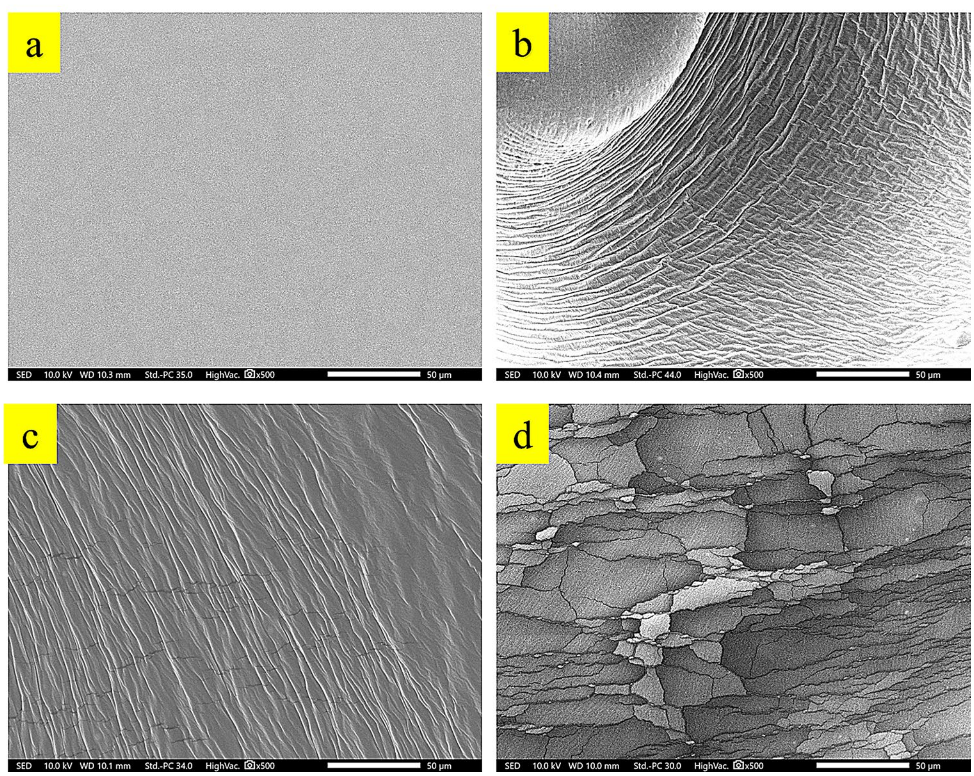

Fig. 5 The SEM images of hybrid asphalt binder (**a**) 0%, (**b**) 3%, (**c**) 6%, and (**d**) 9%

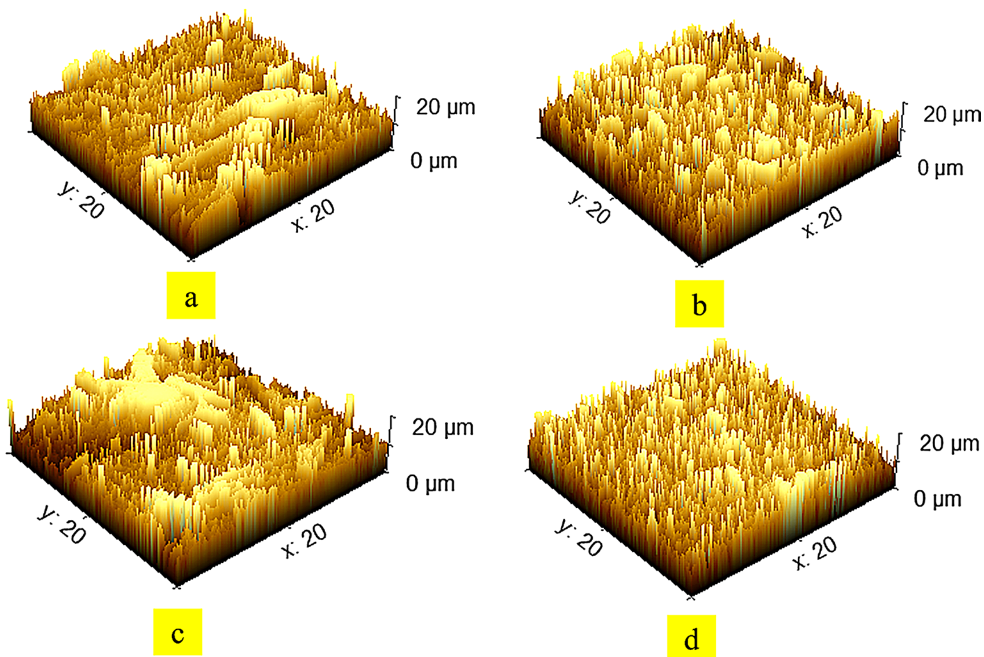

Fig. 6 The AFM images of hybrid asphalt binder (**a**) 0%, (**b**) 3%, (**c**) 6%, and (**d**) 9%

In particular, the 6% hybrid asphalt binder, which demonstrated superior material bonding, benefits from the optimal balance of these modifiers. The porous structure of POFA facilitates enhanced binder cohesion, while the rough, irregular surfaces of garnet waste and sawdust improve the mechanical strength and load-bearing capacity. This synergy at 6% hybrid content results in an optimal blend, contributing to a more resilient asphalt mixture, compared to the 0%, 3%, and 9% hybrid binders.

4.1.3 AFM Analysis

An AFM instrument was used to analyse the topographical features of the hybrid asphalt binders. This study evaluated the surface roughness of the 0%, 3%, 6%, and 9% hybrid asphalt binders by scanning 20 µm × 20 µm areas. Consequently, the hybrid asphalt binder topographies consisted of three unique phases: the bee structure (catana phase), the scattered domain (dark region or peri phase), and the flat matrix (light region or para phase) [39, 40]. Figure 6 depicts the phase images of the 0%, 3%, 6%, and 9% hybrid asphalt binders. These images showcased a clear structural arrangement resembling a bee structure or catana phase dispersed within the matrix. Compared to 0%, the bee structures of the 3%, 6%, and 9% hybrid asphalt binders were redesigned and downsized. The 6% hybrid asphalt binder also acquired a higher dispersed phase. This observation was attributed to a chemical interaction between the constituent materials and the asphalt component, resulting in the elastomeric material swelling and altering the elastic characteristics of the entire bituminous matrix. The distributions of dark region zones in the 3%, 6%, and 9% hybrid asphalt binder were also inconsistent. Conversely, the control asphalt demonstrated constant dispersion, proving the consistent distribution of hybrid asphalt in the asphalt binders. Meanwhile, the AFM analysis at 6% hybrid asphalt binder revealed a more pronounced dispersed phase, with increased particle interactions that enhanced interfacial forces. This led to a noticeable decrease in surface roughness, contributing to the improved performance of the binder. Conversely, study from [41] found that alkane acids accumulate at the bitumen–silica interface, negatively impacting adhesion under wet conditions, while mineral powders like silica or alumina reduce this accumulation, unlike dry calcium carbonate, which proved ineffective.

Table 5 displays the average roughness (Ra), root means square roughness (Rq), and total roughness (Rt) for the 0%, 3%, 6%, and 9% hybrid asphalt mixtures. The Ra parameter is commonly employed in surface roughness analysis for providing value without considering the individual peaks and valleys. On the contrary, the Rq parameter is more susceptible to peak and valley fluctuations. Similarly, the total vertical separation between peaks and valleys is expressed as Rt. Overall, the Ra, Rq, and Rt values of the 3%, 6%, and 9% hybrid asphalt mixtures were comparatively lower than the control asphalt. A downward trend was initially observed until the 6% hybrid asphalt mixture, followed by an upward trend until the 9% hybrid asphalt mixture. Therefore, the 6% hybrid asphalt mixture demonstrated the lowest surface roughness than the other samples. Moreover, the decrease of bee structures and the homogenous peri phase region in the

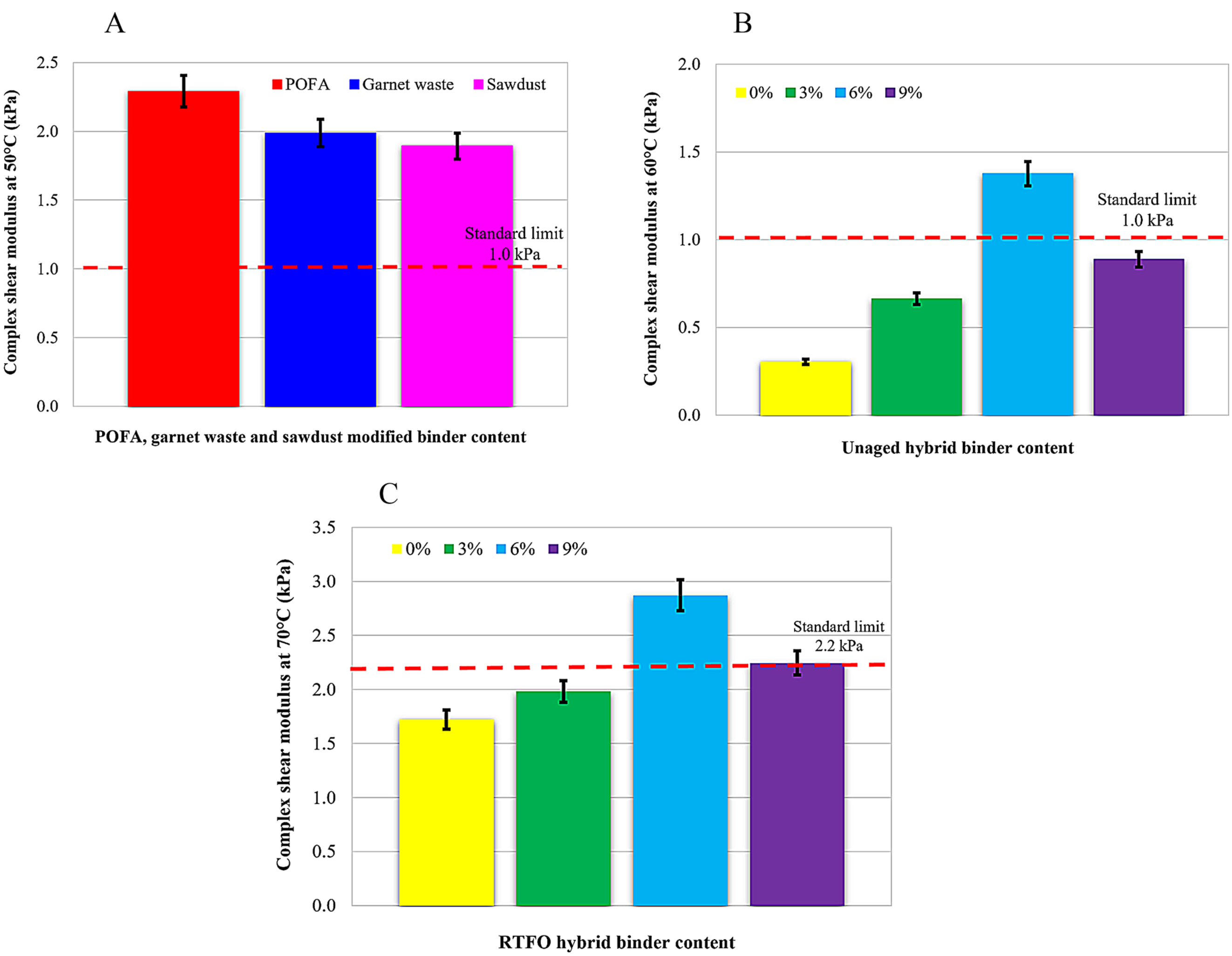

Fig. 7 **a**. Complex shear modulus of the 3% POFA-, 3% garnet waste-, and 3% sawdust-modified asphalt binders. **b**. Complex shear modulus of the 0%, 3%, 6%, and 9% unaged hybrid asphalt binders. **c**. Complex shear modulus of the 0%, 3%, 6%, and 9% RTFO hybrid asphalt binders

6% hybrid asphalt mixture increased the smoothness of the hybrid asphalt surface.

The hybrid materials (POFA, garnet waste, and sawdust) were evenly distributed within the hybrid asphalt matrix, facilitating effective adhesion between the hybrid materials and the asphalt matrix. This dispersion consistency resulted in better interfacial bonding between the hybrid materials and aggregates within the hybrid asphalt mixture. The surface roughness analysis in the stability test revealed that the 6% hybrid asphalt mixture exhibited maximum strength, indicating improved adhesion between the hybrid asphalt mixture and the aggregate.

4.2 Frequency Sweep Evaluation

4.2.1 Complex Shear Modulus, G*

Figure 7a, b, and c portray the complex shear modulus, G*, of the individual-modified (POFA, garnet waste, and sawdust) asphalt binders and the 0%, 3%, 6%, and 9% unaged hybrid and RTFO hybrid asphalt binders, respectively.

As shown in Fig. 7a, for individual waste-modified binders, the G* values indicate that POFA-modified asphalt exhibits the highest modulus at 2.2912 at 50 °C, followed by garnet waste and sawdust with values of 1.9865 and 1.8926, respectively. All three waste-modified binders demonstrate superior G* values compared to the standard binder, suggesting that the inclusion of waste materials enhances the stiffness and elasticity of the binder at this temperature, particularly for POFA. Based on the AASHTO M320/322 specification, the failure temperature for the unaged modified

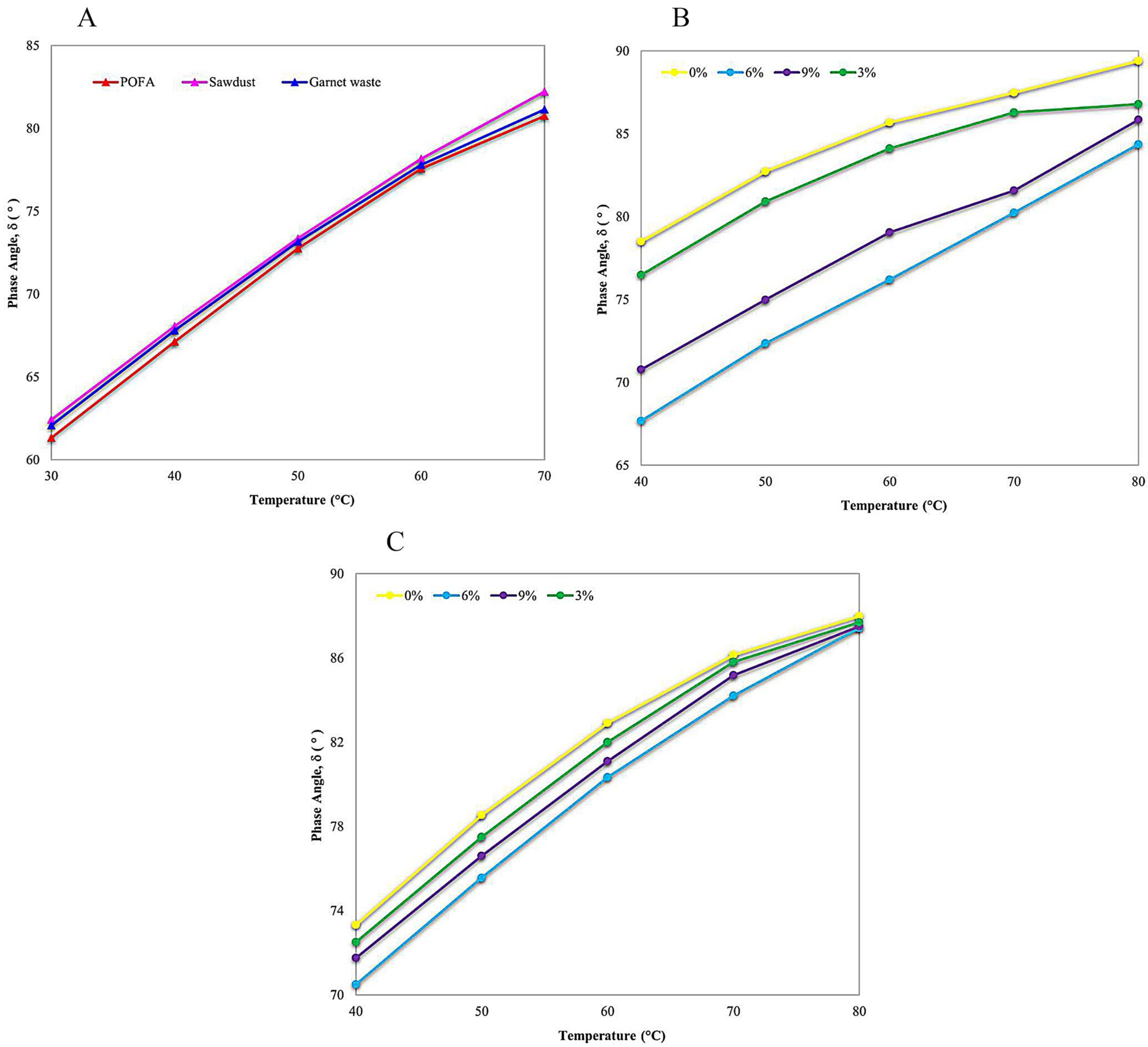

Fig. 8 **a**. Phase angle of the 3% POFA-, 3% garnet waste-, and 3% sawdust-modified asphalt binders. **b**. Phase angle of the 0%, 3%, 6%, and 9% unaged hybrid asphalt binders. **c**. Phase angle of the 0%, 3%, 6%, and 9% RTFO hybrid asphalt binders

asphalt binder is 1.0 kPa. Another possibility of the result is due to the high silica content in POFA compared to garnet waste and sawdust [42].

In the case of hybrid asphalt binders at 60 °C, the G* values increase as the hybrid content rises from 0 to 6%, with the maximum G* observed at 6% hybrid content (1.3761). However, the G* decreases slightly at 9% (0.8876), yet remains above the standard value of 1 for the 3% and 6% mixtures. This suggests that 6% hybrid asphalt provides the optimal balance between binder stiffness and elasticity at this temperature, enhancing the mechanical properties of the binder due to the combined hybrid content that contained higher SiO_2, Fe_2O_3, and CaO reactions in the samples. Beyond 6%, there may be diminishing returns in terms of G*, as indicated by the drop of 35% after the hybrid content was increased to 9%.

For RTFO-aged hybrid asphalt binders at 70 °C, the G* values continue to show an upward trend, with the 6% hybrid asphalt binder again performing best, with a modulus of 2.8711, far surpassing the standard value of 2.2 (Fig. 7c). The 9% hybrid asphalt binder also exceeds the standard, with a G* value of 2.2459, indicating that aging through RTFO further enhances the stiffness of the hybrid binders. The results suggest that hybrid asphalt mixtures, particularly those with 6% content, maintain superior mechanical

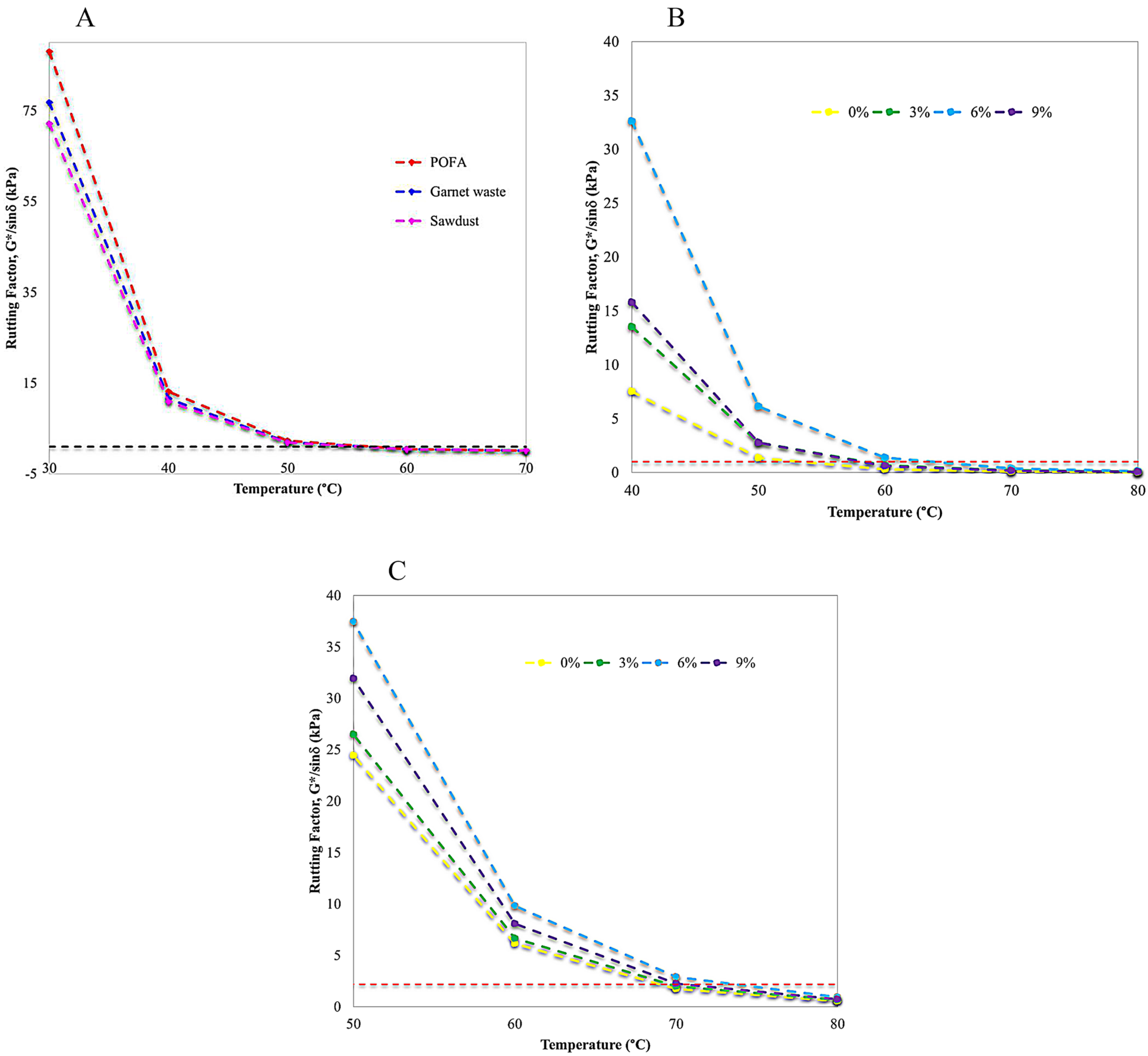

Fig. 9 **a**. Rutting factor of the 3% POFA-, 3% garnet waste-, and 3% sawdust-modified asphalt binders. **b**. Rutting factor of the 0%, 3%, 6%, and 9% unaged hybrid asphalt binders. **c**. Rutting factor of the 0%, 3%, 6%, and 9% RTFO hybrid asphalt binders

performance even after simulated aging, with significant resistance to deformation under high temperatures.

Incorporating POFA, garnet waste, and sawdust into the asphalt mixture enhanced the failure temperature from 50 °C for the individual-modified asphalt binders to 60 °C for the unaged hybrid asphalt binder and 70 °C for the RTFO hybrid asphalt binder. The improvement leads to better resistance performance against permanent deformation, as reflected in the shear strain energy when loading is applied compared to the control sample. The results indicate that the hybrid content increased the stiffness of the asphalt binder, making it more deformation resistant.

4.2.2 Phase angle,δ

The phase angle, δ, which is strongly influenced by temperature and loading frequency, is described as the interval between strain and stress under traffic loading. Specifically, the δ indicates the level of viscoelasticity in the asphalt binder. The temperature sweep test results for the phase angle of the 3% individual-modified (POFA, garnet waste, and sawdust) asphalt binders and the 0%, 3%, 6%, and 9% unaged hybrid and RTFO hybrid asphalt binders are presented in Fig. 8a, b, and c, respectively. Figure 8a shows a similar trend of the phase angle between the POFA-, garnet waste-, and sawdust-modified asphalt binders. The small

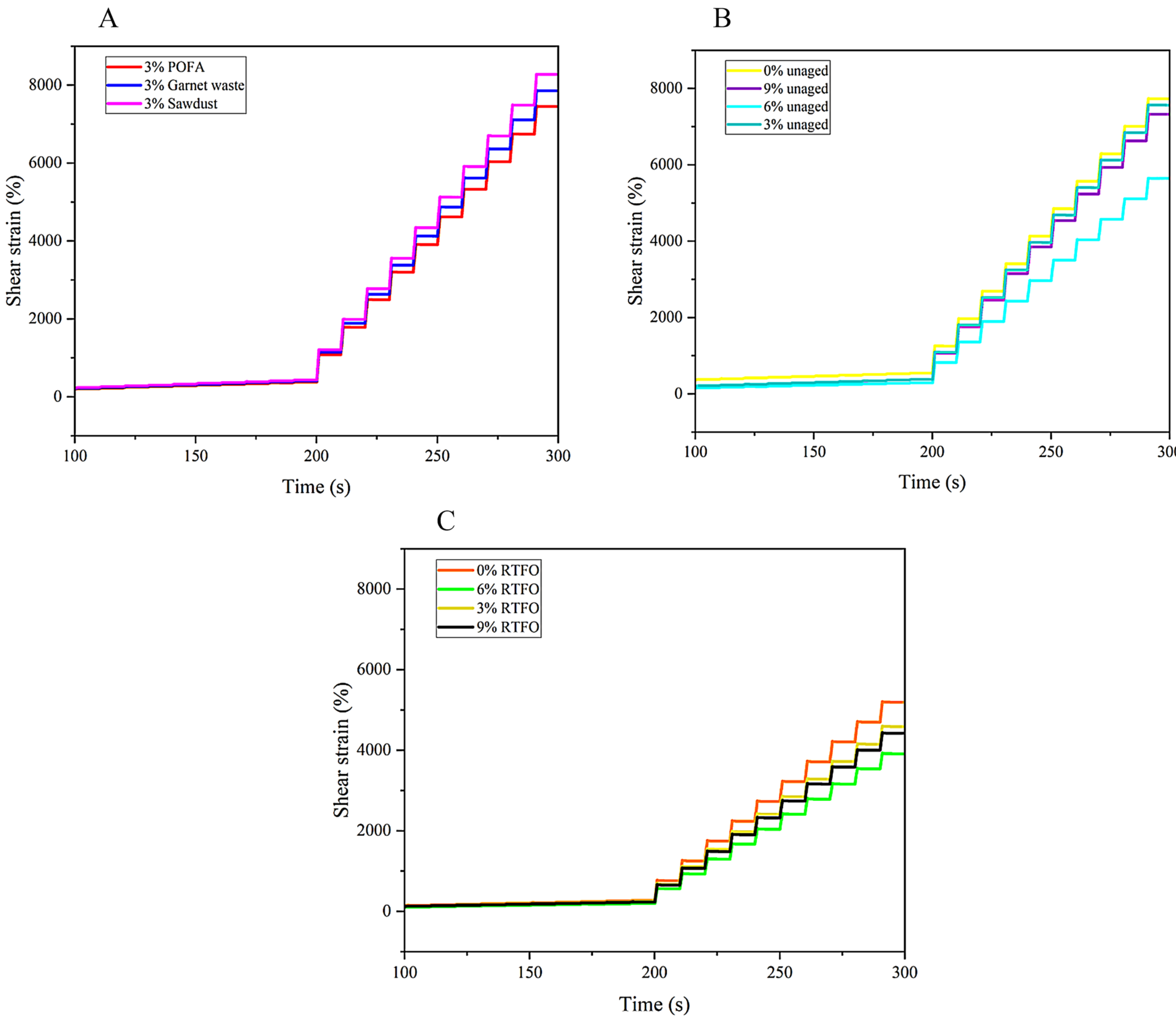

Fig. 10 **a**. MSC R strain curve of the 3% POFA-, 3% garnet waste-, and 3% sawdust-modified asphalt binders. **b**. MSCR strain curve of the 0%, 3%, 6%, and 9% unaged hybrid asphalt binders. **c**. MSCR strain curve of the 0%, 3%, 6%, and 9% RTFO hybrid asphalt binders

phase angle indicates that the individual-modified asphalt binders have a high elastic recovery to resist permanent deformation. Comparatively, the POFA-modified asphalt binder had better resistance to permanent deformation than garnet waste- and sawdust-modified asphalt binders. The δ also increased linearly as the temperature increased from 30 °C to 70 °C. Based on Fig. 8a, the 3% POFA-modified asphalt binder exhibited the lowest δ values of 61.3°, 67.1°, 72.8°, 77.6°, and 80.7° as the failure temperature increased every 10% from 30 °C to 70 °C, respectively, compared to the 3% garnet- and sawdust-modified asphalt binders. The finding demonstrates that the 3% POFA-modified asphalt binder performed better at high temperatures while also behaving close to an ideal binder. Furthermore, a smaller δ value indicates a greatly improved elasticity recovery of the binder [43]. The rising elasticity characteristics due to the reduced phase angle enhanced the phase angle, thereby increasing the rutting resistance of the POFA-modified asphalt binder compared to the other two individual-modified asphalt binders. As shown in Fig. 8b, the phase angle of the unaged hybrid asphalt binders increased with an increase in temperature. Compared to the 0%, 3%, and 9% unaged hybrid asphalt binders, the 6% unaged hybrid asphalt binder recorded the lowest phase angle values of 67.7°, 77.4°, 76.22°, 80.2°, and 84.4° at failure temperatures of 40, 50, 60, 70, and 80 °C, respectively. Although the phase angle of each unaged hybrid asphalt binder gradually increased, a significant spike in the phase angle was recorded for the 6% unaged hybrid asphalt binder. Fig. 8c illustrates the phase angle of the RTFO hybrid modified binders, which

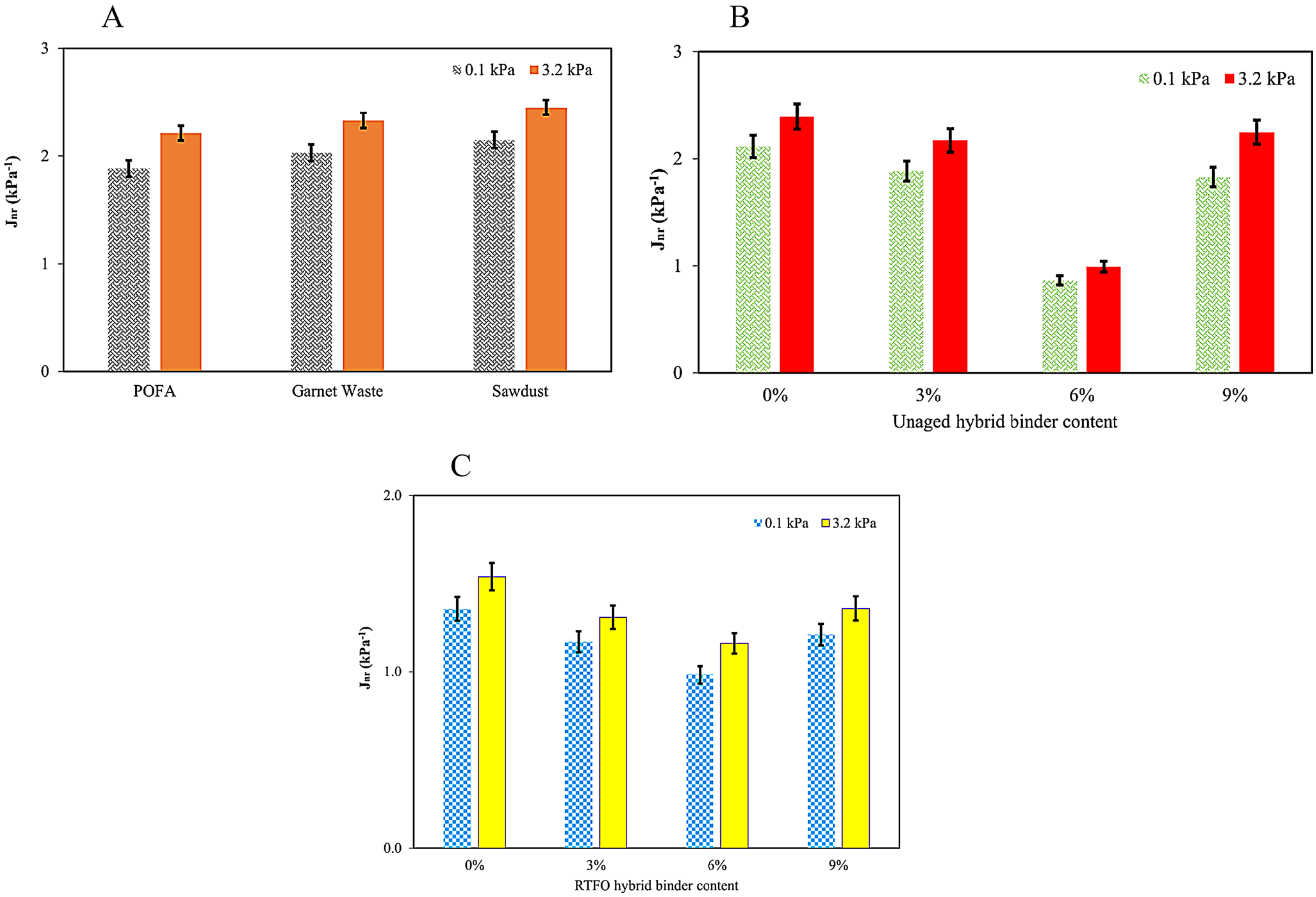

Fig. 11 **a.** The J_{nr} value of the 3% POFA-, 3% garnet waste-, and 3% sawdust-modified asphalt binders at 64°C. **b**. The J_{nr} value of the 0%, 3%, 6%, and 9% unaged hybrid asphalt binders at 64°C. **c**. The J_{nr} value of the 0%, 3%, 6%, and 9% RTFO hybrid asphalt binders at 64°C

showed a similar trend with unaged hybrid asphalt binders. Based on the graph, the linear increase in d corresponds to the rise in the test temperature. In addition, all d values of the RTFO hybrid asphalt binders demonstrate lower d compared to the control sample. In fact, the 6% RTFO hybrid asphalt binder showed the lowest d of 70.5°, 75.6°, 80.3°, 86.2°, and 87.4° at failure temperatures of 40, 50, 60, 70 and 80°C, respectively, compared to the 3% and 9% RTFO hybrid asphalt binders. Consequently, the 6% RTFO hybrid asphalt binders stiffened during the ageing process, altering their physical properties from viscous to elastic compared to those of unaged hybrid asphalt binders. It can be summarised that the RTFO hybrid asphalt binders exhibited higher stiffness, suggesting an increase in elastic characteristics, which enhanced the rutting resistance to achieve recoverable deformation. The effect of dosages in the phase angle behavior can be attributed to the interaction between the waste materials and the asphalt binder. As the dosage of hybrid materials, such as POFA, garnet waste, and sawdust, increases, the stiffness of the asphalt mixture changes due to the different physical characteristics of each modifier. At lower dosages, the binder remains more flexible, leading to a lower phase angle, while higher dosages particularly at 6% promote better material bonding, which reduces the viscoelastic response and increases the mixture's stiffness. This shift in stiffness and elasticity explains the observed trends in the phase angle across varying dosages. temperature increase

4.2.3 Rutting Factor, G*/sinδ

Figure 9a, b and c show the rutting resistance of the 3% individual-modified (POFA, garnet waste, and sawdust) asphalt binders and the 0%, 3%, 6%, and 9% unaged hybrid and RTFO hybrid asphalt binders, respectively. Figure 9a depicts a decreasing trend of the rutting factor of the 3% POFA-, 3% garnet waste-, and 3% sawdust-modified asphalt binders for every 10% temperature increase from 30 °C to 70 °C. Although the 3% POFA-modified asphalt binder recorded the highest G*/sin δ than garnet waste- and sawdust-modified asphalt binders, all three modified asphalt binders recorded a rutting factor above 1.0 kPa at 57 °C, 56 °C, and 55 °C, respectively, which agrees with the standard applied strain and passing criteria for the original

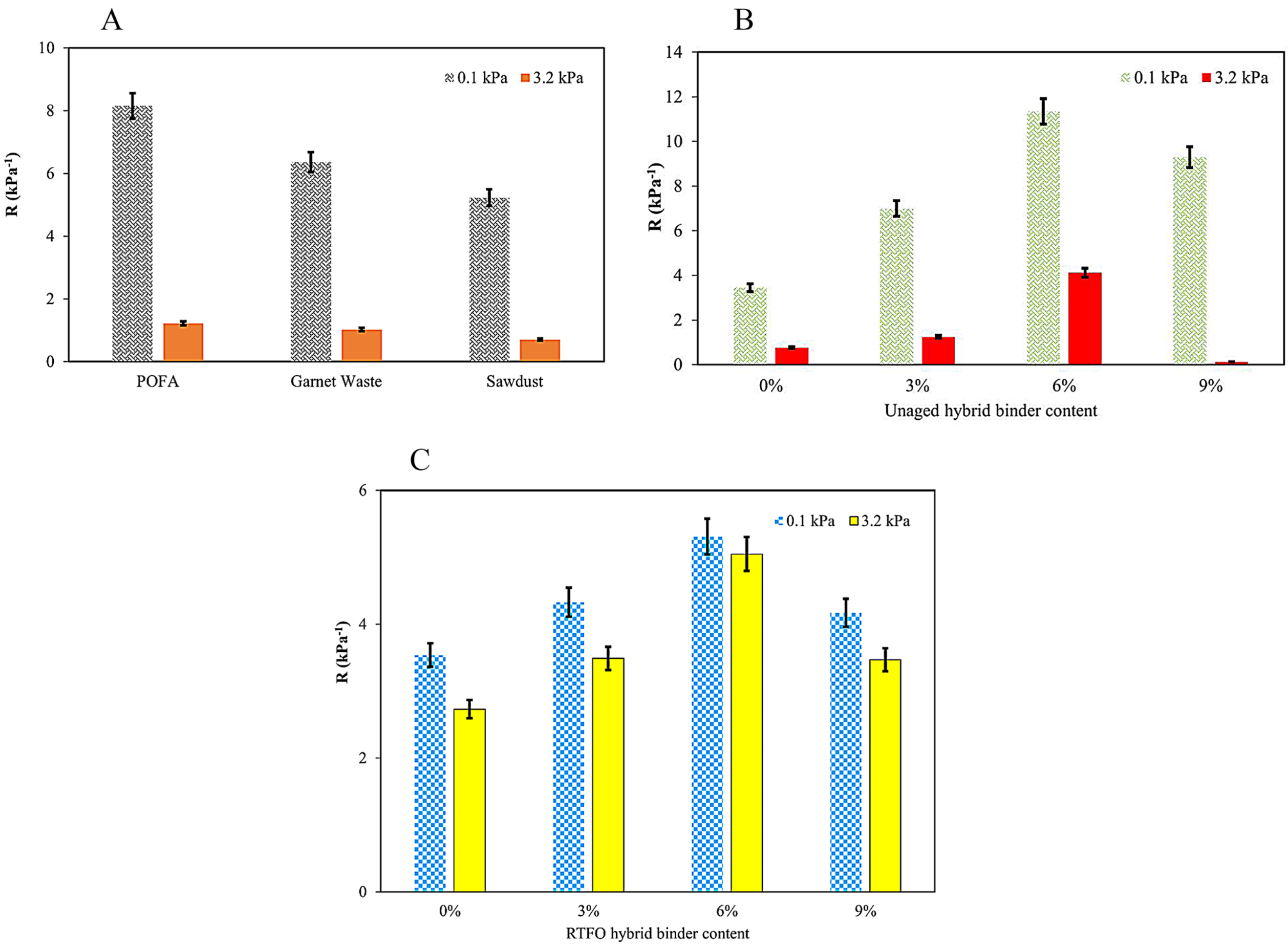

Fig. 12 **a**. The R-value of the 3% POFA-, 3% garnet waste-, and 3% sawdust-modified asphalt binders at 64 °C. **b**. The R-value of the 0%, 3%, 6%, and 9% unaged hybrid asphalt binders at 64 °C. **c**. The R-value of the 0%, 3%, 6%, and 9% RTFO hybrid asphalt binders at 64 °C

binder of G*/sin δ at ≥ 1.0 kPa. In other words, the highly viscous individually-modified asphalt binders achieved significant improvement at high-temperature conditions. Overall, the POFA-modified asphalt binder recorded the best performing individual-modified asphalt binder, followed by garnet waste-modified asphalt binder and sawdust-modified asphalt binder. Figure 9b illustrates the rutting factor of the 0% (control), 3%, 6%, and 9% unaged hybrid asphalt binders. The increasing temperature rapidly reduced the rutting factor of the unaged hybrid asphalt binders. Moreover, when the temperature exceeds 64 °C, the 6% unaged hybrid asphalt binder achieved a significantly improved rutting resistance, which is higher than the control sample and superior high-temperature deformation resistance than the other unaged hybrid asphalt binders. The decrease in rutting factor at 9% dosage may be due to an excess of modifier material, which can lead to reduced binder stiffness, causing a loss of resistance to permanent deformation. The similar rutting factors for 9% and 3% samples above 50 °C suggest that at higher temperatures, the excessive modifier content in the 9% dosage reduces the binder's ability to withstand high-temperature conditions, aligning its performance with the lower 3% dosage. In Fig. 9c, the RTFO hybrid asphalt binders demonstrate a higher temperature reading at 70 °C, which met the criteria of G*/sin δ at 2.2 kPa. Based on the ASTM D7175 and BS EN 14,770 standards, the RTFO hybrid asphalt binders exhibit improved permanent deformation resistance at elevated temperatures and reduced susceptibility to rutting compared to the control sample. Ageing causes the mechanical properties of the modified binders to become harder, leading to higher stiffness that can withstand permanent deformation. Thus, previous study also confirm that the ageing process resulted in a higher rutting resistance than in unaged conditions [44].

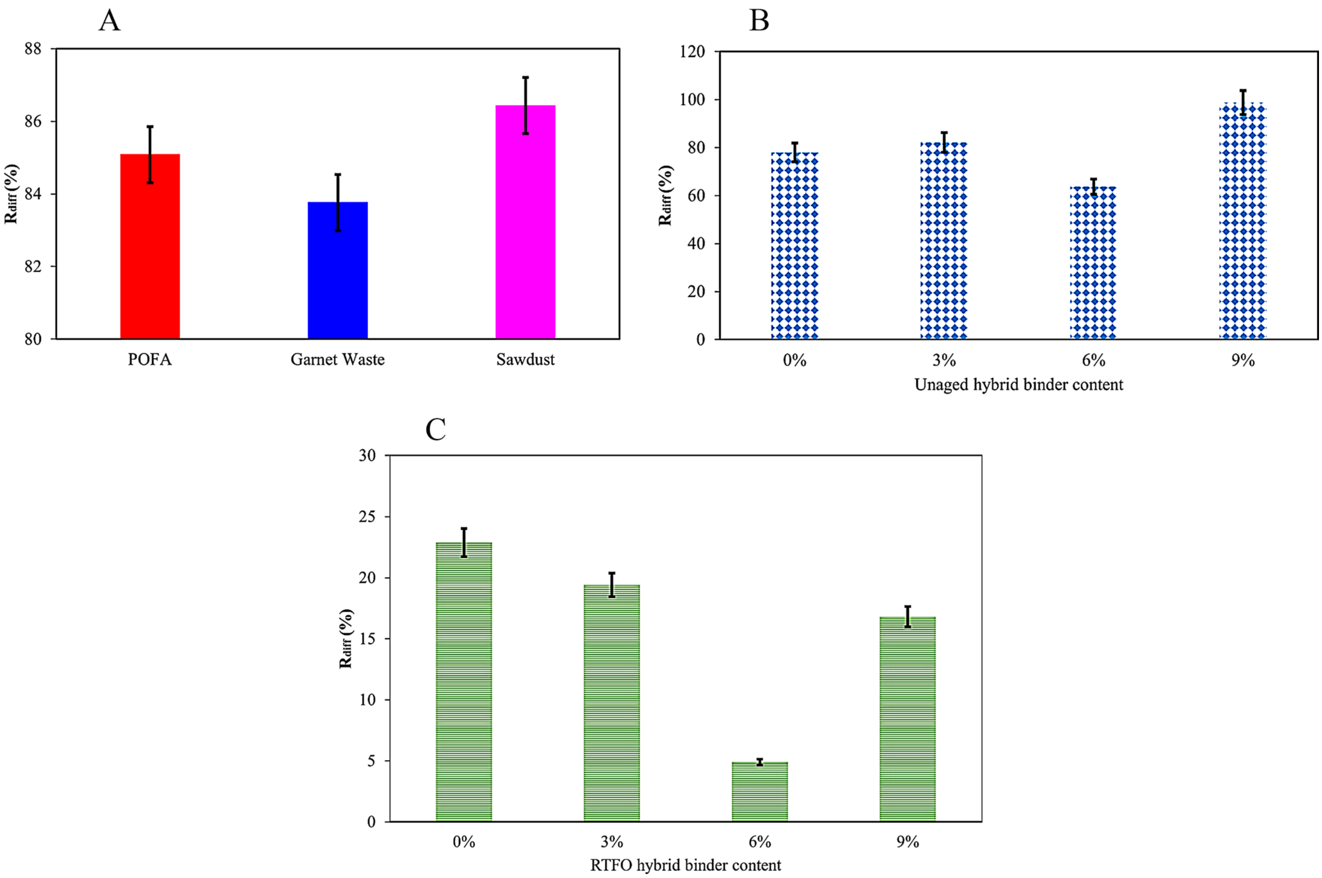

Fig. 13 **a**. The R_{diff} value of the 3% POFA-, 3% garnet waste-, and 3% sawdust-modified asphalt binders at 64 °C. **b**. The R_{diff} value of the 0%, 3%, 6%, and 9% unaged hybrid asphalt binders at 64 °C. **c**. The R_{diff} value of the 0%, 3%, 6%, and 9% RFTO hybrid asphalt binders at 64 °C

4.3 Analysis of the MSCR Test

4.3.1 Strain-time Curve

Previous studies have shown that the test parameters of asphalt pavements obtained under 3.2 kPa of stress conditions demonstrate a stronger correlation with permanent deformation [28, 45]. Figure 10a presents the strain-time curve of the 3% individual-modified (POFA, garnet waste, and sawdust) asphalpresents the strain-timet binders under 3.2 kPa of stress conditions at 64 °C, while Fig. 10b and c show the strain-time curves of the 0%, 3%, 6%, and 9% unaged hybrid and RFTO hybrid asphalt binders, respectively. According to Fig. 10a, the shear strain significantly increased with increasing time. Compared to the hybrid content, using 3% of individual waste materials drastically lowers the shear strain. Similarly, Fig. 10b reveals that the strain curve of the 0%, 3%, 6%, and 9% unaged hybrid asphalt binders increases gradually with increasing time. The strain rose significantly when the temperature reached 70 °C. Besides, no strain recovery component was present during each loading and unloading cycle, indicating that the elastic component of the 6% unaged hybrid asphalt binder almost disappeared above 70 °C, with prominent non-linear viscoelastic characteristics. Thus, the 6% unaged hybrid asphalt binder recorded the lowest strain value. Furthermore, the strain curve of the 0%, 3%, 6%, and 9% RTFO hybrid asphalt binders in Fig. 10c depicts a strain magnitude relationship as follows: 6% < 9% < 3% < 0%. The 6% RTFO hybrid asphalt binder exhibited the lowest strain value than the conventional asphalt, signifying that the hybrid addition of POFA, garnet waste, and sawdust enhanced the deformation resistance of the 6% RTFO hybrid asphalt binder. The formation of the three-dimensional (3D) network comprising the three waste materials plays a role in the crosslinking and bonding of the hybrid asphalt binder. Under external loading, the uniaxial stress can be transferred uniformly to different mastic substrates. The mutual bridging between the POFA, garnet waste, and sawdust also effectively prevents the mineral particles from slipping under heavy loading. Ultimately, the hybrid materials absorb light components in asphalts, such as aromatics and resins, increasing the asphalt's viscosity. Interestingly, Fig. 10b and c show that the unaged and RTFO hybrid asphalt binders exhibit superior rutting performance.

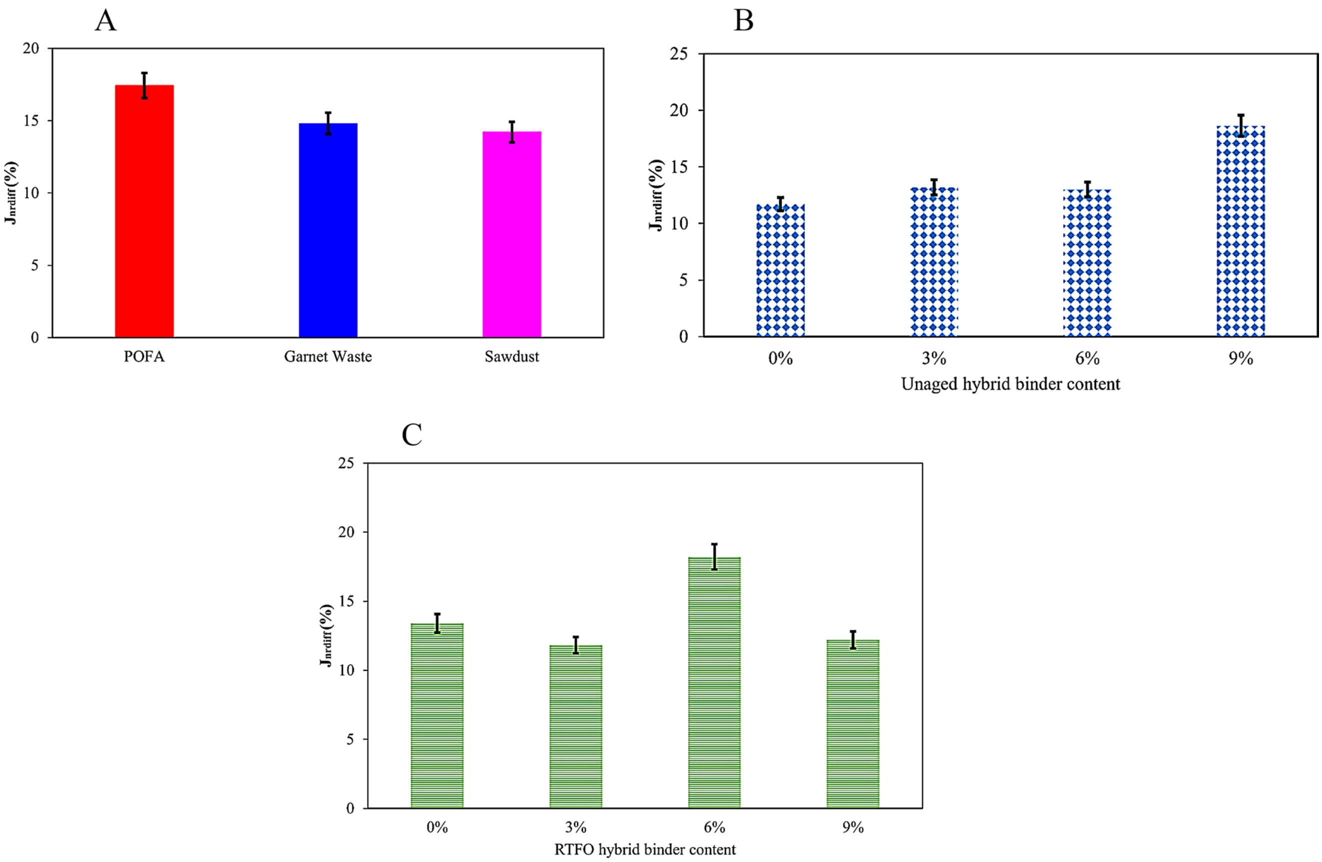

Fig. 14 **a**. The J_{nrdiff} value of the 3% POFA-, 3% garnet waste-, and 3% sawdust-modified asphalt binders at 64 °C **b**. The J_{nrdiff} value of the 0%, 3%, 6%, and 9% unaged hybrid asphalt binders at 64 °C. **c**. The J_{nrdiff} value of the 0%, 3%, 6%, and 9% RFTO hybrid asphalt binders at 64 °C

Table 5 Surface roughness value of hybrid asphalt mixtures

Hybrid content	0%	3%	6%	9%
Average roughness, Ra (nm)	3.454	2.328	1.062	1.652
Root means square roughness, Rq (nm)	6.743	5.041	1.539	3.512
Total roughness, Rt (nm)	84.99	57.83	15.78	40.87

4.3.2 J_{nr}

J_{nr}, known as non-recoverable creep compliance, is the first key parameter applied to determine the viscoelastic behaviour of the modified asphalts, specifically their ability to recover from residual deformation under varying stress conditions. Asphalt materials with a smaller J_{nr} value indicate a stronger rutting resistance at high temperatures.

Figure 11a, b and c present the creep compliance (J_{nr}) of the individual-modified (POFA, garnet waste, and sawdust) asphalt binders and 0%, 3%, 6%, and 9% unaged hybrid and RTFO hybrid asphalt binders, respectively, measured under two shear stresses of 0.1 kPa and 3.2 kPa using the DSR. Based on Fig. 11a, the 3% POFA-modified asphalt binder showed the lowest J_{nr} value at both 0.1 and 3.2 kPa shear stresses. The result indicates that the POFA-modified asphalt binder became softer at higher temperatures, and the cumulative strain rose under repeated load pressure. Moreover, the increase in temperature to 64 °C greatly influenced the change of J_{nr} to 3.2.

As shown in Fig. 11b, the J_{nr} value decreased under the shear stresses of 0.1 kPa and 3.2 kPa at 64 °C when the unaged hybrid asphalt content increased from 0 to 6% but increased upon reaching 9% hybrid content. The 6% unaged hybrid asphalt binder achieved the highest rutting resistance of 0.864 kPa^{-1} and 0.993 kPa^{-1} at 0.1 kPa and 3.2 kPa, respectively (13% increment).

According to Fig. 11c, the RTFO hybrid asphalt binders depict the lowest J_{nr} value at 64 °C than the individual-modified and unaged hybrid asphalt binders. The J_{nr} value generally decreases as the proportion of hybrid content increases in the RTFO hybrid asphalt binders, implying that adding more hybrid content enhances the rutting resistance. It should be noted that the J_{nr} value of the RTFO hybrid asphalt binders is less than the conventional binder at each temperature level, indicating a positive effect of adding the hybrid content. However, the trend is non-linear. For instance, the 3% RTFO hybrid asphalt binder recorded a decreased J_{nr} from 1.308 to 1.1609% but then increased as the proportion increased to 14%. The best performance of the 6% mixture may be related to the uniform distribution observed by SEM (Fig. 5c).

Table 6 relates the J_{nr} values with different traffic classes and their Equivalent Standard Axle Loads (ESAL). Accordingly, the 3% POFA-, garnet waste-, and sawdust-modified asphalt binder is categorised for standard traffic, S, with a lower ESAL when the surface pavement temperature reaches 64 °C. The 3% and 9% unaged hybrid asphalt binders are also categorised for standard traffic, S. Conversely, the 6% unaged hybrid asphalt binder shows the best traffic load for heavy traffic, H, with minimal ESAL, implying its resistance to deformation under high loads. The rutting resistance performance of the 6% unaged hybrid asphalt binder confirmed the result of the G* and δ in previous sections. Remarkably, the 3%, 6%, and 9% RFTO hybrid asphalt binders demonstrate the most improved residual deformation, reflecting their potential application for the heavy traffic class, H. In summary, the incorporation of POFA, garnet waste, and sawdust in the asphalt mixture confirmed the outstanding and rheological properties of both unaged hybrid and RTFO hybrid asphalt binders.

4.3.3 R-value

The recovery percentage, denoted as R%, is a critical parameter in asphalt modification assessment. The R-value quantifies the extent to which the asphalt binder returns to its original state after undergoing a specific modification process, providing the basis for a comprehensive experimental analysis. In general, an asphalt material with a higher R-value implies its greater elastic deformability and better rutting resistance. Figure 12a, b, and c indicate the R% value for the 3% individually-modified (POFA, garnet waste, and sawdust) asphalt binders and 0%, 3%, 6%, and 9% unaged hybrid and RTFO hybrid asphalt binders, respectively.

Figure 12a shows that the 3% POFA-modified asphalt binder exhibits higher R% values of 1.22 and 1.03 at 0.1 kPa and 3.2 kPa, respectively, indicating their potential to restore the original asphalt binder properties effectively. In contrast, the 3% sawdust-modified asphalt binder demonstrates a lower R% of 0.71 at 3.2 kPa, suggesting that it may not be as efficient as its 3% POFA-modified asphalt binder counterpart. These findings highlight the significance of the three waste materials for the hybrid asphalt modification, considering the impact on the recovery percentage and the desired asphalt mixture properties. Further research is warranted to assess the short-term performance implications of the hybrid waste materials comprehensively.

Table 6 J_{nr} value and the applicable traffic classes

Binder grade category	Code	Range of J_{nr} @ 3.2 kPa
Extreme	E	$0.5 \le J_{nr}$
Very heavy	V	$1.0 \le J_{nr} \le 2.0$
Heavy	H	$2.0 \le J_{nr} \le 4.5$
Standard	S	$J_{nr} \ge 4.5$

In Fig. 12b, the R% of the unaged hybrid asphalt binders at 0.1 kPa and 3.2 kPa exhibits a significant increase as the hybrid content increased from 0 to 6%, reaching a peak value of 4.12%. This suggests the positive impact of incorporating the hybrid content on the recovery properties of the unaged hybrid asphalt binders. The higher R% may also be attributed to the enhanced bonding and compatibility between the hybrid content and the asphalt binder. Nevertheless, a sharp drop in R% to 0.12% was observed for the 9% unaged hybrid asphalt binder, indicating the potential limit of the beneficial effects of hybrid materials at higher concentrations.

Conversely, the hybrid content showed a slightly different impact on the R% of the RTFO hybrid asphalt binders, as evident in Fig. 12c. The R% values at 3.2 kPa increased and peaked at 5.05% as the hybrid content increased from 0 to 6%. The findings suggest that the hybrid materials still had a positive effect on the recovery percentage, even in the RTFO asphalt binders, due to the ability of the hybrid materials to rejuvenate and restore the RTFO binder's properties. In contrast, the 9% RTFO hybrid asphalt binder showed a slight drop in R% to 3.47%, indicating a diminished recovery at higher hybrid content concentrations. The difference between the unaged and RTFO hybrid asphalt binders underscores the significance of using RTFO binders when selecting and optimising hybrid materials for asphalt modification.

In short, the unaged hybrid asphalt binders experienced an enhanced R% with increasing hybrid content up to 6%, suggesting a greater potential for improved recovery. However, the saturation point was limited to 9% hybrid content, as the R% significantly dropped. The RTFO asphalt binders also benefitted from a higher hybrid content level, with the R% increased using 6% hybrid content, indicating the rejuvenating effect of the hybrid materials on the RTFO hybrid asphalt binders. Nevertheless, the drop in R% at 9% hybrid content for the RTFO asphalt binders emphasises the need to determine the optimal hybrid content level to balance the desired performance and the potential diminishing recovery. These findings provide valuable insights into the impact of hybrid materials on asphalt binders' recovery properties, with potential applications in asphalt engineering and sustainability.

4.3.4 R_{diff} Value

Figure 13a depicts the difference in the recovery percentage (R_{diff}) of the 3% individual-modified (POFA, garnet waste, and sawdust) asphalt binders under high-temperature conditions at 64 °C. All three asphalt samples exhibit substantial positive R_{diff} values, demonstrating a marked increase in the asphalt binder's recovery capacity compared to the control sample. Specifically, the 3% POFA-modified asphalt binder yields the highest R_{diff} of 85.08%, followed by garnet waste-modified asphalt binder at 83.76% and sawdust-modified asphalt binder at 86.43%. The results signify the exceptional potential of the individual-modified asphalt binders as asphalt modifiers to substantially enhance the asphalt binder's recovery properties, particularly under elevated temperature conditions. This compelling outcome also underscores their viability for sustainable and high-performance asphalt applications through innovative approaches in pursuit of both environmental benefits and improved pavement performance.

Figure 13b and c display the R_{diff} of the 0%, 3%, 6%, and 9% unaged hybrid and RTFO hybrid asphalt binders under an elevated temperature of 64 °C. The recovery capacity of the unaged hybrid asphalt binders showed a remarkable enhancement as the hybrid content increased to 3%, recording a substantial positive R_{diff} of 82.11%. However, R_{diff} values progressively decline as the hybrid content continues to increase to 6% and 9%, although the values remained significantly above the baseline. The findings suggest a saturation point in the effectiveness of hybrid modification in the unaged hybrid binders upon reaching 6% hybrid content. On the other hand, the RTFO asphalt binders displayed a different response upon the addition of the hybrid content. At 3% hybrid content, the R_{diff} was positive but relatively lower at 19.40%, indicating a modest improvement compared to the unaged hybrid asphalt binders. Interestingly, the R_{diff} values remain relatively stable and closer to the baseline as the hybrid content increases to 6% and 9%, suggesting a diminishing impact on the recovery properties of the RTFO hybrid asphalt binders. These results imply the age-dependent and non-linear influence of the hybrid content on asphalt binder recovery, emphasising the need for precise selection of binder age in designing modified asphalt mixtures with optimal performance.

Overall, the presented data highlights the complex relationship between hybrid content and the R_{diff} of the asphalt binders, with significant variations observed between unaged and RTFO hybrid asphalt binders. Unaged hybrid asphalt binders exhibit a more pronounced positive impact from the incorporation of the hybrid content, particularly at 3% hybrid content, leading to a substantial increase in recovery properties. However, a further increase in hybrid content results in diminishing returns. Conversely, the RTFO hybrid asphalt binders experience a modest response to hybrid addition, with a less pronounced R_{diff} increase at 3% hybrid content and diminishing but stable impact beyond this level. These findings stress the need to consider both binder age and hybrid content when designing modified hybrid asphalt binders to achieve the desired recovery properties for specific applications. Besides, this valuable insight is crucial for optimising the sustainability and performance of asphalt binders, offering the potential to improve long-term pavement durability while considering environmental factors. Table 7 lists the minimum recovery of the J_{nr} value (%).

Table 7 Minimum recovery of the J_{nr} value (%)

J_{nr} @ 3.2 kPa	Minimum recovery (%)
2.0–1.01	30
1.0–0.51	35
0.50–0.25	45
0.25–0.13	50

4.3.5 Analysis of Stress Sensitivity, J_{nrdiff}

The difference between the unrecoverable creep compliance of asphalt materials, which presents the sensitivity of the asphalt binder to stress, is termed as J_{nrdiff}. A smaller J_{nrdiff} value signifies a lower temperature sensitivity of the asphalt binder and a prolonged service life of the asphalt pavement. Figure 14a, b, and c illustrate the J_{nrdiff} of the 3% individual-modified (POFA, garnet waste, and sawdust) asphalt binders and the 0%, 3%, 6%, and 9% unaged hybrid and RTFO hybrid asphalt binders, respectively, at 64 °C.

Notably, all three individual waste materials showed positive J_{nrdiff} values, indicating an increase in the J_{nr} compared to the control sample (Fig. 14a). The POFA-modified asphalt binder exhibits the highest J_{nrdiff} of 17.42%, followed by garnet waste-modified asphalt binder at 14.8% and sawdust-modified asphalt binder at 14.21%. This suggests that the incorporation of these waste materials individually leads to an increased sensitivity of the asphalt binder to stress, particularly at elevated temperatures. Comparatively, the significant variation in J_{nrdiff} values among the three waste materials highlights the material-specific impact on the asphalt binder performance, underlining the essential need to precisely select effective materials in asphalt modification to achieve the desired engineering properties and potential sustainability benefits.

Figure 14b and c present the J_{nrdiff} of the 0%, 3%, 6%, and 9% unaged hybrid and RTFO hybrid asphalt binders under an elevated temperature of 64 °C. It is evident that increasing the hybrid content in the unaged hybrid asphalt binders from 0 to 3% results in a substantial rise in J_{nrdiff} from 5.7 to 15.21%, indicating an enhanced sensitivity of the binder to stress following the addition of the hybrid content (Fig. 14b). However, the J_{nrdiff} values remained relatively stable beyond 3%, reflecting a saturation point of the hybrid content addition in the unaged hybrid asphalt binders. In contrast, the incorporation of hybrid content exhibited a less pronounced impact on the Jnrdiff of the RTFO hybrid asphalt binders. Although the J_{nrdiff} relatively increased from

0 to 6%, the values showed a slight decrease as the hybrid content reached 9%. The results suggest that the hybrid content has a less consistent impact on the RTFO hybrid asphalt binders compared to their unaged hybrid counterparts, with a potential optimal hybrid content level to achieve the desired sensitivity to the stress level. These findings highlight the complex relationship between the hybrid content, asphalt ageing, and the sensitivity of the asphalt binders to stress, offering valuable insights for asphalt engineering and sustainability.

In summary, the study reveals distinct behaviour in the sensitivity of unaged and RTFO hybrid asphalt binders to stress (J_{nrdiff}) based on the hybrid content and ageing. Unaged hybrid asphalt binders exhibit a more significant impact on the hybrid content level, with an initial sharp increase in J_{nrdiff} up to 3%, while the RTFO hybrid asphalt binders show a more modest response to the varying hybrid content levels. The saturation point observed in the unaged hybrid asphalt binders implies a possible diminishing return beyond a certain hybrid content level. These findings emphasise the importance of considering both hybrid content and binder ageing when designing modified asphalt binders, as the optimal composition may vary depending on the binder's age and the desired performance criteria. Hence, this research contributes to the understanding of asphalt binder behaviour and offers more effective and sustainable asphalt engineering practices.

4.4 Frequency Sweep

4.4.1 Analysis of the Complex Shear Modulus Master Curve

The master curve is utilised to determine the characteristics of a sample at a particular temperature outside the tested frequency range [46]. In this study, the generated data from the DSR with frequency sweep test was used to construct the master curve based on a temperature reference. The graph was plotted using the time-temperature superposition principle, which allows for shifting. Figure 15a, b, and c show the master curves of the complex shear modulus, G*, for the 3% individual-modified (POFA, garnet waste, and sawdust) asphalt binders and the 3%, 6%, and 9% unaged hybrid and RTFO hybrid asphalt binders, respectively, at 64 °C.

The overall trend shows a similar increasing G* value following the incorporation of the individual waste materials (POFA, garnet waste, and sawdust) and hybrid content in the asphalt mixture. Although the master curves can be used to characterise the rheological properties, it is difficult to identify any rheological alterations based on the graph due to the broad frequency range applied to the master curve. Thus, a detailed rheological property examination following the addition of the three waste materials into both individually and hybrid was conducted by analysing the original frequency sweep result from 0.1 to 100 rad/s at 40, 50, 60, 70, and 80 °C.

Figure 15a depicts the 3% POFA-modified asphalt binder with the highest G* value, followed by garnet waste- and sawdust-modified asphalt binders. The POFA-modified asphalt binder also exhibited more elastic behaviour with an R^2 value of 0.9929 than the garnet waste- and sawdust-modified asphalt binders (R^2 values of 0.9916 and 0.9887, respectively). All three correlation coefficient values indicate a strong association in the master curve graph.

In terms of the 6%, 9%, and 3% unaged hybrid asphalt binders, the master curve in Fig. 15b reveals a declining G* value with increasing angular frequency, respectively. The 6% unaged hybrid asphalt yielded a higher G* value than the 3% and 9% unaged hybrid asphalt binders, suggesting that the higher chemical composition of POFA (SiO_2), garnet waste (Fe_2O_3) and sawdust (CaO) in the hybrid content significantly influenced the overall asphalt performance. The incorporation of the hybrid content in the unaged hybrid asphalt enhances the binder's mechanical response, as indicated by the increase in G* with higher hybrid content proportions. This finding corresponds with the established viscoelastic material behaviour, in which an elevated temperature level affects the material's resistance against shear deformation. The positive correlation also suggests a proportional relationship between the reduced angular frequency and G*. Surprisingly, the 6% unaged hybrid asphalt binder achieved the highest R^2 value of 0.9966, followed by 9% and 3% unaged hybrid asphalt binders. Since POFA, garnet waste, and sawdust consist primarily of SiO_2, Fe_2O_3, and CaO, which are minerals known for their reinforcing and bonding properties, the observed trend could be attributed to the chemical composition of the POFA, garnet waste, and sawdust and their interaction with the binder. The high SiO_2 content of POFA may enhance elasticity through silicon-oxygen bonds, which contribute to a more flexible and resilient binder network by improving molecular interactions and distributing stress more uniformly within the asphalt matrix. This study supports evidence from previous observations [47], the strong correlations observed between rutting with the binder's chemical composition highlight the significant influence of its molecular structure on overall pavement performance.

After the short-term ageing process, the G* values of the 3%, 6%, and 9% RTFO hybrid asphalt binders increased significantly, as shown in Fig. 15c. In particular, the 6% RTFO hybrid asphalt binder recorded a considerably higher G* value at 64 °C up to an order of magnitude for the lowest reduced angular frequency and an R^2 value of 0.9923. Overall, a significant correlation was observed between the three hybrid content levels and the reduced angular frequency of

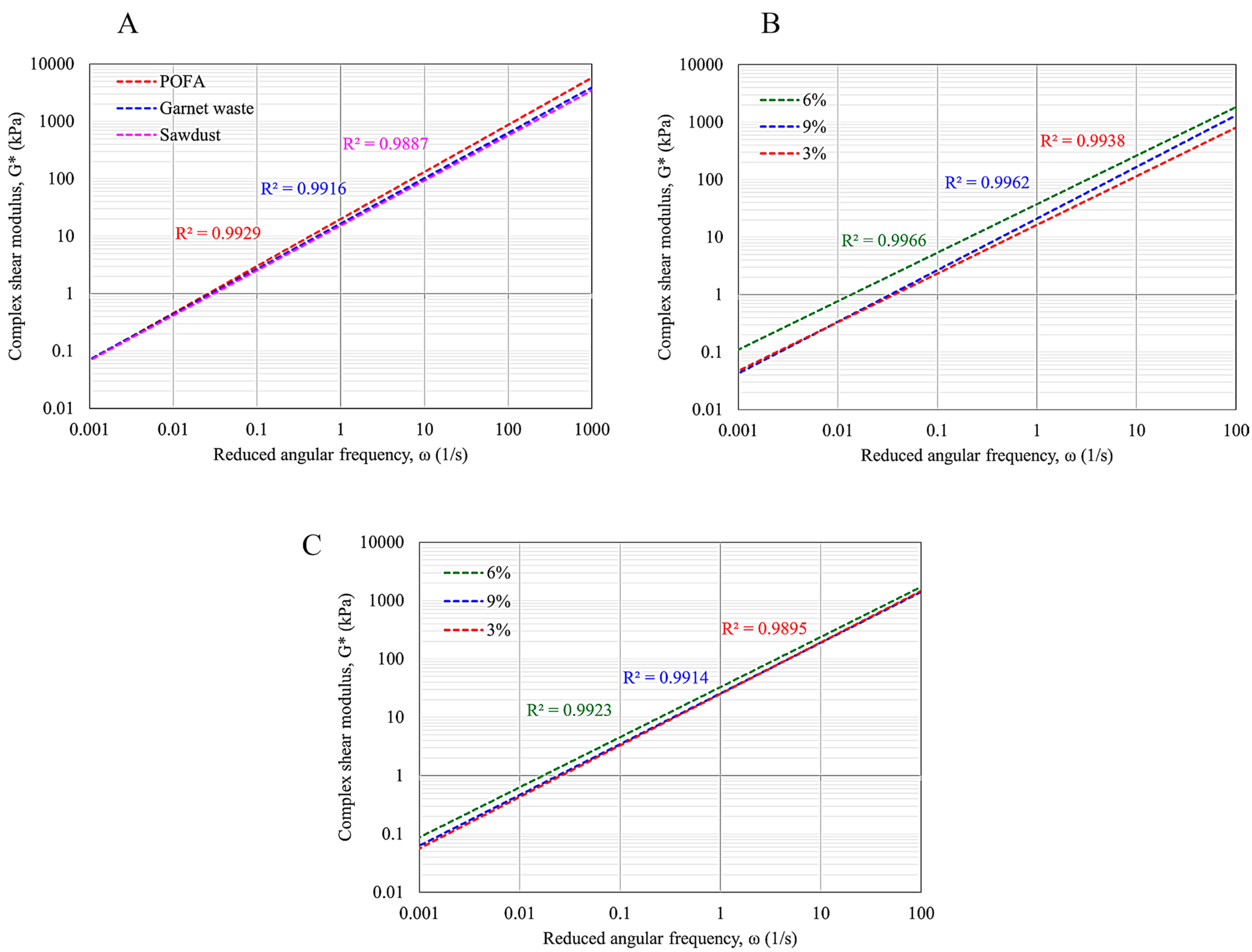

Fig. 15 **a**. Master curve of the complex shear modulus of the 3% POFA-, 3% garnet waste-, and 3% sawdust-modified asphalt binders at 64 °C. **b** Master curve of the complex shear modulus of the 3%, 6%, and 9% unaged hybrid asphalt binders at 64 °C. **c** Master curve of the complex shear modulus of the 3%, 6%, and 9% RTFO hybrid asphalt binders at 64 °C

the hybrid asphalt binders. This result corresponds to the percentage of hybrid asphalt mix design to the specific requirement, contributing to a more accurate prediction of the asphalt's behaviour, which is critical for formulating durable and resilient asphalt pavements. Moreover, the R^2 of the binders were statistically high in the master curve graph.

4.4.2 Analysis of the Phase Angle Master Curve

Figure 16a, b, and c depict the master curves of the phase angle, δ, for the 3% individual-modified (POFA, garnet waste, and sawdust) asphalt binders and 3%, 6%, and 9% unaged hybrid and RTFO hybrid asphalt binders, respectively, at 64 °C. The phase angle offers insight into the viscoelastic behaviour of the material, where lower phase angles imply a more elastic reaction, while higher phase angles suggest a more viscous response. The master curve in Fig. 16a illustrates the phase angle of the three individual-modified (POFA, garnet waste, and sawdust) asphalt binders, with the 3% POFA-modified asphalt binder showing the lowest phase angle. Based on the results, the phase angle decreases with an increasing proportion of the waste materials used.

Figure 16b shows the phase angle of the 3%, 6%, and 9% unaged hybrid asphalt binders, which decreased with increasing addition of the hybrid content. This suggests that a higher proportion of the hybrid content comprising POFA, garnet waste, and sawdust enhances the elasticity of the asphalt binders and reduces their viscous behaviour. The inverse relationship might be due to the potential filler effect of the hybrid content as more hybrid content addition gradually absorbs more asphalt. In contrast to the initial asphalt mixture, adding more hybrid content would alter the asphalt structure, strengthening the contact between the

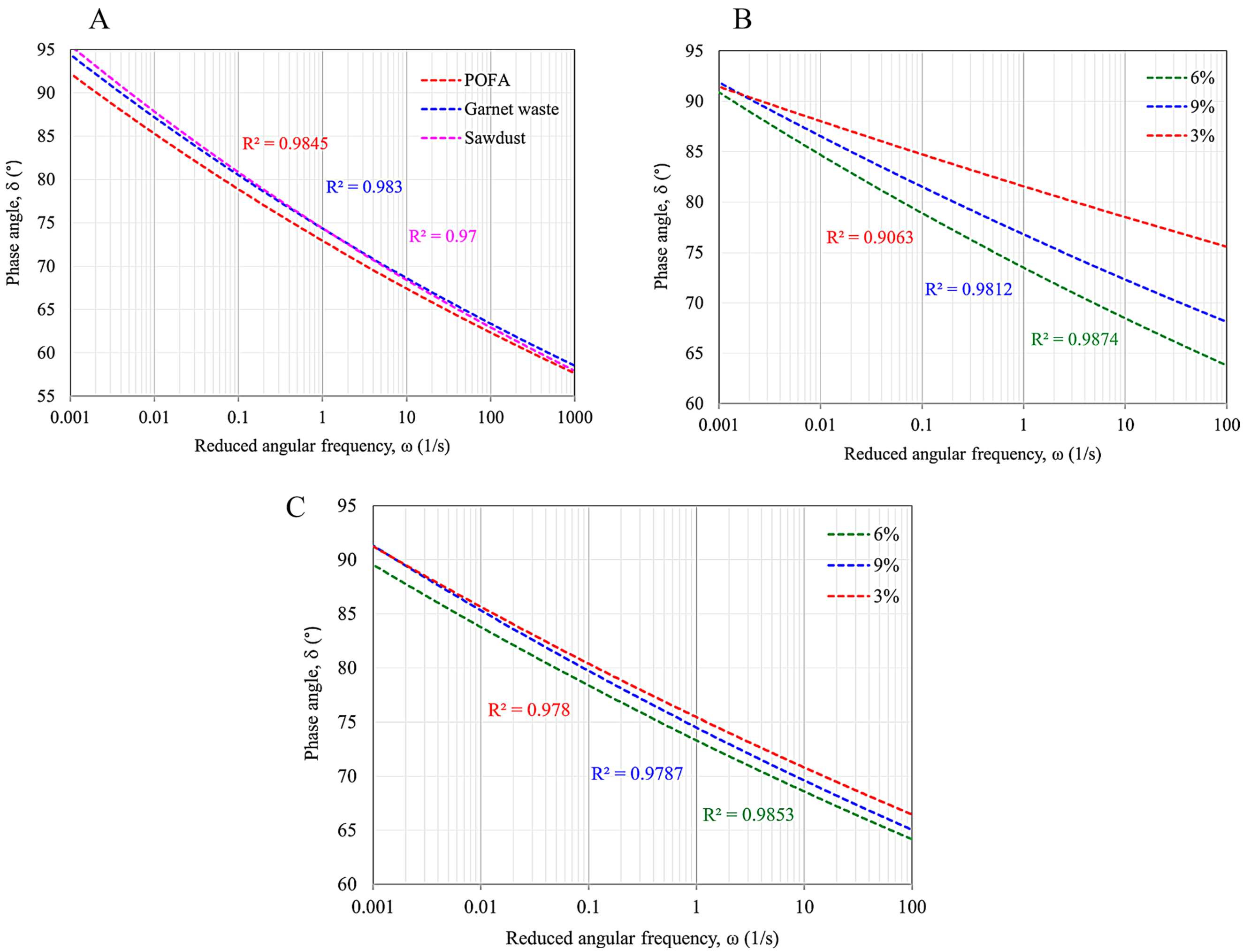

Fig. 16 **a**. Master curve of the phase angle of the 3% POFA-, 3% garnet waste-, and 3% sawdust-modified asphalt binders at 64 °C. **b** Master curve of the phase angle of the 3%, 6%, and 9% unaged hybrid asphalt binders at 64 °C. **c** Master curve of the phase angle of the 3%, 6%, and 9% RTFO hybrid asphalt binders at 64 °C

asphalt molecules. Consequently, the resistance to deformation increased, which led to a decrease in δ.

Furthermore, Fig. 16c depicts the 3%, 6%, and 9% RTFO hybrid asphalt binders, which exhibit a similar trend with the unaged hybrid asphalt binders. As such, increasing the addition of hybrid content could reduce the phase angle value. The changes in the three waste materials' structure or properties at higher temperatures could play a role in the mechanism behind this phenomenon. All samples appeared to have an inverse relationship between the temperature and the phase angle. Simply put, a temperature rise leads to a drop in the phase angle.

The viscoelastic properties are one of the crucial characteristics of asphalt materials. As the temperature increases, the asphalt binder becomes more elastic and less viscous, leading to a lower phase angle. Nevertheless, the decreasing rate is less steep for the hybrid asphalt binders with a higher hybrid content proportion at higher temperatures. This could indicate that the hybrid content maintains the binder's stiffness at higher temperatures. From this analysis, it can be deduced that the POFA, garnet waste, and sawdust are excellent hybrid contents and increase the phase angle when incorporated into the asphalt mixture, indicating an enhancement in the asphalt's stiffness.

5 Conclusion

This study successfully demonstrated the rheological effects and rutting performance of POFA, garnet waste, and sawdust incorporation as hybrid asphalt modifiers for the development of sustainable asphalt pavements. The results indicate that the 6% hybrid content was the most suitable percentage to be incorporated into the asphalt mixture. The conclusion of this study can be summarised as follows:

(1) The DSR analysis revealed that the hybrid asphalt binder incorporating POFA, garnet waste, and sawdust exhibited greater complex shear modulus (G*) values than the individual-modified asphalt binders, with enhanced stiffness and deformation resistance. These results highlight the potential of POFA, garnet waste, and sawdust as asphalt modifiers to improve the rheological behaviour and rutting performance of the asphalt binder.
(2) The G* and δ master curves demonstrate that the hybrid content enhanced the elastic response of the hybrid asphalt binders and protected them from oxidation compared to those of the base asphalt. Correspondingly, the MSCR test indicates that the addition of the hybrid content reinforced the resistance to permanent deformation in the base asphalt at elevated temperatures. Hence, the 6% RTFO hybrid asphalt binder at 64 °C may be used as a suitable ageing index to evaluate the ageing resistance of asphalt samples due to the high sensitivity of the binder to the test temperature.
(3) The addition of 6% hybrid content significantly enhanced the thermal stability and ageing resistance of the hybrid asphalt binders as well as minimised the side effects of the hybrid content on the performance of the hybrid asphalt binders at low-temperature conditions. Thus, the 6% hybrid content was considered the optimum hybrid content level to achieve the most performing hybrid asphalt binders.
(4) There were strong correlations between rheological properties, rutting performance and chemical results of the hybrid asphalt binders. The physical and chemical properties of the modifier affect the overall properties. The high silica content in POFA enhances stiffness and binder stability, contributing to the higher G* values. Garnet waste, rich in ferric oxide, promotes rigidity, which reflects in improved rutting resistance (lower phase angles) and better MSCR performance. The calcium oxide from sawdust improves binder elasticity and reduces permanent deformation, as seen in the MSCR results. Together, these chemical characteristics explain the improved G* values and reduced phase angles, demonstrating enhanced resistance to rutting.
(5) The results of this study generally provide valuable insights into the rheological behaviour of waste-incorporated hybrid asphalt binders. The use of hybrid content as a sustainable asphalt modifier can improve the resilience and durability of asphalt pavements, which could address the ongoing difficulties facing transportation infrastructure.

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Declarations

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