BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 74(2), 2026, Article number: e157096
DOI: 10.24425/bpasts.2025.157096

CIVIL ENGINEERING

Enhancing shear-thinning behavior in asphalt binders through organophilic clay modification

Zhen WU[1,2], **Qingping WANG**[1,2], **Cheng LI**[3], **Yulong GUO**[4], **Hakeem JAN**[5], and **Basit ALI**[6,7]*

[1] Chengdu Industry and Trade College, Chengdu 611731, China
[2] Chengdu Technician College, Chengdu 611731, China
[3] China Merchants ZhiXiang Road Technology (Chongqing) Co., Ltd., Chongqing 400060, China
[4] Guangxi Transportation Investment Group Liuzhou Expressway Operation Co., Ltd., Liuzhou 545000, China
[5] Lincoln University College, Selanger, Malaysia
[6] School of Highway Engineering, Chang'an University, Xi'an, PR China
[7] Public Health Engineering Department, Khyber Pakhtunkhwa, Pakistan

Abstract. This study investigates the influence of shear rate on the non-Newtonian flow behavior of asphalt binders modified with 1–5% organophilic nano clay by weight. Asphalt binders exhibit shear-thinning characteristics, where viscosity decreases with increasing shear rate, enhancing elasticity and reducing temperature sensitivity. Two penetration-grade bitumen samples (60/70 and 80/100) from Attock Refinery Limited (ARL), Pakistan, were modified using the melting method as per ASTM D6606. Rotational viscometer tests (ASTM D4402) were conducted at 135°C, over shear rates from 3.4 to 34 s^{-1}. Viscosity dropped by nearly 60% with increasing shear rate, with the 5% nano clay blend exhibiting the highest viscosity (385.5 cp (mPa·s)) at low shear rates. All concentrations demonstrated improved flow behavior, with 5% yielding the most significant effect. These findings highlight the potential of organophilic nano clay to improve binder rheology, indicating enhanced resistance to rutting and deformation, critical for pavement applications. Further field-scale research is recommended to evaluate long-term performance, mix workability and economic feasibility.

Keywords: organophilic nano clay; asphalt binder modification; shear-thinning behavior; viscosity-shear rate relationship; rutting resistance.

1. INTRODUCTION

The increasing demand for durable and sustainable road infrastructure in Pakistan and other developing countries has intensified the need for innovative asphalt modifiers capable of enhancing pavement performance under severe climatic and loading conditions. In recent years, various environmentally benign additives have been explored to improve the durability and rheological performance of asphalt binders. Materials such as palm-oil fuel ash [1], rejuvenators [2] and hybrid modifiers for recycled binders [3] have all shown promising improvements in binder flexibility, workability and temperature sensitivity.

Asphalt mixtures are multiphase composites comprising binder, aggregate and mineral filler, where the binder functions as the cohesive matrix that ensures load transfer and structural integrity. The binder's viscoelastic response governs the deformation resistance, fatigue behavior and long-term performance of asphalt pavements [4]. Recent research showed that bonding enhancers like alkylamines and polyalkylene glycol improve binder adhesion and moisture resistance through chemical surface modification [5]. Recent advances have explored polymer and plastic waste modifiers, such as low-density polyethylene (LDPE) and high-density polyethylene (HDPE), to enhance mixture stiffness and rutting resistance [6,7]. However, conventional bituminous binders are susceptible to deterioration under high service temperatures, heavy traffic loads and environmental aging, leading to rutting, fatigue cracking and moisture-induced damage [8]. Rutting caused by shear deformation or plastic flow within the asphalt layer is one of the most critical distresses affecting pavement performance, often resulting from mixture instability, over-compaction, and binder softening under thermal and mechanical stress [9]. Recent research on nano-silica-based shear thickening fluid (STF) modification also demonstrated enhanced viscoelastic performance and rutting resistance of asphalt binders [10].

To mitigate these issues, extensive efforts have been directed toward chemical and physical modification of asphalt binders. Among emerging modifiers, organophilic nano clay has attracted significant attention due to its ability to enhance binder viscosity, elasticity and structural stability, thereby improving resistance to deformation and thermal susceptibility [11]. In the context of Pakistan's hot climatic conditions, where rutting and premature pavement failure remain persistent problems, the development of low-cost yet thermally stable binder systems is particularly critical. Local studies have evaluated various additives such as phosphorous methyl compounds (PMC), which were found to improve ductility, penetration and softening point characteristics [12].

---

*e-mail: 2021021904@chd.edu.cn

Manuscript submitted 2025-05-17, revised 2025-11-09, initially accepted for publication 2025-11-14, published in March 2026.

Carbon-based modifiers have also been extensively studied for their reinforcing potential and accessibility [13, 14]. The inclusion of carbon black and pyrolysis-derived carbon nanostructures has been reported to enhance stiffness, reduce temperature sensitivity, and improve the electrical and mechanical behavior of asphalt binders. Nevertheless, the performance of these carbonaceous modifiers strongly depends on their particle morphology, surface chemistry and dispersion within the bitumen matrix [15, 16]. Moreover, many carbon nanoparticles are synthetically produced, raising cost and sustainability concerns.

In contrast, organophilic nano clay offers a renewable, economically viable and environmentally friendly alternative. Derived from montmorillonite modified with quaternary ammonium cations, organophilic nano clay exhibits high basal spacing, surface activity and strong affinity with the polar components of bitumen, enabling effective exfoliation and uniform dispersion within the binder [17]. These structural features make organophilic nano clay particularly suitable for Pakistan's hot-climate pavements, where high-temperature stability and rutting resistance are essential for extending pavement life.

Given these challenges, this research aims to investigate the rheological enhancement of locally available asphalt binders through organophilic nano clay modification, with specific relevance to Pakistan's climatic and material conditions. The scientific objective of the study is to elucidate the relationship between nano clay concentration, shear rate, and non-Newtonian flow behavior, thereby establishing a microstructural explanation for the observed improvements in viscosity and shear-thinning properties. To achieve this objective, the specific aims of the study are as follows:

- To evaluate the effect of organophilic nano clay (1–5 wt%) on the absolute viscosity of asphalt binders at 135°C, using a rotational viscometer (ASTM D4402).
- To quantify viscosity variation across a shear-rate range of 3.4–34 s^{-1} and to determine the degree of enhanced shear-thinning behavior.
- To compare the rheological performance of two penetration-grade binders (ARL 60/70 and ARL 80/100) modified with organophilic nano clay.
- To interpret the mechanistic role of nano clay modification in improving molecular-scale rigidity and its implications for rutting resistance and structural durability of asphalt pavements.

2. METHODOLOGY

The experimental design of this study was developed to establish a direct link between organophilic clay concentration and the shear-thinning response of asphalt binders. Two penetration-grade binders (ARL 60/70 and ARL 80/100) were selected to represent different stiffness levels commonly found in Pakistan, enabling comparative evaluation of modification efficiency. Clay contents of 1–5 wt% were chosen, ensuring coverage of both low- and high-reinforcement regimes. A rotational viscometer (ASTM D4402) was used to measure steady-shear viscosity at 135–175°C, the temperature range corresponding to asphalt mixing and compaction. Each test condition was replicated three times to ensure reproducibility. The study design thus isolates the effect of clay concentration and binder grade under controlled shear and temperature conditions, providing quantitative data for modeling viscosity and evaluating potential improvements in high-temperature performance. All tests were conducted in triplicate under controlled conditions (135°C) to ensure accuracy. The maximum deviation was within ±5%, confirming reliable and consistent rheological data. Figure 1 illustrates the sequential phases from material collection to organophilic clay modification, sample preparation and rheological analysis.

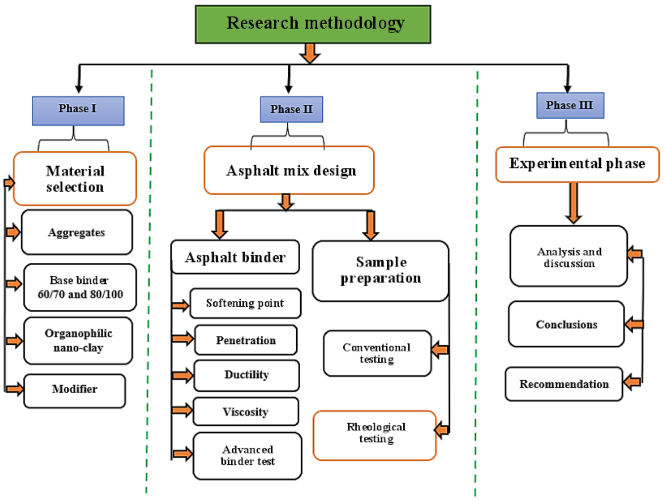


Fig. 1. Flow chart of experimental methodology adopted in this study

2.1. Materials

Primary materials used were modifiers such as organophilic nano clay and asphalt binder. Each of these materials is widely discussed below.

2.1.1. Bitumen

Soft binders (ARL 60/70 and ARL 80/100) were selected as they represent grades locally used in Pakistan, allowing assessment of how organophilic nano clay can enhance their stiffness and rutting resistance for hot-climate pavements. Two different grades of bitumen were obtained from Attock Refinery Limited (ARL), including ARL-60/70 and ARL-80/100. ARL 60/70 and ARL 80/100 were selected to compare the effects of nano clay on binders with different stiffness levels. ARL 60/70 is stiffer and offers higher rutting resistance, while ARL 80/100 is softer and more workable. This contrast helps assess how shear-thinning behavior varies with binder grade. Bitumen was stored in a container of 2.5 kg in capacity. Each sample was prepared by addition of 1% organophilic nano clay. The first sample was prepared without the addition of organophilic nano clay while the remaining 12 samples of the bitumen were prepared by addition of organophilic nano clay ranging from 0% to 5%. In the conventional binders testing, only virgin binder samples were tested. Moreover, the other organophilic-modified binder was tested using advanced techniques such as shear thinning tests through a rotational viscometer to assess its rate of microstructure reversibility. At 135°C, the modified bitumen samples, including the virgin sample, were sheared from 3.4 (1/s) to 34 (1/s) in steps. Following a rest period of 1 hour, at 3.4 (1/s) the samples were sheared again to determine how much of the viscosity was gained during that rest period and to assess the rate of microstructure rearrangements in the virgin bitumen and modified bitumen. Bitumen was stored in sealed 2.5 kg metal containers at 25 ± 2°C to ensure consistency prior to nano clay modification and rheological testing.

2.1.2. Organophilic clay

The organophilic nano clay used in this study was a modified montmorillonite (MMT) supplied by GDBentonite Co., China (www.gdbentonite.com) [18]. It was produced by replacing sodium ions in natural bentonite with quaternary ammonium cations, converting it from hydrophilic to organophilic form. The modification introduces long-chain alkyl groups that expand the basal spacing (~ 1.8 nm) and enhance compatibility with bitumen. The quaternary ammonium structure provides both polar and nonpolar affinities, enabling strong interaction with asphaltenes and resins while allowing intercalation and exfoliation of bitumen molecules within the clay galleries. The modification process increases the interlayer spacing of montmorillonite, facilitating the formation of a three-dimensional nano-composite network that improves viscosity, shear-thinning behavior and high-temperature stability. The key properties provided by the supplier include a surface area of 68 m^2/g, particle size of 40–70 nm, and cation exchange capacity of 90–100 meq/100 g.

2.2. Sample preparation

For each batch, 100 g of virgin bitumen (ARL 60/70 and ARL 80/100) was preheated to 175 ± 5°C in a thermostatically controlled oil bath to achieve complete fluidity while minimizing oxidative hardening. Organophilic nano clay was incorporated at concentrations of 1%, 2%, 3%, 4% and 5% by weight of binder. To ensure homogeneous dispersion, the mixture was first subjected to low-speed pre-mixing (500 rpm for 10 min) followed by high-shear blending at 1500 rpm for 60 min using a mechanical shear mixer (IKA RW 20 digital). The temperature was continuously monitored with a thermocouple and maintained within ±2°C of the target value throughout mixing.

Immediately after blending, each batch was subjected to ultrasonic agitation for 10 min to disrupt any residual agglomerates and enhance exfoliation of clay platelets. The visual uniformity of the dispersion was verified by the absence of visible particles and by microscopic inspection of a thin film sample. Each concentration was prepared in triplicate to ensure repeatability, and 50 g subsamples were drawn from the homogenized blend for testing. Prior to rheological measurements, all specimens were conditioned at 135°C for 60 min to eliminate thermal history effects and to simulate field processing temperature. The rest period of one hour at 135°C allowed partial network reformation of the clay structure, enabling evaluation of microstructural recovery and shear-thinning reversibility.

2.3. Bitumen testing

The penetration value of bituminous material serves as a proxy for its hardness or consistency. It is the vertical distance that, given specific stress, duration and temperature conditions, a typical needlepoint may travel or pierce into bituminous material. This distance is expressed in millimeters, to the tenth. This test is used for the evaluation of asphalt consistency. The asphaltic bonding and stretchable qualities are evaluated using the ductility test. In a flexible pavement, a small deformable coating of adhesive must accumulate around the particles to enhance the physical interaction of the particles. A comparison to previous road surfaces is produced when a binding material substance is subjected to repetitive traffic volumes and breaks. A standard briquette sample of the substance extends to a length per cm before shattering when connected to both ends and is pulled apart at a certain temperature and elongation rate.

The softening point of the material is the degree to which petroleum product or asphalt melts to a particular extent. Additionally, under specific test conditions, the temperatures (°C) that occur when a conventional ball warmed in glycerin and water penetrates a bituminous sample in a mold and drops through it with a height of 2.5 centimeters. The asphalt binder softening point should be determined in order to heat the product adequately for various highway purposes. The softening point could be determined using just a ring & ball. The minimal temperature during which, under specific tests, the introduction of an ignition source permits the substance vapors to momentarily burst into flames or for flashing to appear is referred to as a "flash point". The substance ignites and burns for at least five seconds just at critical temperature when an ignition source is applied. This is referred to as the "fire point". All physical properties of asphalt binder (ARL 60/70 and ARL 80/100) with their ASTM standard are mentioned in Table A1.

2.4. Brookfield rotary viscosity test

Viscosity measurements were performed using a Brookfield DV2T rotational viscometer (ASTM D4402) at 135–175°C and shear rates of 3.4–34 s^{-1}. Although Dynamic Shear Rheometers (DSR/DHR) are used for SHRP performance grading, this study focused on steady-shear viscosity and shear-thinning behavior, for which the Brookfield viscometer was suitable. Future work will employ DSR testing to determine viscoelastic parameters (G, δ). Viscosity measurements of nano clay-modified asphalt binders were conducted using a Brookfield DV2T rotational viscometer in accordance with ASTM D4402. The selected shear rate range of 3.4 to 34 s^{-1} corresponds to typical field conditions experienced during asphalt mixing, pumping and compaction, as reported in [19] and supported by ASTM D2493 guidelines. These shear rates enable the evaluation of flow behavior under real-world processing conditions.

To examine the material's response across varying shear and thermal conditions, the time-temperature superposition principle (TTSP) was used. This approach allows for prediction of viscosity at different temperatures based on a master curve generated at a reference temperature. The Williams–Landel–Ferry (WLF) equation was applied to determine the shift factor aa_T

as follows:

$$\log(a_T) = \frac{C_1(T - T_{\mathrm{ref}})}{C_2 + (T - T_{\mathrm{ref}})}, \tag{1}$$

where a_T is the shift factor, T is the test temperature (°C), T_{ref} is the reference temperature (135°C in this study) and $C_1 = 8.86$, $C_2 = 101.6$: typical empirical constants for asphalt binders.

To ensure accuracy, the viscometer was calibrated weekly using certified Brookfield standard fluids (100 mPa·s and 500 mPa·s) at 25°C, following manufacturer protocols (Table A2). Each test condition defined by binder type, nano clay concentration, and shear rate was repeated in triplicate, and mean values with standard deviations were recorded to ensure reliability.

As per ASTM D4402, the viscosity, shear stress and shear rate of nano clay-modified asphalt binders were measured using a Brookfield DV2T viscometer (Fig. 2). Tests were conducted across a temperature range of 135oC to 175°C and a shear rate range of 3.4 to 34 s^{-1}, enabling evaluation of temperature-dependent flow behavior. Table A3 summarizes the test conditions, including nano clay content, temperature and the shear rates applied. These parameters supported the generation of viscosity-shear rate flow curves and the application of the time-temperature superposition principle to evaluate and predict binder behavior under operational conditions.

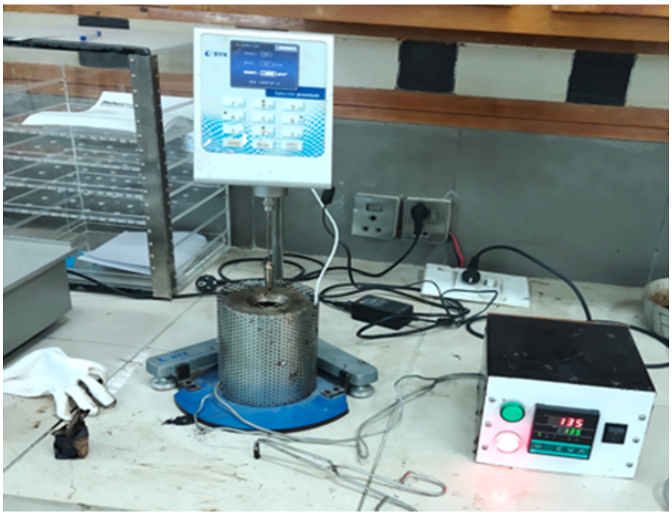


Fig. 2. Brookfield DV2T viscometer setup used for steady-shear viscosity testing (ASTM D4402)

3. RESULTS AND DISCUSSION

The results describe changes in viscosity, shear stress and torque, and interpret them based on bitumen microstructure and nano clay interactions. Organophilic nano clay modifies the binder's internal structure by forming intercalated/exfoliated layers that restrict molecular motion and enhance shear-thinning and temperature stability.

3.1. Gradation curve

Figure 3 presents the aggregate gradation used in this study together with the standard gradation limits specified by the National Highway Authority (NHA, 2020). To ensure compliance with NHA specifications, the aggregates were carefully sieved and adjusted within the allowable limits. NHA is the governing body responsible for the planning, construction and maintenance of Pakistan's primary road network.

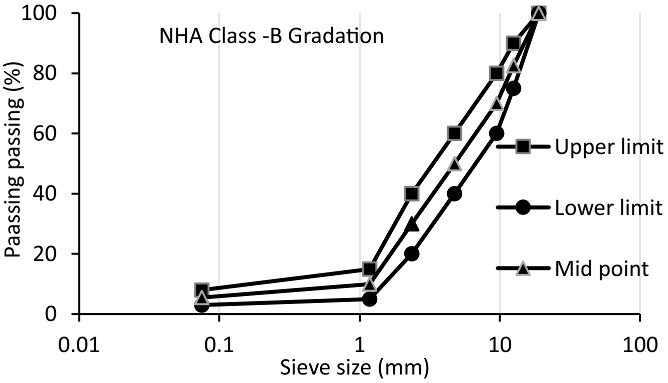
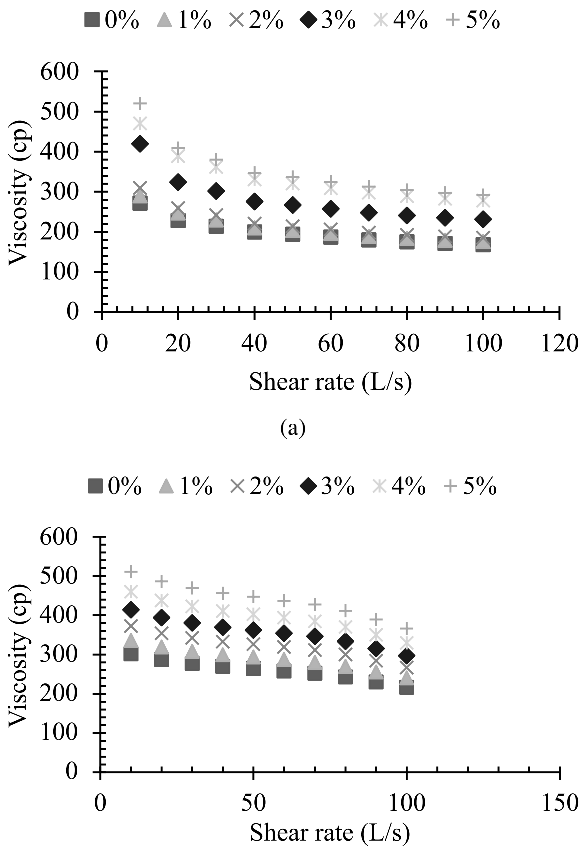


Fig. 3. NHA Class-B Gradation

3.2. Effect of shear rate on bitumen viscosity

Viscosity decreases with shear rate due to the breakdown of asphaltene-clay networks. At low shear, the structure resists flow, improving rutting resistance, while at high shear it facilitates workability. The ratio of shear stress to shear rate in a simple shear flow at constant high temperatures is called viscosity. Shear stress is linearly related to shear rate and viscosity constants in Newtonian asphalt behavior. The shear rate is mostly affected by modified asphalt and a small number of unmodified binders with large percentages. Plotting viscosity-temperature graphs is most commonly done using the ASTM D 2493 Specification. The viscosity difference of the asphalt binder after modification with six different percentages of organophilic material at 135°C is displayed in Fig. 4a–b. Shear rate has a larger effect on the modified asphalt binders at this temperature. The relationship between shear rate and modified asphalt viscosity for several percentages of the organophilic material (0%, 1%, 2%, 3%, 4% and 5%) is depicted in Fig. 4a–b. Because the viscosity of changed binders depends on both temperature and shear rate, it can be seen that the viscosity values fall as the shear rate increases. Viscosity decreased with increasing shear rate within the 10–100 s−1 range, confirming shear-thinning behavior. However, adding more organophilic nano clay to the asphalt mixture causes it to become more viscous. The highest viscosity was achieved when 5% of the organophilic nano clay was added to the mixture. Moreover, ARL 60/70 has more viscosity as compared to ARL 80/100, as shown in Fig. 4a–b. The improved rheological stability observed here agrees with previous findings [5], which reported increased binder shear strength and durability under aging and moisture conditions.

At 3.4 s^{-1} and 0% nano clay, ARL 60/70 exhibited 23.4% higher viscosity than ARL 80/100, due to its lower penetration grade and inherently stiffer nature. This difference persisted across all clay concentrations, making ARL 60/70 more suitable for high-temperature, high-traffic conditions. Similar improve-



(a)

(b)

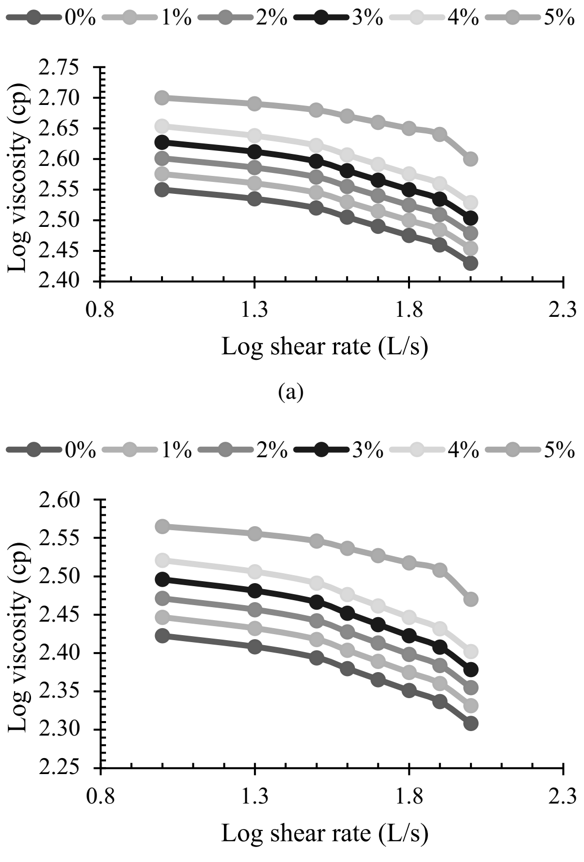
Fig. 4. Influence of shear rate (L/s) on the viscosity of asphalt mixture: (a) for ARL 60/70; (b) for ARL 80/100

ments in deformation resistance have been reported when marble dust was incorporated into polymer-modified binders [20].

While viscosity decreased with shear rate across all samples, binders with higher nano clay content maintained greater resistance to flow, particularly at low shear mimicking conditions under static loading or slow-moving traffic. These improvements are critical for rutting resistance and long-term pavement performance, especially in hot climates.

3.3. Effect of log shear rate on viscosity

Figure 5 depicts the result of log shear rate (L/s) and log viscosity (cp) for two distinct types of asphalt binder including ARL-80/100 and ARL-60/70, respectively. Both of these asphalt binders have been modified with varying concentrations of organophilic nano clay ranging from 0% to 5%. Figure 5a–b depicts the rheological characteristics of asphalt binders, especially shear thinning behavior. Figure 5a illustrates the result of log viscosity for asphalt binder of ARL-80/100. Every single line within a plot shows various quantities of organophilic nano clay utilized for the modification of asphalt binder. The viscosity representing a shear thinning behavior decreases by increasing the values of the shear rate from 10 to 100. The viscosity of the unmodified sample was slightly higher than that of the modified sample with a nano clay range of 1% to 5% at lower values of shear rate. The result suggests the significance of clay in increasing its resistance to flow by the result of viscosity (lower) at a higher value of shear rate. At higher values of shear rates, shear thinning reduces the influence of clay because of the viscosity between various clay concentrations.



(a)

(b)

Fig. 5. Effect of log of shear rate on log of viscosity of ARL: (a) ARL-80/100; (b) ARL-60/70

The decrease in viscosity by means of increasing the shear rate is referred to as shear thinning. It was exhibited by both samples including ARL-80/100 and ARL-60/70. The shear thinning property of asphalt binder is useful and has practical implications due to the easy flow of binder in the mixing stage as well as its application phase but still resists under-load deformation because of its sufficient viscosity. The incorporation of organophilic clay has an impact on the rheological characteristics of ARL 60/70 and ARL 80/100. The clay raises the viscosity at lower shear rates, indicating that the parts have interactions with the asphalt binder matrix to form a more intricate, interconnected structure that impedes movement. This viscosity increase is advantageous since it can improve the binder's capacity to resist rutting and various other changes. Higher shear rates, however, cause the viscosity of all samples to drop and the distinctions between the modified and untreated binders to become less noticeable. This suggests that in situations with strong shear, such as those seen during compaction or asphalt mixing, the shear forces outweigh the structural interactions brought about by the clay, resulting in a comparable decrease in viscosity in every sample. Viscosity adjustment is adequate when ARL 60/70 is used.

Figure 5a–b illustrates the logarithmic relationship between shear rate and viscosity for both ARL 60/70 and ARL 80/100 modified with 0–5% organophilic nano clay. As expected, viscosity decreased logarithmically with increasing shear rate, consistent with shear-thinning, pseudoplastic behavior.

At low shear (3.4 s^{-1}), 5% clay-modified ARL 60/70 binder showed a 57% increase in viscosity as compared to the unmodified binder. However, at higher shear rates ($\sim$ 34 s^{-1}), the viscosity differences narrowed significantly. For example, the viscosity difference between 0% and 5% clay was only 12–15% at 34 s^{-1}, indicating the nano clay's effect is most pronounced under low shear or static loading conditions. At 100 s^{-1}, simulated using extrapolated data from time–temperature superposition, viscosity values for all formulations converged further, supporting this observation.

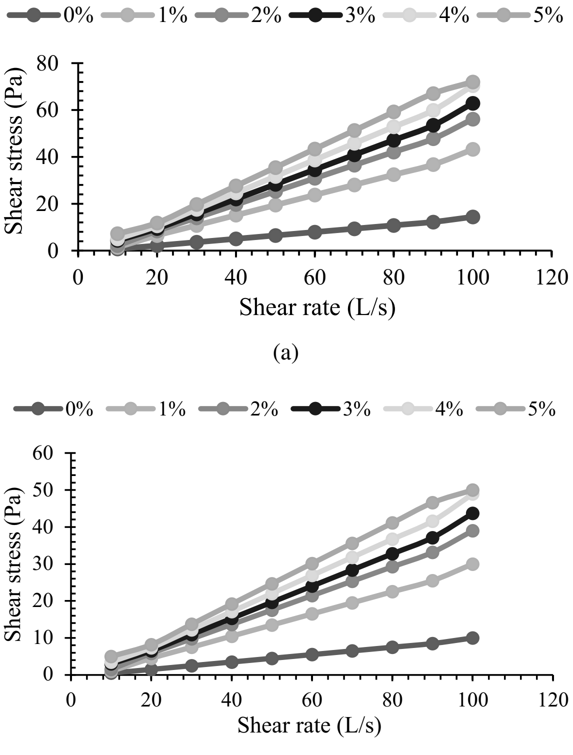
The increase in low-shear viscosity with the inclusion of nano clay suggests enhanced resistance to permanent deformation. Based on comparable studies, a 50–60% increase in viscosity at low shear rates can translate into a 20–30% improvement in rutting resistance. Thus, incorporating 5% nano clay may offer substantial benefits in hot-climate or high-load pavements [11].

ARL 60/70 consistently showed higher viscosity than ARL 80/100 due to its lower penetration grade and likely higher asphaltene content, which increases structural rigidity and resistance to flow. Asphaltenes act as rigid domains within the bitumen matrix, contributing to higher baseline viscosity, especially under low-shear conditions.

The enhanced low-shear viscosity is attributed to the exfoliated and intercalated structure of organophilic nano clay within the binder. As shown in Fig. 4b, exfoliated clay layers create a network-like architecture that restricts binder molecule movement under shear. This mechanism is supported by Chuaicham *et al.* [17], who found that exfoliated nano clays significantly improved the viscosity and structural integrity of clay-based composites.

3.4. Effect of shear rate on shear stress

Figure 6a–b depicts the relationship between shear rate and shear stress for two different types of asphalt binder such as ARL-80/100 and ARL-60/70 with varying quantities of organophilic nano clay, ranging from 0% to 5%. The plots indicate a linear relationship between shear rate and shear stress. The plots also demonstrate how the organophilic nano clay influences the shear stress of the asphalt modification. The deviation from linearity at high clay contents indicates viscoelastic network formation, enhancing deformation resistance. Figure 5a depicts the result of ARL-80/100 and shows the trend observed for shear stress. The result demonstrates the increase in shear stress by increasing the values of the shear rate from 10 to 100, indicating that the rate of shear increases is the reason for the binder requiring more force to continue flowing. The lowest value of shear stress was noticed for the binder without any percentage of clay mixed in while the highest value of shear stress was obtained at 5% addition of clay. The result suggests that increasing clay content increases resistance of the binder to change caused by the shear.



(a)

(b)

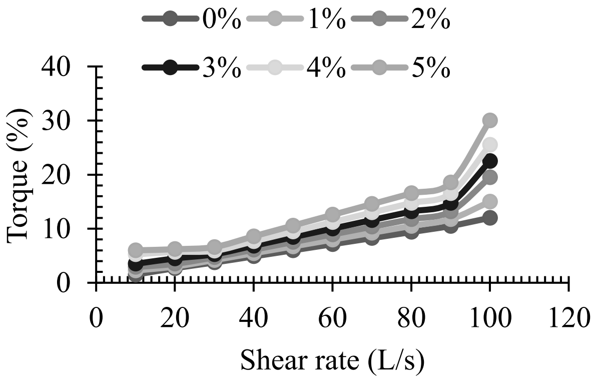
Fig. 6. Relationship between shear rate and shear stress: (a) ARL-80/100; (b) ARL- 60/70

Figure 6b depicts the result of shear stress in the case of ARL-60/70 asphalt binder. Figure 6b shows an increase in shear stress by increasing the values of shear rates indicating viscoelastic behavior. Similarly to ARL-80/100, the ARL-60/70 binder has the same trend of shear stress under various shear rate conditions. The existence of the clay content serves as evidence of increasing its resistance to the shear. The analysis indicated an approximately linear relationship between shear stress and shear rate, characteristic of viscoelastic materials. However, the modification of binder with clay content increases shear stress, resulting in more complex and non-Newtonian behavior of the asphalt binder. The addition of clay content into both ARL-80/100 and ARL-60/70 made the internal structure within the binder more rigid, rendering it more shear force resistant. The higher shear stress values achieved indicate more viscoelastic characteristics of the binder, offering significant resistance to change caused by external loads.

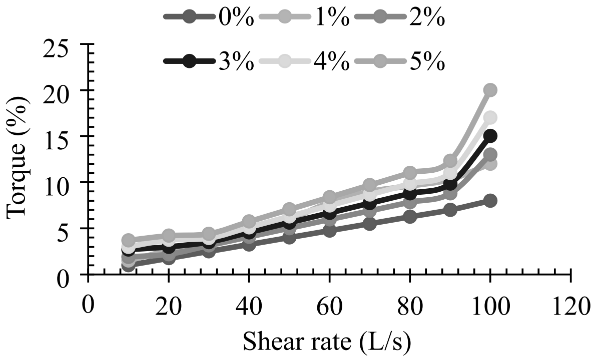
ARL 80/100 is more susceptible to stiffening as compared to ARL 60/70, resulting in higher values of the shear stress in the case of ARL 80/100. Another reason are the intrinsic characteristics of the ARL 80/100 binder. The result demonstrates the significance of ARL 80/100 in the context of its practical applications in the field of pavement engineering because of its higher values of shear stress and resistance to external loads. Moreover, ARL 80/100 is more sensitive to clay modification as compared to ARL 60/70.

3.5. Effect of shear rate on torque

Figure 7a–b shows the impact of shear rate on torque for various percentages of nano clay in asphalt binder. Figure 7 depicts the relationship between torque (%) and shear rate (L/s) for both ARL 60/70 and ARL 80/100 modified by varying concentrations of nano clay content. The torque increases with increasing the shear rate of ARL 60/70 and ARL 80/100, indicating that for maintaining shear more energy is required as the rate increases. The unmodified asphalt binder sample has lower torque as compared to the modified asphalt binder. The 0% nano clay content in the asphalt binder exhibited lower torque as compared to 5% nano clay in the asphalt binder. The difference between the values of torque obtained against different concentrations of nano clay content indicates that clay content becomes more noticeable at higher values of shear rate. The increase in concentrations of nano clay content results in higher torque.



(a)



(b)

Fig. 7. Relationship between shear rate and shear stress: (a) ARL-80/100; (b) ARL- 60/70

Torque was found to increase proportionally with shear rate for all clay concentrations. Increased torque resulting from increased clay content reflects stronger particle-matrix interaction, improving stability under heavy traffic. The rotational load required to sustain the shear rate was considered as torque in this context. The higher the concentrations of the nano clay, the higher the rotation, resulting in higher torque. With increasing the shear rate from 10 to 100 and clay content from 0% to 5%, a difference of 60% was observed in the torque. The increase in torques indicates the increase in internal friction and resistance of asphalt binder. Moreover, the addition of nano clay increases the torque because of the increase in internal friction of the binder, leading to resistance against shear and a need for greater energy.

The processing and functionality of asphalt binders are significantly impacted by the increase in torque that occurs with greater clay content and shear rate. Increased torque suggests that the binder becomes more difficult to flow, which may have an impact on the asphalt mix's general workability, compaction and mixing. Even though the clay's increased stiffness and resistance could increase the pavement's resilience to stretching, it might also necessitate modifying the techniques used to guarantee that the asphalt is mixed and laid properly. The lower torque values for ARL 60/70 indicate that it may be easier to work with during processing but may have slightly less resistance to deformation than ARL 80/100, especially when modified with higher clay content. The higher torque values for ARL 80/100 suggest that it may be more difficult to process, but its greater shear resistance may make it appropriate for applications that require increased durability and resistance to severe loads.

The observed increase in viscosity and torque with 5% organophilic nano clay indicates greater structural rigidity and resistance to deformation under shear. These rheological improvements are directly associated with enhanced rutting resistance in asphalt binders. Based on comparative rheological studies, such modifications can lead to an estimated 25–35% improvement in rutting resistance, particularly under high-temperature conditions and heavy traffic loads [11].

4. CONCLUSIONS

This study systematically evaluated the effect of organophilic nano clay on the rheological behavior of two penetration-grade asphalt binders (ARL 60/70 and ARL 80/100) under varying shear conditions. The following conclusions can be drawn:

- Organophilic nano clay enhanced the rheological performance of asphalt binders, particularly under low shear conditions, by increasing structural integrity and deformation resistance.
- The 5 wt% nano clay addition yielded the greatest improvement, with significant viscosity gains, and pronounced shear-thinning behavior, beneficial for high-temperature, heavy-traffic pavements.
- The improvement is attributed to an intercalated/exfoliated nano clay network that restricts molecular mobility and strengthens the bitumen matrix.
- ARL 80/100 showed a greater relative viscosity increase, while ARL 60/70 maintained broader flexibility and stability across the shear range.
- The study was limited to binder-level tests at ≥ 135°C; so further work is required to assess service-temperature and mixture-level performance.

Future studies should employ Dynamic Shear Rheometer (DSR) testing to evaluate viscoelastic performance under PG conditions and to assess the long-term durability of nano clay-modified binders through aging and moisture resistance analysis. In addition, field-scale mixture evaluations and life-cycle assessments are recommended to verify practical performance and economic feasibility.

STATEMENT AND DECLARATIONS

Data availability statement: All data used in this research appear in the submitted article.

Funding sources: This research did not receive any specific grant from funding agencies in the public, commercial or-not-for-profit sectors.

Conflicts of interest: The authors declare that there is no conflict of interest.

APPENDIX A

REFERENCES

[1] K.R. Usman, M.R. Hainin, M.K.I.M. Satar, M.N.M. Warid, S.N.N. Kamarudin, and S. Abdulrahman, "Palm oil fuel ash application in cold mix dense-graded bituminous mixture," *Constr. Build. Mater.*, vol. 287, p. 123033, 2021, doi: 10.1016/j.conbuildmat.2021.123033.

[2] M. Bilema, Y.B. Aman, N.A. Hassan, Z. Al-Saffar, K. Ahmad, and K. Rogo, "Performance of aged asphalt binder treated with various types of rejuvenators," *Civil Eng. J.*, vol. 7, no. 3, Mar. 2021, doi: 10.28991/cej-2021-03091669.

[3] Z.H. Al-Saffar *et al.*, "Physical, rheological and chemical features of recycled asphalt embraced with a hybrid rejuvenating agent," *Int. J. Pavement Eng.*, vol. 23, no. 9, pp. 3036–3054, 2021, doi: 10.1080/10298436.2021.1878517.

[4] W. Jiang, D. Yuan, J. Shan, W. Ye, H. Lu, and A. Sha, "Experimental study of the performance of porous ultra-thin asphalt overlay," *Int. J. Pavement Eng.*, vol. 23, pp. 2049–2061, 2022, doi: 10.1080/10298436.2020.1837826.

[5] H. Osman, M.R.M. Hasan, T.W.L. Xin, O.O. Sougui, and D. Khan, "Effects of bonding enhancers on shear stress and bonding strength of modified asphalt binders under different aging and

Table A.1

Physical properties of asphalt binder

Properties	Reference	Unit	ARL 60/70	ARL 80/100	Specification limit
Penetration @ 25°C	ASTM D5	1/10 mm	62	91	≥ 60
Softening point (°C)	ASTM D36	° C	49	44	≥ 43
Ductility at 25°	ASTM D113	cm	102	112	⩾ 100
Dynamic viscosity @ 135°C	ASTM D4402	Cp (mPa·s)	385.5	340.4	≥ 300

Table A.2

Viscometer settings and test parameters

Parameter	Value / Description
Instrument	Brookfield DV2T Viscometer
Test standard	ASTM D4402
Test temperature	135°C
Shear rate range	3.4–34 s^{-1}
Rotational speed range	5–50 rpm
Spindle type	SC4-27
Sample volume	10.5 mL
Number of replicates	3 per condition
Calibration fluids	100 mPa·s, 500 mPa·s (Brookfield Standard)
Calibration frequency	Weekly

Table A.3

Experimental conditions for Brookfield rotary viscosity tests

Organophilic clay (%)	Test temperature (°C)	Shear rate (1/s)
0, 1, 2, 3, 4, 5	135	3.4, 6.8, 10.2, 13.6, 17, 20.4, 23.8, 27.2, 30.6, 34

moisture conditions," *Constr. Build. Mater.*, vol. 453, p. 139020, Nov. 2024, doi: 10.1016/j.conbuildmat.2024.139020.

[6] M. Junaid, C. Jiang, U. Gazder, I. Hafeez, and D. Khan, "Evaluation of asphalt mixtures modified with low-density polyethylene and high-density polyethylene using experimental results and machine learning models," *Sci. Rep.*, vol. 14, no. 24601, pp. 1–13, 2024, doi: 10.1038/s41598-024-74657-1.

[7] B. Ali, P. Li, D. Khan, and I.U. Haq, "Evaluation of the properties of hot mixed asphalt modified by plastic waste," *Quaid-E-Awam Univ. Res. J. Eng., Sci. Technol.-Nawabshah*, vol. 19, no. 2, pp. 106–113, Dec. 2021, doi: 10.52584/QRJ.1902.16.

[8] C. Xing *et al.*, "A comprehensive review on the blending condition between virgin and RAP asphalt binders in hot recycled asphalt mixtures: Mechanisms, evaluation methods, and influencing factors," *J. Clean. Prod.*, vol. 398, p. 136515, 2023, doi: 10.1016/j.jclepro.2023.136515'

[9] E.R. Brown and C.E. Bassett, "Effects of maximum aggregate size on rutting potential and other properties of asphalt-aggregate mixtures," *Transp. Res. Rec.*, vol. 1259, pp. 107–119, 1990.

[10] T. Hassan, N. Ahmad, D. Khan, M.R.M. Hasan, A. Aman, and U. Farooq, "Performance evaluation of asphalt binder modified with shear thickening fluid," *J. Mater. Civ. Eng.*, vol. 35, no. 7, p. 04023187, Apr. 2023, doi: 10.1061/JMCEE7.MTENG-15322.

[11] A.A. Gandapur, H. Javed, W. Haroon, and H.R. Almujibah, "Effect of Organophilic Nano clay Modified Binder on High-Temperature Performance of Asphalt Mixture," *Preprints*, 2023, doi: 10.20944/preprints202308.0718.v1.

[12] Y. Ma *et al.*, "Performance evaluation of temperature effect on hot in-place recycling asphalt mixtures," *J. Clean. Prod.*, vol. 277, p. 124093, 2020, doi: 10.1016/j.jclepro.2020.124093.

[13] C. Shi, J. Wang, S. Sun, D. Lv, L. Xu, and S. Zhang, "Research on properties of basalt fiber-reinforced asphalt mastic," *Front. Mater.*, vol. 10, p. 1277634,Oct. 17, 2023, doi: 10.3389/fmats.2023.1277634.

[14] C. Li, Z. Fan, S. Wu, Y. Li, and Y. Gan, "Effect of carbon black nanoparticles from the pyrolysis of discarded tires on the performance of asphalt and its mixtures," *Appl. Sci.*, vol. 8, p. 624, 2018, doi: 10.3390/app8040624.

[15] B.C. Bai, D.-W. Park, H.V. Vo, S. Dessouky, and J.S. Im, "Thermal Properties of Asphalt Mixtures Modified with Conductive Fillers," *J. Nanomater.*, vol. 16, p. 255, 2015, doi: 10.1155/2015/926809.

[16] S. Zhao, B. Huang, X. Shu, and P. Ye, "Laboratory Investigation of Biochar-Modified Asphalt Mixture," *Transp. Res. Rec.*, vol. 2445, pp. 56–63, 2014, doi: 10.3141/2445-07.

[17] C. Chuaicham *et al.*, "Recent Clay-Based Photocatalysts for Wastewater Treatment," *Separations*, vol. 10, p. 77, 2023, doi: 10.3390/separations10020077.

[18] GDBentonite, "Organophilic bentonite product specifications," GDBentonite Co., 2023. [Online]. Available: https://www.gdbentonite.com

[19] K.A. Bohn, L.P. Thives, and L.P. Specht, "Physical, rheological, and permanent deformation behaviors of WMA-RAP asphalt binders," *Sustainability*, vol. 15, no. 18, p. 13737, 2023, doi: 10.3390/su151813737.

[20] D. Khan, R. Khan, M.T. Khan, M. Alam, and T. Hassan, "Performance of hot-mix asphalt using polymer-modified bitumen and marble dust as a filler," *J. Traffic Transp. Eng.-Eng. Ed.*, vol. 10, no. 3, pp. 385–398, 2023, doi: 10.1016/j.jtte.2022.12.002.