Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 10, No. 02, February, 2024

Influence of Filler Materials on Bituminous Mastic Rheology at High Temperatures

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Received 10 October 2023; Revised 08 January 2024; Accepted 11 January 2024; Published 01 February 2024

Abstract

The mixing and compaction temperatures of the bituminous mixture are determined by the viscosity of the binder. It was always a concern to understand the influence of the type of filler on the workability of the bituminous mixture. The interaction of the filler with the bitumen plays a key role in this. The inert filler has a physical interaction with the binder, and the active filler will have both a physical and chemical interaction. Based on the type of interaction, the viscosity and shear thinning characteristics of the mastic (binder + filler) change, which will hence influence the workability of the bituminous mixture. An experimental investigation is conducted to measure the viscosity of the mastic with two types of filler, one chosen from the active filler category (hydrated lime) and another from the inert filler category (quarry dust). A shear rate sweep experiment was carried out within the temperature range of 100 to 160 °C to analyze the Newtonian and shear thinning responses of the mastic. Results indicate that, for an equivalent weight proportion of the filler, mastic containing quarry dust exhibited elevated Newtonian viscosity and zero-shear viscosity (as predicted using the Carreau Yasuda Model). Additionally, quarry dust mastic demonstrated a higher rate of shear thinning. Consequently, the beneficial effect of shear thinning during the compaction of bituminous mixtures has the potential to enhance workability and streamline the compaction process.

Keywords: Bituminous Mastic; Workability; Shear Rate Sweep Test; Newtonian Viscosity; Shear Thinning Behavior; Zero Shear Viscosity.

1. Introduction

The bituminous mixture consists of bitumen binder, filler, and aggregate in predetermined proportions and gradation. Temperature is a fundamental variable that significantly impacts both the production process and the ultimate mix of volumetric and mechanical properties [1]. However, its importance is frequently overlooked. Throughout the manufacturing of Hot Mix Asphalt (HMA), the temperature of various components, including bitumen and virgin aggregate, can vary over a broad range [1]. To be precise, the evaluation of asphalt binders' behavior at high temperatures, where irreversible deformation occurs [2], needs more focus. The mixing of binder, filler, and aggregate is carried out at a higher temperature, which is determined by the viscosity of the binder. The temperature corresponding to the binder viscosity of 0.17 Pa.s is used as the mixing temperature [3]. The mixing of bitumen with aggregate is conducted at an elevated temperature that is determined from the binder viscosity. Here, the assumption is made that the binder exhibits a Newtonian response [4, 5] at higher temperatures. This assumption is justified by the shear rate independent of viscosity at these elevated temperatures. It is understood that after mixing and before the compaction of the mixture starts, the temperature decreases. During the compaction process, the bituminous mixture exhibits a non-Newtonian response that is based on assumption, considering the shear-thinning behavior observed during compaction.

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http://dx.doi.org/10.28991/CEJ-2024-010-02-013

The temperature corresponding to the binder viscosity of 0.28 Pa.s is considered the compaction temperature [3]. These assumptions and their justifications provide insights into the rheological behavior of the mixture during the key phases of the manufacturing process.

Different approaches have been proposed to determine the mixing and compaction of bituminous mixtures. Bitumen exhibits shear thinning behavior in the temperature range 80 to 120 °C used for the compaction [5]. Saboo & Kumar [6] used the zero shear viscosity of binder to predict mixing and compaction temperatures. Wang et al. [7] proposed an equi-torque approach using Warm Mix Asphalt (WMA) binder for determining mixing and compaction temperature. Yildirim [8] used the advantage of shear thinning of the binder during the compaction process and used the shear rate concept in determining the mixing and compaction temperature of the modified binder. Yildirim et al. [3] modified the viscosity range proposed in ASTM D 2493 [9] to 0.275 Pa.s and 0.55 Pa.s and included high shear rate viscosity to determine the mixing and compaction processes. Watson et al. [10] computed mixing and compaction temperatures using the phase angle of the bitumen. Bitumen exhibits a phase angle near 90° when it behaves as Newtonian. Watson et al. [10] used frequency corresponding to the phase angle of 86° to determine mixing and compaction temperatures.

Asphalt viscosity is the overall governing factor that influences the workability of the bituminous mixture. Over the years, various methods have been developed to accurately measure asphalt viscosity, with a notable parameter being the Zero-shear viscosity (ZSV). ZSV, a well-established viscosity parameter for asphalt binders, provides crucial insights into the material's rheological properties, particularly its response to deformation [11]. Understanding these viscosity dynamics is pivotal for optimizing the mixing and compaction processes, ensuring the longevity and performance of road pavements under diverse environmental conditions [12, 13].

While the equiviscous concept is a promising method for determining the mixing and compaction temperature of unmodified binder, it was proved ineffective for modified binder [14]. All the above-discussed approaches were proposed based on binder properties. However, it is understood that the workability of the bituminous mixture is more influenced by the bituminous mastics and not just the binder [15]. The combination of mineral filler (particles less than 0.075 mm in size) and binder, known as bituminous mastic, is recognized as the actual binder responsible for bonding the aggregates in the bituminous mix [16]. It is essential to recognize the substantial influence of bituminous mastics, which encompass the binder-filler interaction. The temperature determination process should not solely rely on binder characteristics but also consider the role of mastics in governing the workability and performance of bituminous mixtures. Recent advancements in bituminous mixture design have explored the incorporation of filler materials to enhance mixture properties. These fillers are known to alter the rheological behavior of mastics, affecting the viscosity, shear, and temperature susceptible properties of the binder [17, 18]. The inclusion of fillers introduces an additional layer of complexity in determining the optimal mixing and compaction temperatures.

The fillers used in the bituminous mastic can be classified as active and inert fillers. Fillers such as granite and stone dust are inert fillers, and hydrated lime is an active filler [19]. The interaction of filler with bitumen influences the shear thinning/thickening behavior of the mastic and hence affects the workability of the material. Another physicochemical interaction that governs the viscosity of the mastic is the influence of filler on the age-hardening of the binder [20]. Fillers affect the aging of bitumen through two mechanisms, such as physical presence and interactions. The physical presence of filler compels the oxygen molecules and reduces the rate of oxidative aging of bitumen. Interactions lead to the catalysis of bitumen oxidation. Therefore, filler particles increase the oxygen diffusion path in mastics, thus reducing bitumen oxidation [21]. This interaction may influence the Newtonian and non-Newtonian behavior of the mastic. The determination of the flow curve of the mastic at the mixing and compaction temperature range can be used to classify Newtonian and non-Newtonian responses of the mastic. The mastic may exhibit shear thinning behavior at the mixing temperature range, and this shear thinning behavior at a high shear rate may ease the mixing process. However, the extent of shear thinning may depend on the type of filler used. With the above-mentioned complexity in the interaction between the filler and binder, it becomes essential to evaluate the influence of different fillers on the viscosity of bitumen at various temperatures. This will help in understanding the mechanism that occurs during the mixing and compaction process of the bituminous mixture.

The role of zero shear viscosity (ZSV) in characterizing the permanent deformation resistance of mastic asphalt mixtures has gained considerable attention, as evidenced by recent studies. Notably, a comprehensive laboratory investigation by Kołodziej et al. [22] and Adnan et al. [23] explored the intricate interplay between ZSV, binder modification, and mastic composition in the context of rutting resistance. By assimilating insights from ZSV research, we aim to extend the understanding of how filler-binder interactions, influenced by ZSV, impact the workability of bituminous mixtures during the critical phases of mixing and compaction under elevated temperatures.

While various methods have been proposed to determine the mixing and compaction temperatures of bituminous mixtures, most of these approaches primarily focus on binder properties and overlook the significant influence of bituminous mastics. The existing methodologies, often based on the equiviscous concept, have proven ineffective for modified binders, limiting their applicability. The intricate interplay between binder and mineral filler, known as bituminous mastic, is recognized as the actual binder responsible for bonding aggregates in bituminous mixtures. Despite the advancements in bituminous mixture design, there is a research gap in considering the role of mastics, especially in the context of modified binders and the inclusion of fillers. In this study, we propose to address this research gap by investigating the influence of different fillers on the viscosity of bitumen at various temperatures. The goal is to understand the mechanisms occurring during the mixing and compaction process of bituminous mixtures, with a specific focus on the interaction between fillers and binders. Unlike previous approaches that solely rely on binder characteristics, our approach recognizes the crucial role of bituminous mastics in governing the workability and performance of the mix. By considering the impact of active and inert fillers on the shear thinning/thickening behavior of mastics, as well as their influence on the age hardening and oxidative aging of bitumen, we aim to develop a comprehensive understanding of the complex rheological properties of bituminous mixtures.

This paper embarks on an in-depth analysis of the rheological behavior of bituminous binders and mastics at temperatures between 90 and 150 °C, focusing on the critical distinctions between Newtonian and non-Newtonian responses. This work focuses on the investigation of two types of mastics: Hydrated Lime Mastics (HLM) and Quarry dust Mastics (QDM), and assesses how the inclusion of these filler materials modifies the viscosity-shear rate relationships at elevated temperatures. To accomplish this, the study employed the Carreau-Yasuda model, a well-established rheological model, to model the shear-thinning behavior of mastic. This modeling approach enables the underlying rheological mechanisms governing the non-Newtonian behavior observed at specific temperature intervals within the range of the study. Furthermore, the model-derived Zero shear viscosity (ZSV) emerges as a crucial parameter for further analysis, reflecting the viscoelastic properties of these mastics under different temperature conditions. This paper provides a comprehensive understanding of how bituminous mastics, in conjunction with binder-filler interactions, respond to elevated temperatures. Such insights are instrumental in tailoring bituminous mixtures to meet the demands of diverse road construction scenarios, ensuring durability, sustainability, and superior performance.

2. Materials

2.1. Bitumen

The bitumen of grade VG30, as per IS 73 (2019) [24], is used for the experimental investigation. The basic properties of bitumen are listed in Table 1. Bitumen, before usage, is conditioned for 30 minutes at 60 °C to remove any steric hardening in the binder.

Table 1. Basic properties of bitumen

Tests (as per IS 73, 2013)	Results obtained	Specification compliance for VG30 as per IS 73:2013
Penetration at 25 ºC	61 mm	Minimum of 45 mm
Absolute viscosity at 60°C	2677 Poise	2400-3600 Poise
Kinematic viscosity at 135°C	510 cSt	Minimum 350 cSt
Softening point (R&B)	51.5 °C	Minimum 47°C
Tests on residue from rolling thin film oven test		
a) Viscosity ratio at 60°C	2.6	Maximum of 4
b) Ductility at 25°C	>100 cm	Minimum of 40 cm

2.2. Bituminous Mastics

Two different fillers, one from the inert filler category (stone dust or quarry dust) and another from the active filler category (hydrated lime), are used for the preparation of mastic. The filler passing 75 microns is used here. The bituminous mastics are prepared by heating the base binder to 165 °C and then mixed with the filler material in the proportion of 1:1 by the weight of base binder. Hand-mixing of the bitumen and filler is carried out at 165 °C for 10 minutes. The mastics prepared are stored in a container and tested within 48 hours. The materials are conditioned in the water bath at 60 °C for duration of 45 minutes before testing. Further in the study, the mastic prepared with quarry dust is designated as QDM, and the mastic with hydrated lime is designated as HLM.

3. Experimental Investigations

The experiments were performed in a Brookfield HA DV-II rotational viscometer with a torque capacity of 1.44 mNm [5, 25]. The temperature was controlled using a thermosel attached to the equipment, as shown in the Figure 1. An SC4-21 spindle was chosen, and 8 g of sample weight were used for each sample. The sample preparation and the required pre-shearing were performed as per ASTM D4402 (2006) [26].

Figure 1. Materials and Experimental setup

The experimental investigation is carried out in two stages, as shown in Figure 2. In the first stage, the speed of the spindle (shear rate) corresponding to 10 % torque was identified for all the test temperatures. For this purpose, the steady shear test was conducted on the binder and two different mastics for every 5 °C temperature in the range of 90 to 150 °C. The shear rate corresponding to 10 % torque was identified and used as the initial shear rate for the shear rate sweep test. Figure 3 shows the spindle speed that corresponds to 10 % torque.

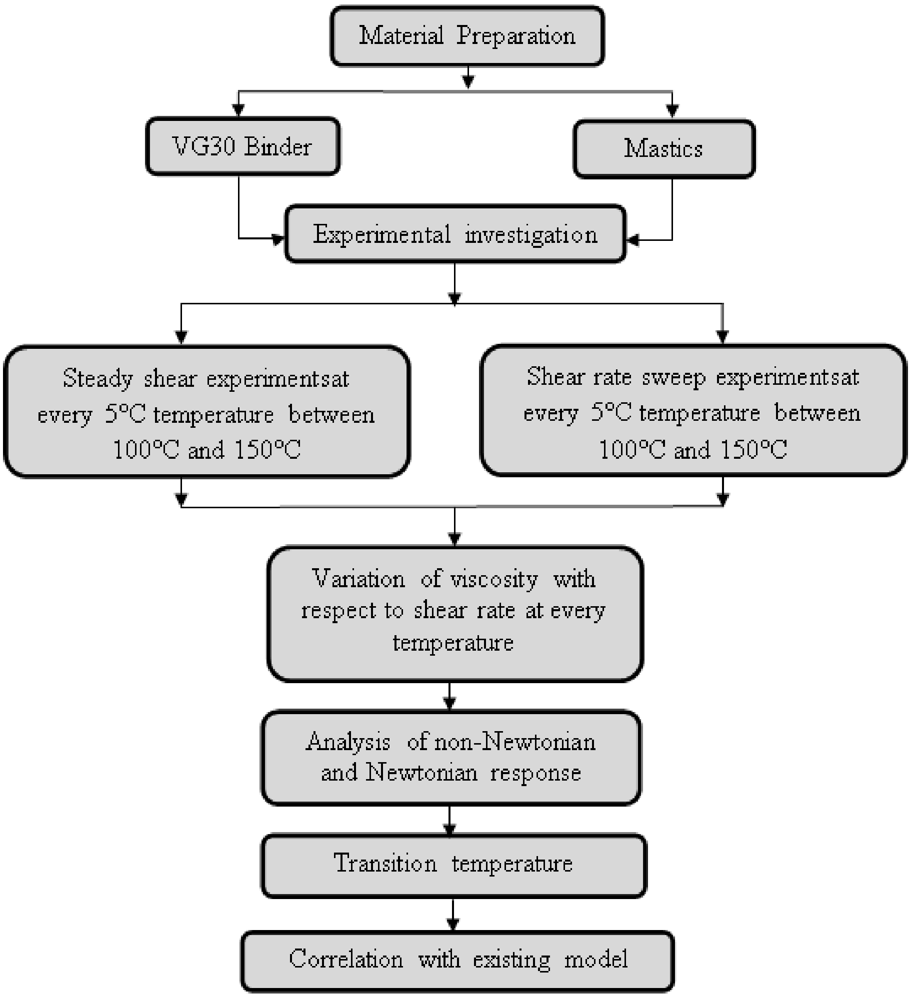


Figure 2. Flowchart of the Methodology

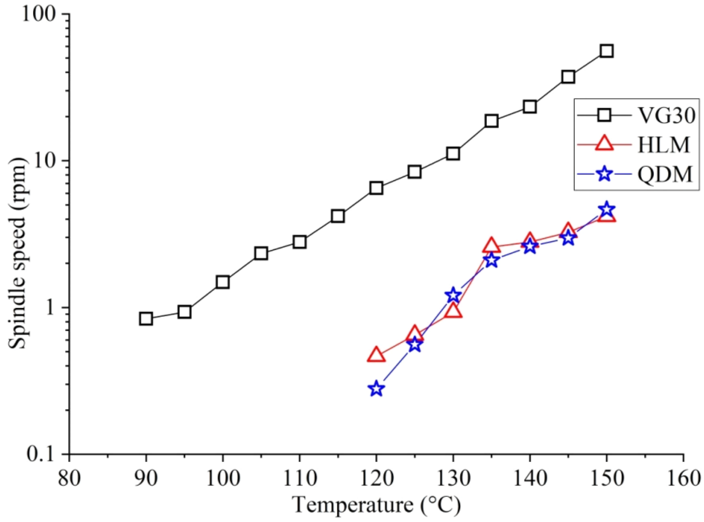


Figure 3. Shear rate corresponding to 10% torque at various temperatures

In the second stage of experimental investigations, the shear rate sweep was conducted over a range of temperatures. For the bitumen, tests were conducted at every 5 °C temperature in the range of 90 to 150 °C. On the other hand, the two distinct mastics were subjected to shear rate sweep tests within the range of 120 to 150 °C. The samples were conditioned at the test temperatures for 15 minutes to ensure thermal equilibrium. Subsequently, a pre-shearing was carried out for 5 minutes, by applying the shear rate corresponding to 10 % torque, as determined in prior steady shear experiments. A gradual ramp of 0.02 rpm/s was applied in the shear rate sweep and carried out until the torque of 90 % is reached [5]. The schematic diagram of the shear rate sweep test is shown in Figure 4. The range of shear rate used at different temperatures is shown in Table 2. The viscosity at different shear rates for every one second was recorded.

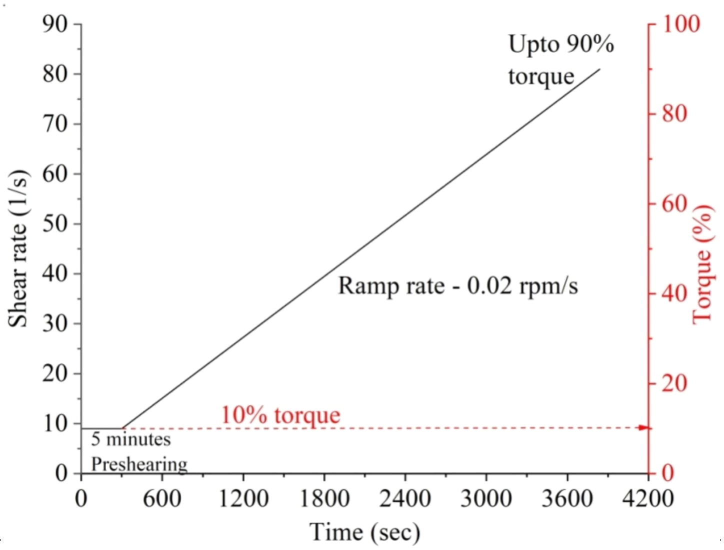


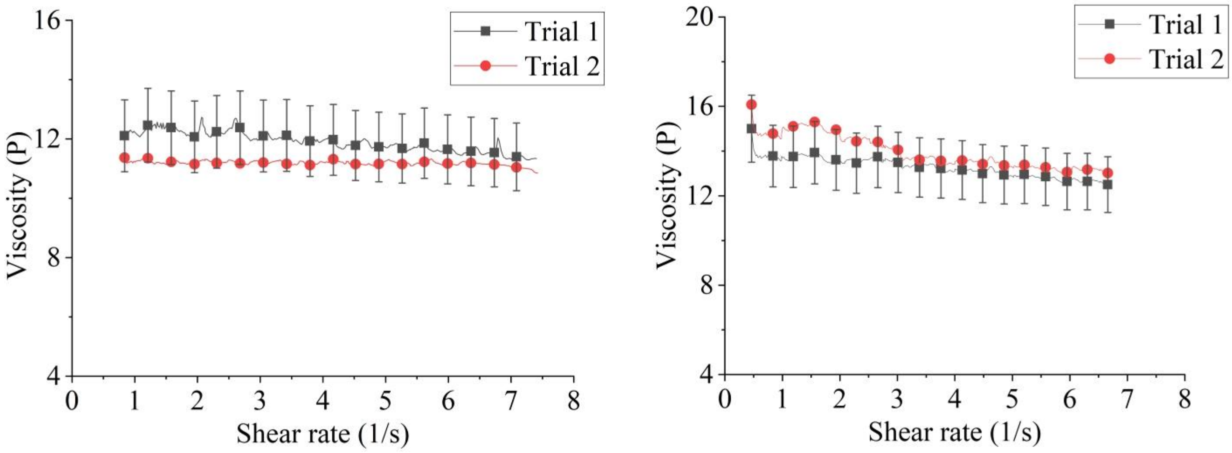
Figure 4. Schematic diagram of the shear rate sweep test

Table 2. Shear rate range at different test temperatures

Temperature (°C)	Shear rate range		
	VG30	HLM	QDM
90	0.84 – 7.40		
95	0.93 – 12.75		
100	1.49 – 17.43		
105	2.23 – 25.02	-	-
110	2.79 – 37.14		
115	4.18 – 46.11		
120	6.51 – 71.53	0.46 – 6.66	0.28 – 4.15

125	8.37 – 98.37	0.65 – 7.62	0.56 – 4.33
130	11.16 – 134.50	0.93 – 11.25	1.21 – 12.83
135	18.6 – 159.60	2.58 – 21.65	1.86 – 14.27
140	23.25 – 186.00	2.79 – 24.72	2.60 – 23.06
145	37.2 – 148.10	3.25 – 28.25	2.98 – 34.11
150	55.8 – 148.90	4.18 – 38.97	4.65 – 46.30

The test was repeated atleast twice so that the difference in the viscosity between two trials has not exceed 10 %. The sample repeatability results are shown in the Figure 5. The repeatability in the viscosity value is ensured for the entire range of shear rate used for testing.



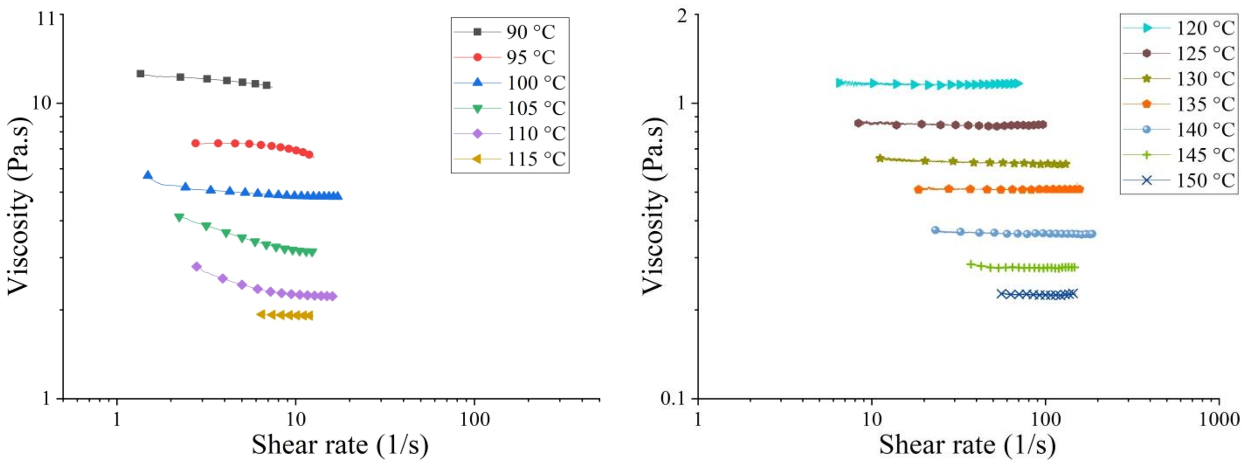
(a) (b)

Figure 5. Test repeatability (a) VG30 at 90 °C (b) HLM at 120 °C

4. Results and Discussion

4.1. Mixing and Compaction Temperature

Figure 6 shows the viscosity of VG30 measured at different temperatures. The viscosity of the bitumen at 90 to 115 ^{0} C is shear rate dependent, and it exhibits slight shear thinning behavior from 90 to 115 ^{0} C. The viscosity of VG30 when tested at 120 ^{0} C and above is observed to be shear rate independent and hence Newtonian. This observed Newtonian response at 120 ^{0} C aligns with the findings reported in the study conducted by Nivitha & Krishnan [25]. Further, this Newtonian viscosity is used in determining the mixing and compaction temperatures. Figure 7 shows the mixing and compaction temperature determined from the viscosity of the binder. The temperatures corresponding to the viscosity of 0.17 Pa.s and 0.28 Pa.s are considered as the mixing and compaction temperatures respectively. Therefore, the mixing temperature and compaction temperature of the bitumen as per the equiviscous method were found to be 156 °C and 145 °C respectively. Further, Newtonian and non-Newtonian behavior of QDM and HLM are analyzed in this temperature zone.



(a) at 90 to 110^0 C (b) at 120 to 150 ^{0} C

Figure 6. Viscosity – shear rate plot of VG30 binder

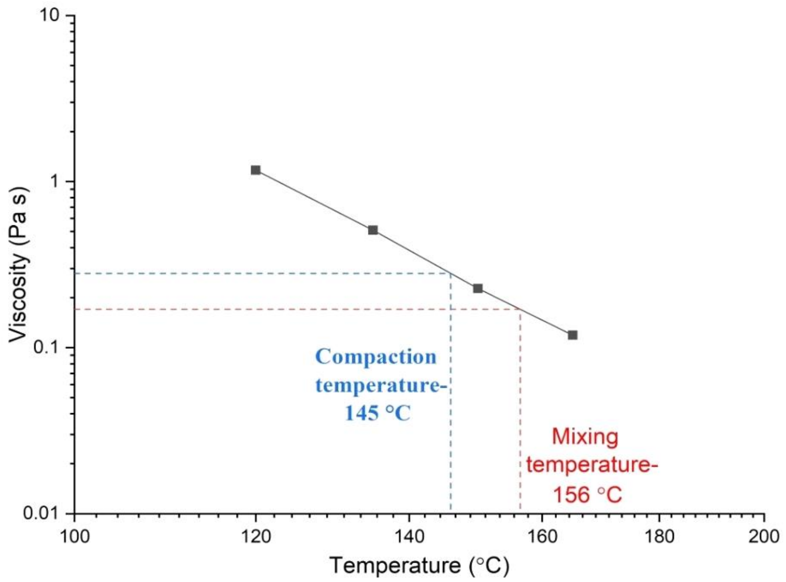
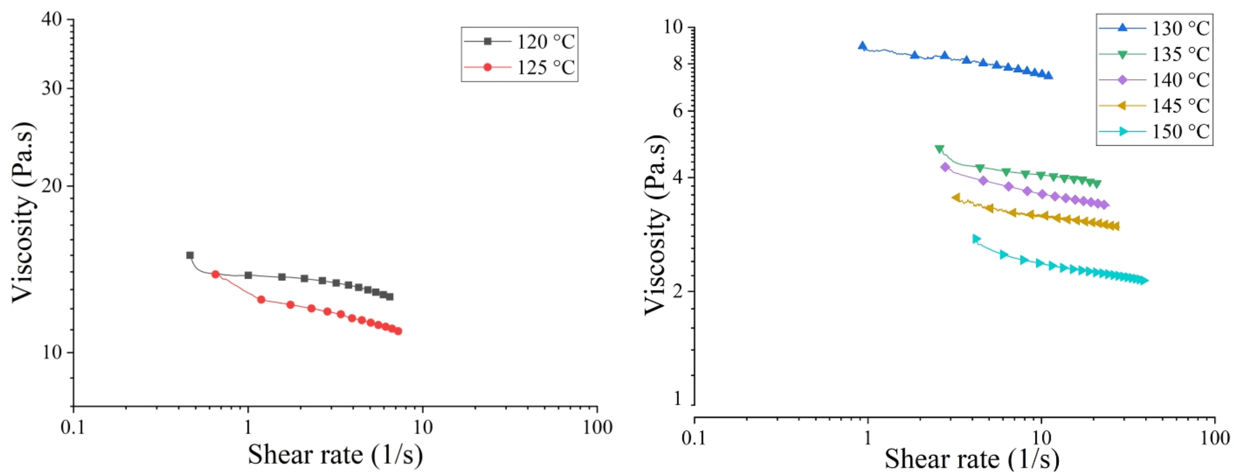


Figure 7. Mixing and compaction temperature determined based on equi-viscous concept

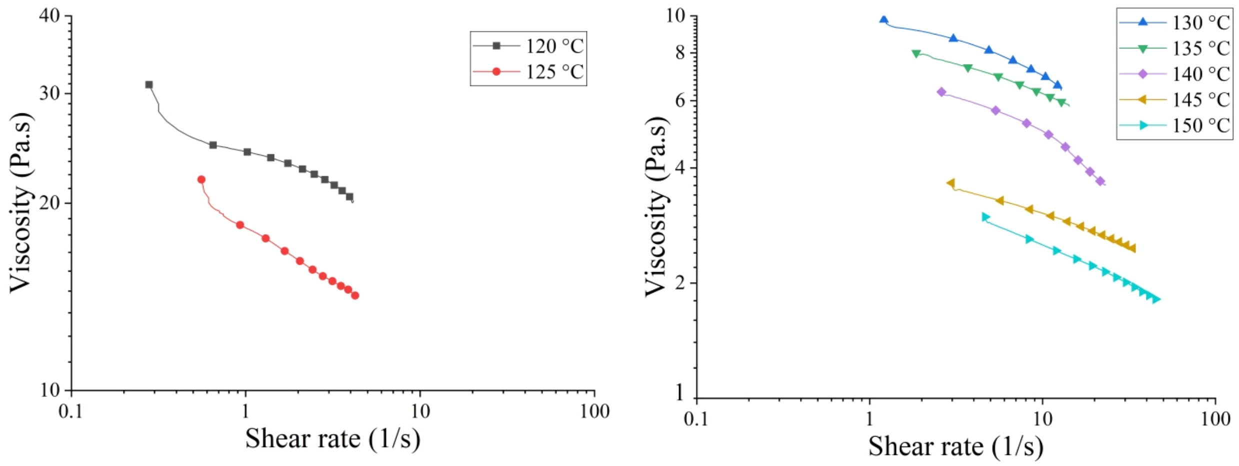
4.2. Newtonian – non-Newtonian Behavior of Mastic

Figure 8 shows the viscosity as a function of the shear rate for HLM measured 120 to 150 ℃. The viscosity of HLM is shear rate-dependent, and hence it exhibits non-Newtonian behavior in this temperature zone. Figure 9 shows the shear rate-dependent viscosity of QDM. With viscosity decreasing with shear rate increase, QDM exhibits non-Newtonian behavior in this temperature zone. Figure 10 compares the viscosity of HLM and QDM with the VG30 binder. On comparing the viscosity of HLM and QDM with VG30 binder, both the mastics exhibits higher viscosity than the binder. At 120 ^0C, VG30 exhibits Newtonian behavior with the viscosity of 1.16 Pa.s. HLM exhibits shear thinning behavior at 120 ^0C, with the viscosity varying from 10 to 12 times the binder. Likewise, QDM also exhibits shear thinning behavior at 120 ^0C, with the viscosity varying from 17 to 26 times the binder. For the same volume proportion of filler, at 120 ^0C, QDM exhibits higher viscosity than HLM. But, at 150 ^0C, both the mastics exhibit nearly the same viscosity, and it is found to be 10 times that of VG30 binder. However, QDM exhibited a higher shear thinning rate when compared to HLM. The average rate of shear thinning of HLM at 120 ^{0} C is found to be 0.355 Pa.s/s^{-1} and at 150 ^0C, it is 0.019 Pa.s/s^{-1}. Likewise, the average rate of shear thinning of QDM at 120 ^0C is found to be 1.240 Pa.s/s^{-1}, and at 150 ^0C, it is 0.027 Pa.s/s^{-1}. As expected, the rate of shear thinning reduced with an increase in temperature. The rate of shear thinning is higher in QDM when compared to HLM. Hence, the beneficial effect of reduction in viscosity due to shear thinning (if any) during mixing (that was carried out at a higher shear rate) is more pronounced in QDM. Hence, if one considers the beneficial effect of shear thinning for the determination of mixing temperature, hydrated lime (active filler) mastic needs higher mixing and compaction temperature when compared to QDM.



(a) at 120 and 125 ^{0} C (b) at 130 to 150 ℃

Figure 8. Shear rate dependent viscosity of HLM



(a) at 120 and 125 ⁰ C (b) at 130 to 150 ℃

Figure 9. Shear rate dependent viscosity of QDM

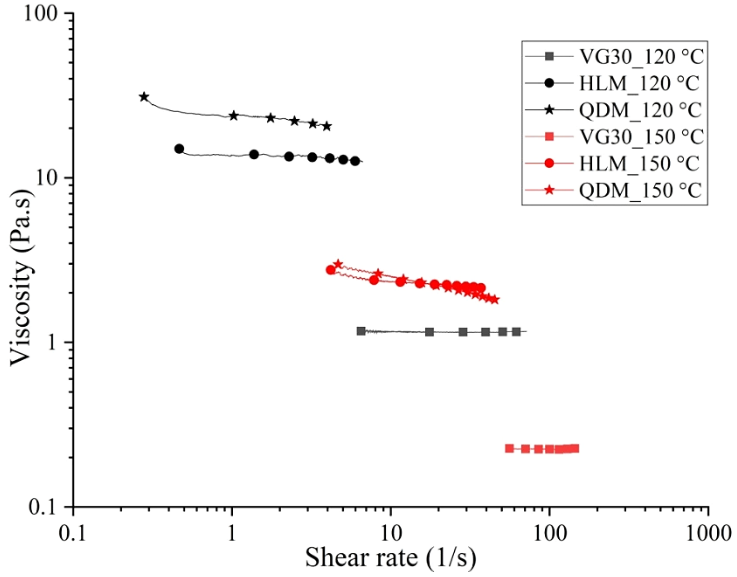


Figure 10. Comparison of viscosity of binder and mastics

4.3. Model

QDM and HLM exhibit shear thinning behavior and the Carreau Yasuda Model is used for the evaluation of the shear thinning behavior of the material. The model relating viscosity and shear rate is given in Equation 1,

$$\frac{\eta-\eta_\infty}{\eta_0-\eta_\infty} = [1 + (k\dot{\gamma})^a]^{\frac{n-1}{a}} \quad (1)$$

where η represents the viscosity at any given shear rate $\dot{\gamma}$, η_0 represents viscosity at the low shear plateau and is called zero shear viscosity (ZSV), η_∞ represents viscosity at a high shear plateau and is also called as infinite shear viscosity. *k, a, n* are the constants. Here, the shape parameter '*a*' elucidates the transition from low to high shear behaviors. The time constant '*k*' governs the rate of transition, while the flow behavior index '*n*' characterizes the material's response to changes in shear rate.

The Carreau Yasuda model is fitted with the experimental results using the MATLAB software. The utilization of the Curve Fitting Tool within MATLAB facilitated a more refined process of model fitting, contributing to the optimization of model parameters following predefined criteria. The model parameters of the Carreau Yasuda model were determined for the R-square value ranging from 0.95 to 1. The model parameters were identified for the VG30 binder at all temperatures of non-Newtonian behavior (105 ℃ to 115 ℃) and are listed in Table 3. The model parameters for HLM and QDM are listed in Tables 4 and 5. Further, the model parameters are used to analyze the temperature-sensitive and shear-sensitive characteristics of the mastic with different fillers.

Table 3. Carreau Yasuda model parameters for VG30

Temperatures	η_o	η_∞	a	k	n	R-square
105 ℃	11.040	2.761	18	3.977	0.19	0.9956
110 ℃	7.062	2.099	18	2.988	0.01	0.9596
115 ℃	2.494	1.891	18	2.498	0.01	0.9925

Table 4. Carreau Yasuda model parameters for HLM

Temperatures	η_o	η_∞	a	k	n	R-square
120 ℃	19.16	9.961	18	15.680	0.8	0.9209
125 ℃	15.58	10.54	18	14.740	0.7	0.9794
130 ℃	11.49	5.241	18	13.840	0.8	0.9689
135 ℃	8.586	3.095	18	11.950	0.7	0.969
140 ℃	6.855	2.522	18	9.405	0.7	0.9929
145 ℃	5.173	2.443	18	7.964	0.7	0.9918
150 ℃	4.108	1.681	18	6.480	0.7	0.9638

Table 5. Carreau Yasuda model parameters for QDM

Temperatures	η_o	η_∞	a	k	n	R-square
120 ℃	29.89	6.001	18	9.121	0.8	0.9508
125 ℃	25.53	5.222	18	7.889	0.8	0.9596
130 ℃	18.85	4.336	18	7.444	0.7	0.9505
135 ℃	12.83	2.180	18	5.974	0.8	0.9926
140 ℃	9.55	1.221	18	3.803	0.7	0.969
145 ℃	5.245	0.656	18	2.797	0.8	0.9896
150 ℃	5.031	0.540	18	2.018	0.7	0.9936

The variation in zero shear viscosity (ZSV) (η_o) with temperature is analyzed to understand the temperature-sensitive property of two mastic samples. The variation of the ZSVof all three samples with the temperature is shown in Figure 10. The ZSV of QDM at all temperatures is found to be higher when compared to HLM. On comparing the ZSV of the mastic and bitumen, the filler added to the binder increased the viscosity at zero shear rate. For the same proportion of quarry dust and hydrated lime filler, ZSV of QDM is higher than HLM, indicating the influence of different fillers in the binder. Zero shear viscosity of the binder with temperature is expected to exhibit an exponential relation with the temperature [19]. Figure 11 clearly shows that the ZSV of the mastic also exhibits an exponential decrease with the temperature. The constants of the exponential function given in Equation 2 are listed in Table 6.

$$\eta_o = ae^{bT} \tag{2}$$

where *T* represents temperature and *a* and *b* are model constants. A negative value of *b* in Table 6 indicates the decrease in viscosity with temperature and the magnitude of *b* represents the temperature sensitive characteristics of the material. The values of *b* of HLM and QDM are nearly the same, indicating the identical temperature-sensitive property of both the mastics. However, on comparing the mastic value of *b* with the binder data, the variation of zero shear viscosity of mastic with temperature is considerably lesser than the binder.

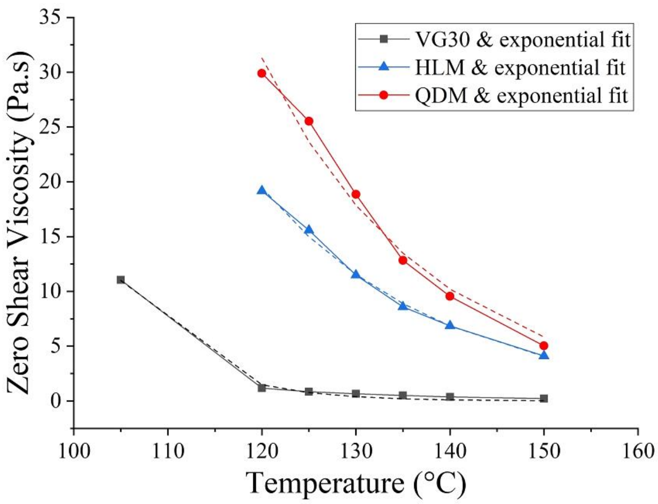


Figure 11. Variation of ZSV with temperatures

Table 6. Exponential fit parameters of zero shear viscosity

Material	a	b	R^2
VG30	1.359×10^7	- 0.1336	0.9959
HLM	1.011×10^4	- 0.05212	0.9966
QDM	2.598×10^4	- 0.05602	0.9826

To understand the influence of higher shear rate on the viscosity of the mastic, viscosities at higher shear rates of 500 and 5000 s^{-1} are computed using the Carreau Yasuda model parameters listed in Table 4 and 5. The high shear rate viscosities of the mastic are listed in Table 7. The zero shear viscosity of QDM is higher than HLM; however, due to higher rate of shear thinning of the QDM sample, viscosity of QDM at higher shear rates is lesser than HLM. With the temperature-sensitive characteristics of both the mastics being the same, QDM exhibited higher shear thinning behaviour. This indicates that during compaction, to achieve the same level of compaction, HLM may need more effort of compaction than QDM.

Table 7. Viscosity (in Pa.s) of mastics at higher shear rates

Mastic Type	125 °C			135 °C			145 °C		
	ZSV	500 s^{-1}	5000 s^{-1}	ZSV	500 s^{-1}	5000 s^{-1}	ZSV	500 s^{-1}	5000 s^{-1}
HLM	15.58	10.89	10.71	8.586	3.5	3.3	5.173	2.67	2.56
QDM	25.53	8.56	7.24	12.83	3.8	3.12	5.245	1.73	1.34

5. Conclusions

- The experimental investigation in this study has highlighted the significant influence of filler type on the behavior of bituminous mixtures. The choice between active filler like hydrated lime (HLM) and an inert filler like quarry dust (QDM) has substantial implications for the viscosity and shear-thinning characteristics of the mastics.
- The viscosity of bitumen (VG30) exhibits a transition from shear rate-dependent (shear thinning) to shear rate-independent (Newtonian) behavior at temperatures above 115 °C which is aligned with the study carried out by Nivitha & Krishnan [25]. This transition plays a key role in determining the mixing and compaction temperatures of bituminous mixtures.
- The mastics containing HLM and QDM both show shear-thinning behavior in the temperature range of 120 to 150 °C. However, QDM exhibits a higher shear-thinning rate than HLM, indicating its potential advantage during the mixing and compaction process.
- The Carreau Yasuda model provided a valuable framework for characterizing the shear-thinning behavior of mastics. The model parameters, including zero shear viscosity, were used to analyze the temperature-sensitive and shear-sensitive characteristics of the mastics with different fillers.
- Both HLM and QDM exhibited temperature-sensitive properties, as demonstrated by the exponential decrease in zero shear viscosity (ZSV) with increasing temperature. This property is essential to consider while determining the mixing and compaction temperatures.
- The addition of filler materials (HLM and QDM) to the bitumen increases the viscosity at zero shear rate. This comparison underscores the influence of different fillers on bituminous mixture properties.
- This helps to conclude that for the same level of compaction, HLM may require more effort during the compaction process than QDM due to its lower shear-thinning behavior. This has practical implications for optimizing bituminous mixture designs and compaction procedures in road construction.

6. Declarations

6.1. Author Contributions

Conceptualization, S.G. and P.A; methodology, S.G. and P.A.; software, S.G.; validation, S.G. and P.A; formal analysis, S.G. and P.A; investigation, S.G.; writing—original draft preparation, S.G. and P.A; writing—review and editing, S.G. and P.A.; supervision, P.A.; All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

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