Rheological Investigation of Soft Grade Asphalt Binder Modified With Crumb Rubber-Nanosilica Composite

Tabish Mehraj, Mohammad Shafi Mir, and Bijayananda Mohanty

Abstract This study aims at investigating the effect of using nanosilica (NS) as a modifier for Crumb rubber (CR) modified asphalt binder. In this study, the concentration of CR was kept constant as 12% (wt of base binder) and the nanosilica concentration was varied from 1% to 6%. The effect of varying concentrations (1, 2, 3, 4, 4.5, 5 and 6%) of nanosilica (by weight of binder) on CR modified binder were evaluated by utilizing various physical tests like penetration, softening point, and ductility. The rotational viscosity (RV) and dynamic shear rheometer (DSR) tests were used to analyze rheological properties of base binder and nanosilica polymer modified asphalt binder. In addition, the performance of modified asphalt after thin film oven (TFO) (short-term aging) and Pressure aging Vessel (PAV) test (long term aging) were assessed as well. Furthermore, the storage stability of modified asphalt binder was evaluated. Results showed that the addition of nanosilica has a positive effect on rutting performance of CR modified asphalt binders. Storage stability of the CR modified asphalt binders improved significantly after the addition of nanosilica. Using softening point and rheological parameters (complex modulus (G*) and phase angle (δ), the best values were possessed by 12% CR-4% NS modified binder. During rheological characterization, it was found that complex modulus increases, phase angle decreases, superpave rutting parameter increases and failure temperature increases with increasing nanosilica content. It was also found that Brookfield viscosity increases with increasing nanosilica concentration as the binder becomes stiffer. All the test results confirmed the fact that the crumb rubber-nanosilica modifier is effective in enhancing the high temperature properties (rutting resistance) of the soft grade binders and at the same time, it increases the elasticity of the binders.

Keywords Crumb rubber · Nanosilica · Superpave rutting parameter · Superpave fatigue parameter · Viscosity · Ageing · Storage stability

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T. Mehraj (✉) · B. Mohanty
Department of Civil Engineering, National Institute of Technology, Mizoram 796012, India
e-mail: tabish_10mtech20@nitsri.net

M. S. Mir
Department of Civil Engineering, National Institute of Technology, Srinagar 190006, India

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1 Introduction

Today is a world of sustainable technology and researchers are interested in finding sustainable, eco-friendly and cost-effective materials. Use of crumb rubber, also called black pollutant [34] in asphalt production is such cost-effective, ecofriendly [4, 30] and sustainable material which transforms an unwanted residue into a new bituminous mixture which is highly resistant to rutting and fatigue. The use of crumb tire rubber (CTR) is an interesting alternative from both economical and environmental perspectives [13]. CTR is dangerous due to its potential environmental threat and fire hazards [17] and its usage in pavements solve its disposal problem [37] and such threats. Crumb rubber modified binder (CRMB) provides improved mechanical properties, increases pavement durability and reduces reflective cracking and fatigue resistance [23]. Compared to conventional road surfaces, those made from CRMB have a longer service life, with 50–70% decrease in noise level raised cold- and heat-resistance properties and improved slip resistance, resulting in shorter braking distance and a higher safety coefficient [34].

Crumb rubber can be incorporated into asphalt mixtures either by wet or dry process. In the dry process, CR is used as partial substitution for fine aggregate. However in wet process, the CR powder is first blended with hot base asphalt and then swelled in the matrix to prepare modified asphalt. The wet process can generate two totally different modified asphalts, called as asphalt rubber (AR or wet-process-high-viscosity) and terminal blend (TB or wet-process-no-agitation). AR binders can be produced by using more coarser rubber (minus 30 mesh, greater than 15% wt of virgin asphalt), and are resistant to rutting and reflective cracking but cause issues due to higher viscosity such as difficult to handle while paving, inability to store over long periods and modification of mixing equipment by contractors [15]. Thus, a good alternative is the TB binder that overcomes the viscosity issue by using less and finer CR (plus 30 mesh, less than 10%wt of virgin asphalt) and by applying high temperature shear in the modification. TB has better storage stability than AR [24].

TB binder holds many advantages such as low viscosity, good workability and applicability to dense graded mixture [25] but degradation of CR might impair the elasticity of binder and high temperature performance [22, 24]. Although digestion of rubber in TB improves its thermal storage stability it still has some separation problems due to partially undissolved rubber particles [14]. To remove such anomaly, modification with a second modifier can be done.

In recent years, nanomaterials have been widely used to enhance the physical, rheological and mechanical properties of asphalt binder [29]. Addition of nano-sized additives improves the performance of asphalt binder and overcomes the drawbacks of polymers. Thus, Polymer nanocomposites are considered to be more powerful modifiers [28]. Nanosilica is an inorganic nanomaterial that has been being widely used to enhance the performance of polymer modified asphalt [1]. Nanosilica can be produced by agricultural waste materials such as rice husk ash, sorghum vulgare seed heads and bagasse ash by precipitation method, bio-digestion process and sol–gel process (Bhat and Mir 2020). Addition of Nanosilica improves the storage modulus, elasticity and ageing resistance of the asphalt binder [27] because of its high specific surface area, high functional density and high strain resistance.

Various researches have been done to improve the physical, rheological, and mechanical properties of CRMA in recent years. For example, Attia has added 2% SBS to improve the binder performance [6]. Khasawneh added MSW and NS to CRMB and found no enhancement by MSW of high temperature performance but a negative effect on low-temperature performance. Addition of 12% CTR was recommended because it produced the greatest enhancement for high temperature performance [5]. Abedali added bentonite (khawa clay) and crumb rubber to asphalt. The addition of bentonite and crumb rubber enhanced asphalt properties such as the viscosity, ductility and softening point, decreased penetration [2]. Liu added NS to pre-oxidized CR. H_2O_2 and NaClO were used to oxidize the CR. Overall, Storage stability and high temperature performance was enhanced [18].

The purpose of the current study is to use nanosilica to improve the performance of CRMB at high and intermediate temperatures as well as its storage stability. The goal of this study is to determine whether it is feasible to use 12% CRMB with NS particles while utilising seven different NS contents (NS contents of 1, 2, 3, 4, 4.5, 5, and 6%). To learn more about the properties of CR-NS binders, several experiments were carried out, including the standard tests, brookfield viscosity (BV), dynamic shear rheometer (DSR), storage stability, short term ageing, and long term ageing.

2 Goals of the Study

(1) To determine Optimum Mixing Time for preparation of Crumb rubber-Nanosilica modified bitumen.
(2) To evaluate the Optimum Nanosilica content for the Crumb rubber modified binder (CRMB) using softening point method and rheological parameters (G^* and δ).
(3) To investigate the influence of Crumb rubber-Nanosilica nanocomposite on viscosity of the asphalt binder.
(4) To study the effect of Crumb rubber-Nanosilica content on rheological behavior of the asphalt binder based on rutting and fatigue.
(5) To evaluate the effect of Crumb rubber-Nanosilica on Ageing and high temperature storage stability of the asphalt binder.

Table 1 Base binder physical properties [8]

Test	Standard code	Values	Specification limit (minimum)
Softening point (°C)	IS: 1205	46	40
Ductility (cm)	IS: 1208	100+	75
Penetration 0.1 mm at 25 °C	IS: 1203	88	80
Dynamic viscosity at 60 °C	1S: 1206(Part II)	1064	800
Kinematic viscosity at 135 °C	1S: 1206(Part III)	278	250

Table 2 Crumb rubber physical properties

Specification	Value
Particle size	<0.9 mm
Relative density	1.18
Natural rubber	35–58%
Rubber hydrocarbon	45–54%
Ash	4–6.5%
Carbon black	29–35%

3 Programme and Technique for Experiments

3.1 Compositional Description of Material

The base binder for this investigation is 80/100 penetration grade bitumen (VG-10), which was bought from a nearby distributor. Table 1 displays the mentioned base binder's numerous characteristics. For the purpose of altering the asphalt binder, nanosilica (NS) and crumb rubber (CR) were both taken into consideration. Platonic Nanotech Private Limited provided the nanosilica, while a regional distributor provided the CR. Tables 2, 3 and 4 (which were provided by the supplier), respectively, present the fundamental characteristics of CR and Nanosilica. Figures 1 and 2 show the SEM images of CR and nanosilica, respectively. The optimal concentration of CR was determined in this study to be 12% [5], while the concentration of nanosilica was changed from 1 to 6% [1]. Additionally, the mixing temperature (180 °C) was maintained [19].

3.2 Preparation of Samples

Crumb rubber and nanosilica were added to the asphalt binder using a high-shear mixer. To start, a consistent liquid was created by heating the asphalt binder on its own. CR was added to the asphalt binder at 12% [5] by weight of the asphalt binder. Finally, nanosilica was slowly added to the mixture at different concentrations (0, 1,

Table 3 Nanosilica physical properties [7]

Specification	Value
Purity	99.5%
Average size of the particle	30–50 nm
Specific surface area	200–250 m^2/g
Bulk density	0.10 g/cm^3
True density	2.5 g/cm^3
Morphology	Porous

Table 4 Nanosilica particles' elemental make-up [7]

SiO_2	Al	Fe	Mg	Ca
99.5%	0.02%	0.05%	0.1%	0.08%

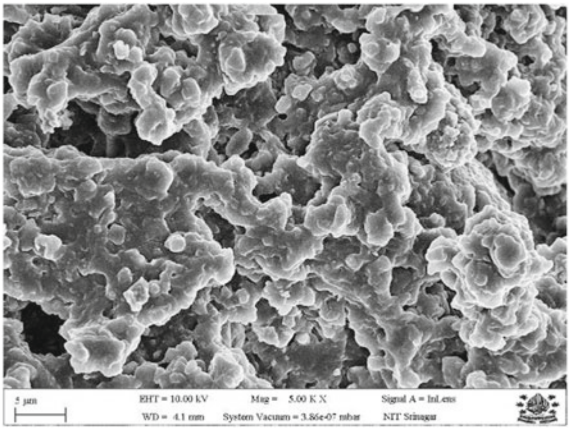


Fig. 1 Crumb rubber in a SEM image

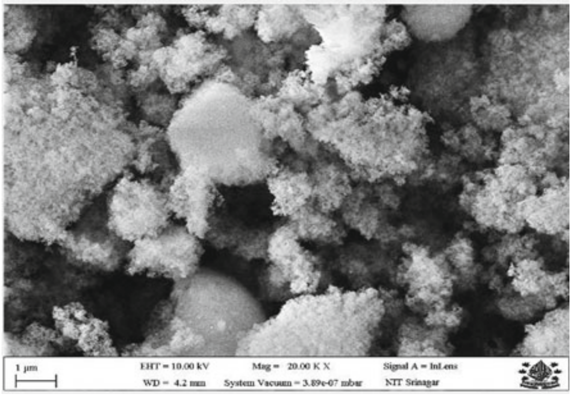


Fig. 2 Nanosilica in a SEM image

2, 3, 4, 5.5, and 6%) and mixed with the asphalt binder at 3000 rpm at a temperature of 180 °C [19]. The ideal mixing time was discovered to be 120 min using the softening point approach. Two stages make up the entire experimental strategy and are shown in Fig. 3.

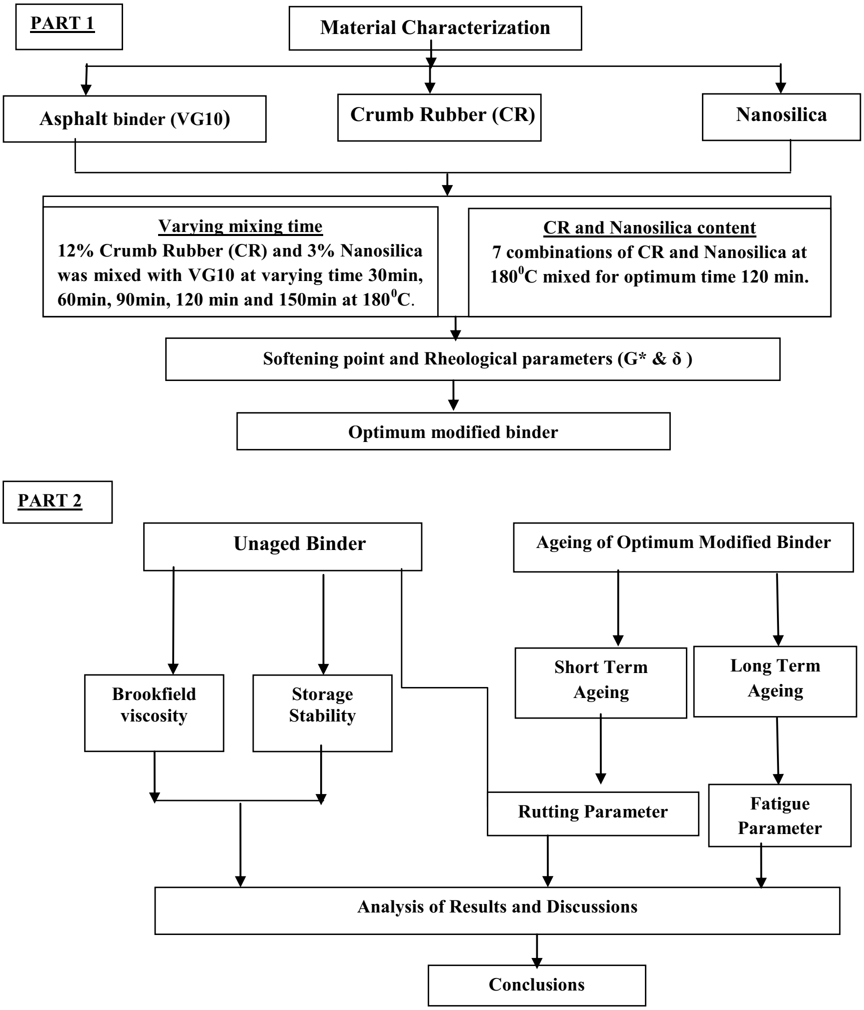


Fig. 3 Experimental flow chart

4 Test Procedures

4.1 Scanning Electronic Microscope (SEM)

The nanosilica powder and crumb rubber powder morphologies were examined using the SEM analysis.

4.2 Physical Characterization of the Binders

Utilising penetration (IS: 1203), softening point (IS: 1205), viscosity (AASTHO T316-13), and ductility (IS: 1208), the fundamental parameters of the base binder and crumb rubber-nanosilica modified binder were assessed.

4.3 Viscosity Test

In the Brookfield apparatus @ AASTHO T316-13, rotational viscosity was utilised to calculate viscosity at the temperatures for mixing and compacting. By measuring the torque needed to rotate the vertical shaft, the viscosity of the binder was ascertained. A chamber maintained at 135 °C with a spindle moving at a speed of 20 rpm was used to test 8–11 g of base and modified binders [31]. Assuming that 135 °C is the laying temperature, viscosity is computed at this temperature.

4.4 Rheological Characterisation of Binders

Using a dynamic shear rheometer (DSR) i.e., an Anton Paar MCR 102, the linear viscoelastic characteristics of unaged and aged bitumen were evaluated over a range of frequencies and temperatures in compliance with D7175 - 15. Complex modulus (G*), phase angle (δ), rutting parameter (G*/Sinδ), fatigue parameter (G*.Sinδ), T_{SHRP}, and ageing index were the parameters collected. A temperature range of 46, 52, 58, 64, 70, 76, 82, 88, and 94 °C was used, while an angular frequency of 10 rad/s was maintained (Bhat and Mir 2020). For fatigue characterization, the samples needed for testing were created in a silicon mould that was 2 mm thick, 8 mm in diameter, and had a gap of 2 mm between parallel plates. For rutting, however, a mould that was 1 mm thick, 25 mm in diameter, and had a gap of 1 mm was utilised. According to SHRP recommendations, aged samples are tested at a strain rate of 10%, whereas unaged samples are tested at a strain rate of 12%. For unaged binders and aged binders, the value of G*/sinδ is restricted to 1 kPa and 2.2 kPa, respectively.

Rutting resistance using Superpave rutting parameter: It is provided by G*/Sinδ and used to evaluate the asphalt binder's resistance to rutting. Rutting resistance will be stronger for an asphalt binder with a higher G*/Sinδ ratio because less energy will be lost during each cycle of loading.

Fatigue resistance using Superpave fatigue parameter: It is stated by G*.Sinδ and means that there will be less stress accumulation if there is less energy dissipated per cycle. As a result, materials with lower G*.Sin have superior fatigue resistance. The highest value of G*.Sinδ is 5000 kPa, according to SHRP. A 25 °C test temperature was used.

4.5 Ageing Process

Thin Film Oven was used to age the base and modified binders over a short period of time in accordance with ASTM: D1754. A moving film of the asphalt binder was heated in this oven for 5 h at 163 °C. This technique's primary objective is to quantify the impact of heat and air on a moving film of semi-solid asphaltic materials. Certain qualities are investigated before and after this test to ascertain the impact of ageing on the binders. "The resistance to hardening under the impact of air and heat is determined by short-term ageing. This apparatus simulates the circumstances that exist during the mixing and laying out of asphalt mixes" [21]. Pressure ageing vessels (PAVs) were used for the long-term ageing of base and modified binders in line with ASTM: D6521. 20 h at 100 °C and 2.1 MPa of air pressure were used for the Long Term Ageing experiment. It mimics the conditions in the field during a pavement's first 5–7 years of use.

4.6 Effect of Crumb Rubber and Nanosilica on Ageing Resistance

During the mixing and laying process as well as throughout their service life, binders oxidise. In addition to some of the lighter and more volatile components of the binder evaporating, unsaturated bonds present mostly in the aromatics and resin fractions undergo oxidation during the ageing process, rendering the binder brittle and perhaps contributing to pavement degradation. Consequently, binders with a reduced level of oxidation are desired. The ageing resistance of unmodified and modified binders is assessed in the current study utilising two parameters: ageing index and incremental softening point.

Softening point incremental (SPI): It is a difference between the age-related softening point of aged and unaged binders. For binders with strong ageing resistance, a lower value of the softening point incremental is necessary. Equation 1 serves as a representation.

$$\mathrm{SPI} = \mathrm{SP}_{\mathrm{aged}} - \mathrm{SP}_{\mathrm{unaged}} \tag{1}$$

where SPI is softening point increment, $\mathrm{SP}_{\mathrm{aged}}$ is the softening point of the short term aged binder and $\mathrm{SP}_{\mathrm{unaged}}$ is the softening point of unaged binder [26].

Ageing index: The ageing resistance is calculated using the superpave rutting parameter, which also determines the ageing index. As the value of AI rises, so does the sensitivity to ageing. The temperature was maintained at 60 °C with a 10 rad/sec frequency. Equation 2 serves as a representation.

$$\mathrm{AI} = \left|(\mathrm{G}*/\mathrm{Sin}\delta)_{\mathrm{aged}}/(\mathrm{G}*/\mathrm{Sin}\delta)_{\mathrm{unaged}}\right| \tag{2}$$

where $(\mathrm{G}^*/\mathrm{Sin}\delta)_{\mathrm{aged}}$ and $(\mathrm{G}^*/\mathrm{Sin}\delta)_{\mathrm{unaged}}$ are rutting factor parameter of the short-term aged and unaged asphalt binder respectively [21].

4.7 Storage Stability Test

Because the modifier has a propensity to separate from the asphalt binder at higher temperatures, the storage stability test is performed to assess the stability of the modified asphalt binder. This test is used to determine whether the modifier and base binder have been blended evenly. The test's aluminium tube has a height of 140 mm and a diameter of 25 mm. In line with ASTM D7173-14, it was filled with the modified sample and then kept vertically at 163 °C for 48 h [11]. Two representative samples were obtained from the tube's top and bottom. According to [12], the modified asphalt sample is regarded to be high-temperature storage stable if the difference between the asphalt sample's softening point between the top and bottom portion is less than 2.5 °C.

5 Results and Discussion

5.1 Determination of Optimum Mixing Time

Using the Softening point, the optimum mixing time was discovered. At various mixing times (30, 60, 90, 120, 150, and 180 min), the softening point of the 12% CR-3% NS modified binder was discovered. Figure 4 illustrates the fluctuation in the softening point with varying mixing times. It is evident that as mixing time rises, the softening point rises till 120 min. Nevertheless, it falls when the mixing time is increased from 120 to 180 min. This is consistent with the results of Al-Mansob et al. [3], Cong et al. [10]. This is because prolonged mixing degrades the

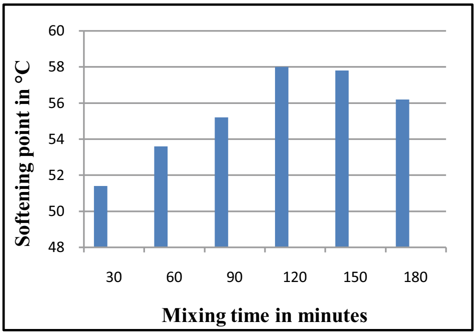


Fig. 4 Variation of softening point with mixing time for 12% CR-3% NS modified binder

qualities of the binders, which may be linked to changes in the binders' physical and chemical properties. At 120 min, or 58 °C, the most softening point improvement was discovered. So, based on the softening point, we can say that 120 min is the optimum mixing duration.

5.2 Determination of Optimum Mixing Concentration

Figures 5, 6, and 7 display the results of the softening point test, complex modulus (G*), and phase angle (). Figure 5 illustrates how all modified binders have higher softening points than basic binders. They are therefore stronger and less prone to long-term deformation [36]. As demonstrated in Fig. 5, the softening point increases at constant CR concentrations up to 4% of nanosilica, while it decreases at lower concentrations. This is as a result of NS's ability to stiffen the binder and increase its temperature susceptibility [7]. According to other studies where it was found that an excessive amount of nanomaterials in nanocomposite modified asphalt binders may cause the elastic nature of modified asphalt binders to be destroyed, at a constant CR concentration, the softening point initially increases slightly and later remains unaffected [26]. The most flexible binder, with a softening point of 62 °C, is 12% CR-4% NS modified. Therefore, it might be said to be the ideal concentration.

Figures 6 and 7 illustrate the complex modulus and phase angle obtained from the DSR test for aged and unaged samples, respectively, at varied concentrations of NS and 12% CR. Figures 6 and 7 show that the G* value increases as the concentration of NS in the polymer modified binder increases, however it drops after 4% NS concentration. Thus, it demonstrates that the bituminous binder becomes stiffer as the NS content in PMB increases. Additionally, it is clear that as binders age, they stiffen and exhibit higher values for complex modulus and lower values for δ.

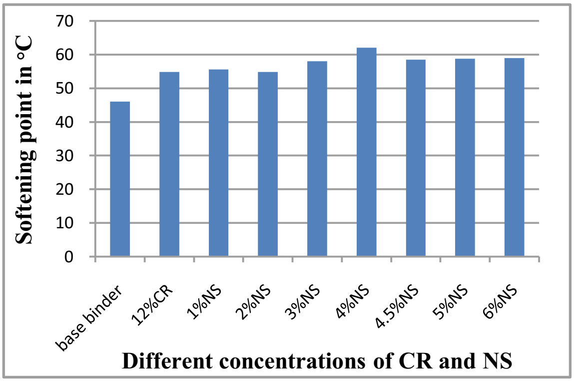


Fig. 5 Base and modified binders softening points

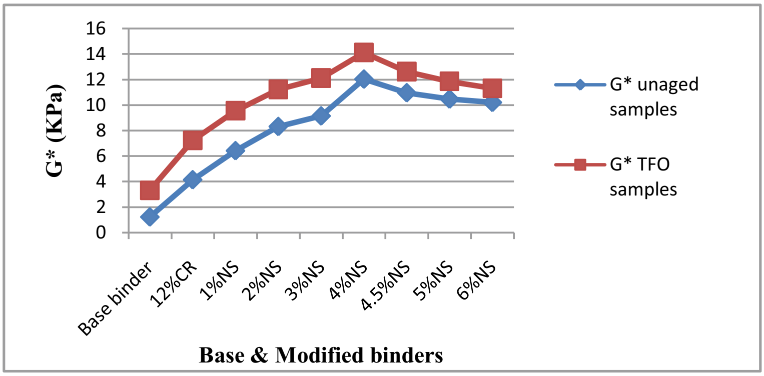


Fig. 6 Complex modulus of unaged and TFO samples at test temperature of 60 °C

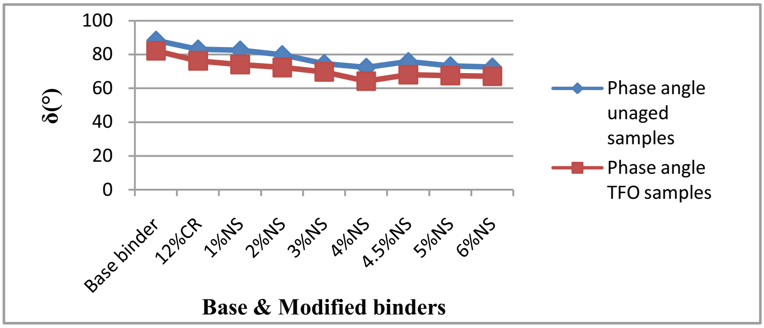


Fig. 7 Phase angle of unaged and TFO samples at test temperature of 60 °C

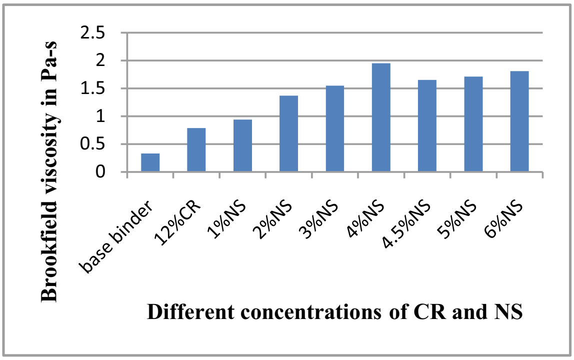


Fig. 8 Base and modified binders' Brookfield viscosities

5.3 Determination of Brookfield Viscosity

According to AASHTO T316-13, the Brookfield viscosity test is used to assess the viscosity of the modified and unmodified asphalt binder at 135 °C. Figure 8 shows that viscosity increases as NS concentration increases, which may be caused by the hardening impact of nanoparticles. The improved dispersion of the additional nanomaterial layers in the base binder may also be responsible for the modified asphalt binder's enhanced viscosity, which boosts the bonding strength by limiting the flow of asphalt [16]. Due to the modified asphalt binders' enhanced hardness, their increased viscosity suggests an improvement in their physical characteristics and an improvement in their high temperature qualities. Binders treated with nano-silica to have 12% CR-4% have the highest viscosity. At 135 °C, modified asphalt has a viscosity that is significantly greater than the base binder, this difference may be caused by the influence of polymers from the composition analysis of the modifier. As the extremely viscous binders are combined with the aggregates and create thicker films surrounding them, the resistance to water, environmental deterioration, and cohesive forces between the components rise [35]. Additionally, because the viscosity is not excessively high, there are no construction issues because binders with extremely high viscosities become hard and challenging to compact.

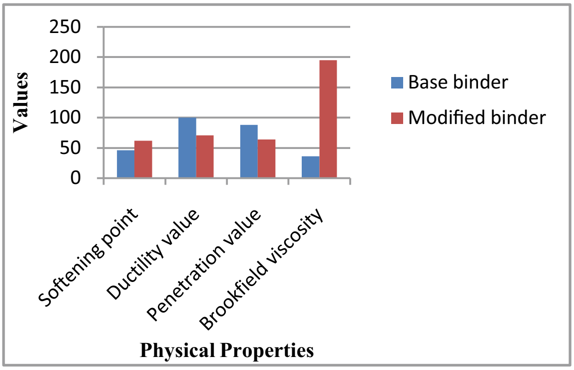
5.4 Physical Properties of Optimum Modified Binder

The physical characteristics of the 12% CR-4% NS modified binder are given in Table 5 and Fig. 9. As it can be seen from table, the softening point increases, ductility decreases and penetration value decreases as compared to the base binder, suggesting that the binder becomes stiffer. As a result, high temperature properties are enhanced due to addition of modifiers.

Table 5 Physical characteristics of 12% CR-4% NS modified binder

S.no	Test	Unit	Code	Value
1	Softening point	°C	IS:1205	62
2	Ductility value	Cm	IS:1208	71
3	Penetration value	0.1 mm	IS:1203	64
4	Brookfield viscosity	Pa-s	AASTHO T316-13	1.95

Fig. 9 Physical characteristics of optimum modified binder



5.5 *Rheological Characterization*

Complex shear modulus (G*): It provides a measurement of the binder's overall resistance to deformation when repeatedly sheared. The graph of all modified and unmodified samples (Fig. 10) demonstrates an exponentially declining trend in G* with rising test temperature. The G* value increased as the percentage of NS in CRMB grew from 0 to 4%, indicating that the modified asphalt binder is more stiff than the unmodified one. This indicates that NS-modified binders are slightly stiffer, more durable, and more resistant to deformation than unmodified binders. These results are consistent with findings of [1, 15] for NS. The nanocomposite has a greater complex modulus value, which indicates that a polymer network has formed in the changed binder. Furthermore, the complex modulus is falling as temperature rises, suggesting that this could drastically reduce the deformation resistance of both the base and modified binders. The 12% CR-4% NS modified binder has the highest value of G*, demonstrating the greatest improvement in rutting resistance. Furthermore, as seen from the charts, the complex modulus does not significantly change above 4% NS concentration.

Phase angle: Figure 11 depicts how the phase angle changes with temperature for base and modified binders. For the alteration of asphalt, phase angle measurement is typically thought to be more sensitive to chemical and physical structure than complex modulus [38]. Phase angle, according to Zheng et al. represents the proportional

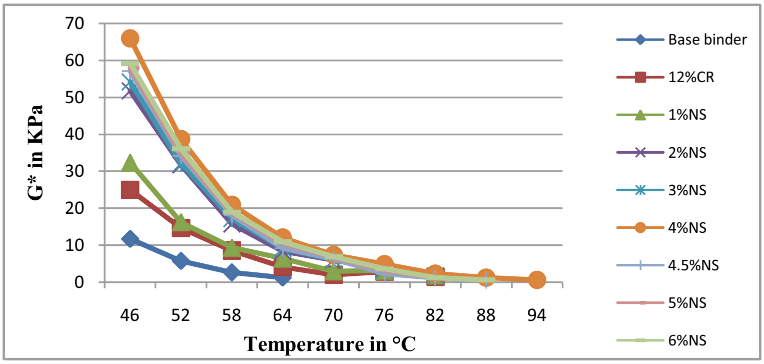


Fig. 10 Variation of G* with temperature for base and modified binders

distribution of the overall response between an in-phase (elastic) component and an out-of-phase (viscous) component in the shear dynamic loading mode. Figure 11 makes it obvious that the inclusion of CR-NS reduces the phase angle and, as a result, improves the elastic behaviour of the asphalt. Base binder begins to become viscous at higher temperatures and transforms into a Newtonian fluid when the phase angle approaches 90° [20]. Phase angle falls as NS content rises, indicating increased elasticity and raising the possibility for elastic recovery of pavement deformation. The modified binder with 12% CR and 4% NS has the smallest value for phase angle.

Superpave rutting parameter: Rutting parameter is thought to be a useful indicator of how well the improved binders prevent rutting. Figure 12 illustrates how different binders exhibit various rutting parameter values at a certain temperature. At all temperatures, 12% CR-4% NS showed the highest improved rutting metrics. It follows that adding NS can increase the asphalt binders' tolerance to high temperatures.

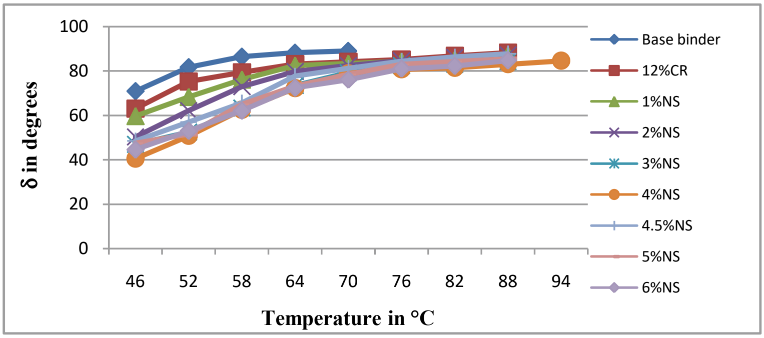


Fig. 11 Variation of phase angle with temperature for base and modified binders

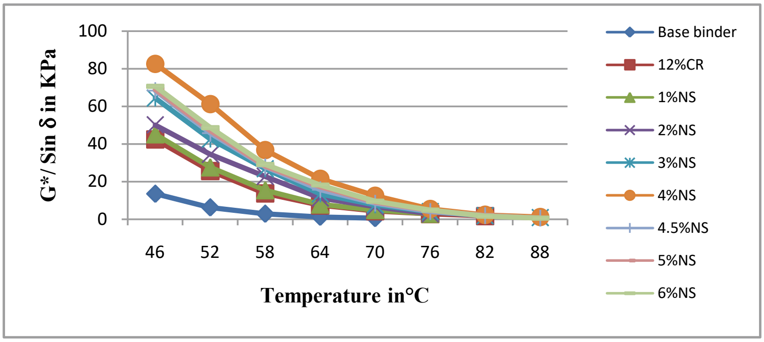
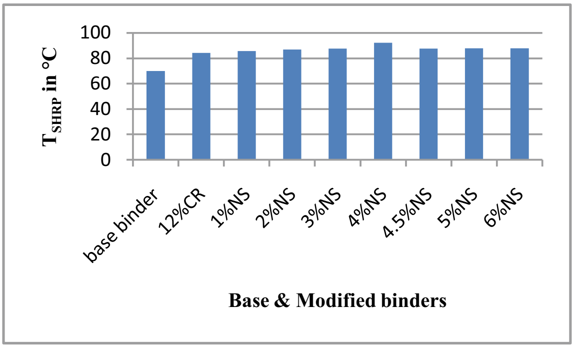


Fig. 12 Variation of superpave rutting parameters with temperature for base and modified binders

Failure temperature T_{SHRP}: According to Superpave binder grade requirements, it is referred to as the point at which G*/sin(δ) drops below 1.0 kPa. Road Materials and Pavement Design typically make use of this feature 13. Failure temperatures of modified and unmodified binders are used to determine the performance grade (PG) of asphalt binders [33]. Additionally, the base binder's failure temperature is 70 °C, which is the lowest. In Fig. 13, the T_{SHRP} values are displayed. The outcomes show that the NS-modified asphalt binders have better high temperature rheological characteristics. The asphalt binder had the maximum failure temperature at 4% NS in 12% CRMB. As can be observed from the graph, the failure temperature rises as NS concentration does, and this is due to NS functioning as the nanofiller in the CR matrix. The degree of NS dissipation in the polymer matrix of CR determines how much the mechanical characteristics will improve.

Fatigue Performance: Figure 14 illustrates the fluctuation of the fatigue parameter (G*.Sinδ) for modified and unmodified asphalt binders at 25 °C with various concentrations of CR and NS. According to [1], pavement microdamage is a result of fatigue damage brought on by repetitive bending stresses. Such distress causes stiffness and reduces the pavement's ability to withstand more pain. Additionally, an increase in

Fig. 13 Modified binders T_{SHRP} values



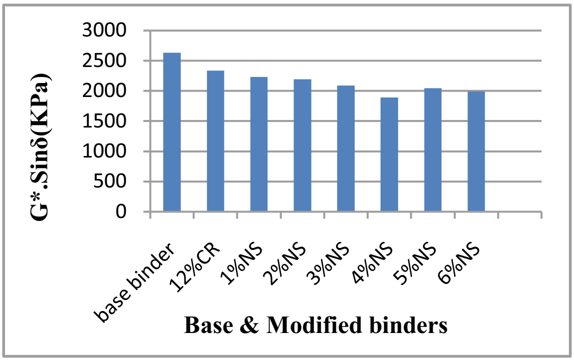


Fig. 14 Modified binders G*.Sinδ values

G*.sinδ was seen when NS was added at varied concentrations (with the exception of 4%), demonstrating the detrimental effect on fatigue failure. As a result, the addition of 12% CR-4% NS can improve the fatigue resistance performance at intermediate temperatures.

5.6 Determination of Ageing Effect

The impact of modifiers on the ageing resistance of the binders has been investigated using two parameters.

Softening point incremental: As binders age, they get tougher, hence the softening point of aged binders is higher than that of unaged binders. Figure 15 displays the values of the softening point incremental following short-term ageing. The resistance to ageing rises as the values of SPI fall with rising CR-NS concentration. The modified binder with 12% CR-4% NS shows the lowest SPI value.

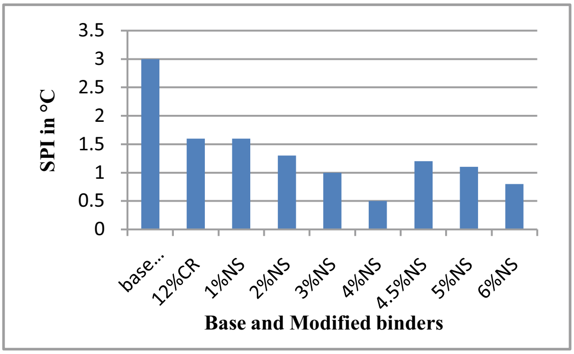
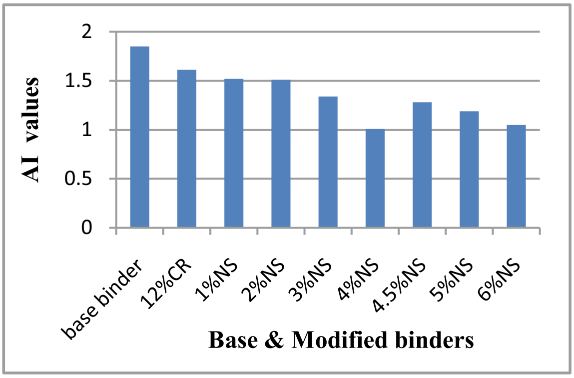


Fig. 15 SPI values for base and modified binders

Fig. 16 AI values for base and modified binders



Ageing index: Figure 16 displays the results of the calculation of the rutting ageing index values at 60 °C and 10 rad/s frequency. The CRMB exhibits increased ageing resistance as CR percentage increases due to decreased carbonyl and sulphoxide indices, but as CR percentage increases, the likelihood of agglomeration also increases; in order to avoid this situation, as well as to increase ageing resistance, NS can be added to the CRMB [32]. Increased NS concentration has been observed to reduce the value of AI, indicating an improvement in oxidative stress resistance and ageing resistance. In terms of ageing resistance, NS is a good modifier (Bhat and Mir 2020). The 12% CR-4% NS modified binder once more demonstrates the lowest value of AI.

5.7 Storage Stability

Because the CR particles operate as a defect and the amount of stress that can be transferred across the interface is constrained, the modified asphalt is potentially unstable and requires a strong interface between the CR and the base asphalt. Here, NS serves as that interface because it can increase the bitumen's storage stability [7]. The internal characterization of this interaction is exceedingly challenging due to the complexity of the interaction between base asphalt and CR. In order to study the interaction, storage stability is utilised, and the result is established by measuring the softening point difference [9]. The sample is considered to have adequate storage stability when the softening point difference (SPD) between the top and bottom regions of the tube is less than 2.5 °C [12].

NS affects whether CR and asphaltenes are compatible. The copolymer blocks and inorganic filler interact when NS is added to CRMB, changing the microstructure. Table 6 shows that when the NS content increases, the difference between the softening points of the top and bottom regions of CR modified binder's diminishes. For 12% CR-4% NS, there is the smallest difference.

Table 6 Storage stability results of different combinations of CR-NS modified binders

S.no	Binders	Softening point difference between top and bottom of tube
1	12% CR modified binder	9
2	12% CR-1% NS modified binder	2.1
3	12% CR-2% NS modified binder	1.9
4	12% CR-3% NS modified binder	1.3
5	12% CR-4% NS modified binder	0.84
6	12% CR-4.5% NS modified binder	1.5
7	12% CR-5% NS modified binder	1.2
8	12% CR-6% NS modified binder	1.01

6 Conclusions

This research was done to create a modified asphalt binder containing CR-Nanosilica. This study assesses the impact of CR-NS on the modified binder's rutting, fatigue, and storage stability behaviour in Superpave. From the findings and conversations, the following conclusions can be drawn:

(1) The optimum mixing time was obtained as 120 min on the basis of the softening point method. The NS content was varied from 1% to 6% by weight of bitumen and CR concentration was taken as 12% by weight of bitumen. Thus, overall seven combinations of CR-NS were prepared. The best rheological performance was shown by 12% CR-4% NS.

(2) The Softening point increased by 34.7%, penetration and ductility decreased by 37.5% and 40.84% respectively as compared to neat asphalt. This demonstrates the increased stiffness and decreased temperature susceptibility of the CR-NS modified bitumen.

(3) High temperature rutting resistance improved as reflected by an increase in the value of complex modulus and Superpave rutting parameter. Complex modulus increased from 11.72 kPa to 65.98 kPa and Superpave rutting parameter increased from 13.57 kPa to 82.54 kPa at 46 °C (of neat and optimum modified asphalt respectively). It was also observed that as temperature increased from 46 °C to 88 °C, Complex modulus and Superpave rutting parameter decreased.

(4) The failure temperature of neat asphalt was obtained as 70 °C and that of optimum modified was 92.3 °C. Thus, CR-NS addition could improve the high failure temperature in the unaged binder state.

(5) CR-NS improves the elasticity of the binders as the value of phase angle decreases. The value of phase angle for neat asphalt was 71° and that of optimum modified was 40.55° indicating a decrease of 42.88% and thus an increase in elasticity.

(6) NS plays an important role in increasing the ageing resistance of CRMB which can be derived from the fact that the softening point incremental and ageing index decreases due to the addition of CR-NS. The SPI of neat asphalt was obtained as 3 °C and minimum value was obtained for optimum modified bitumen i.e., 0.5 °C. Also, ageing index of neat asphalt was 1.85 and minimum value was obtained for optimum modified bitumen i.e., 1.01.

(7) The viscosity of CR-NS modified bitumen increases as NS content increases and maximum value is shown by 4% NS concentration, added to 12% CRMB which is 1.95 Pas.

(8) The results of Superpave fatigue parameter showed that there is an improvement in the fatigue resistance as G*.Sinδ value decreases as NS concentration increases upto 4%. Hence, the intermediate temperature performance is enhanced and maximum enhancement is shown by 12% CR-4% NS for which the value was obtained as 1890 kPa.

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