



Performance Evaluation of Asphalt Concrete Mixed with Nano Antimony (III) Oxide

Abdullah Faiz Al Asmari

Department of Civil Engineering, King Khalid University, Abha, Saudi Arabia

corresponding author's e-mail: afsaeed@kku.edu.sa

Abstract: Globally, a huge budget expenditure is borne by countries for the smooth operation of road networks. This led to many research works to develop an asphalt mix that is sturdy enough to damage and thereby reduce the maintenance cost. Several studies have indicated enhancement of asphalt mix properties using a range of admixtures and additives. However, most research studies are restricted to a high temperature range of 40°C, 50°C and 60°C. This study aims to evaluate the performance of asphalt concrete mixed with Sb₂O₃ nanomaterial. The dynamic performance of the nano-modified asphalt mix was evaluated at 40°C, 30°C and 20°C. The parameters used for performance evaluation were indirect tensile fatigue test, dynamic creep test and wheel track test. Indirect tensile fatigue test of specimens with Nano Sb₂O₃ had an improved performance by 3-15%. Dynamic creep test results indicated an improved Sb₂O₃ modified asphalt mix performance by 14-26%. The optimum dosage was observed to be 0.5% of Sb₂O₃. However, this study suggests a dosage range of 0.5-0.75%. Further studies regarding the lower temperature range are required to investigate nano-modified asphalt mix performance.

Keywords: asphalt concrete, Sb₂O₃, indirect tensile fatigue, dynamic creep, wheel tracking

1. Introduction

Transportation is a key factor for economic development at present (Khosla & Ayyala 2013). Asphalt mix is the most widely used material for pavement construction globally. This is attributed to its properties of reduced construction time, smooth surface, reduced noise seam-less, and comfortable driving experience (Mukhtar et al. 2023). This has led to a focus on increasing highways' durability and service life to achieve sustainable transportation in many countries (Gul et al. 2021). The surface of pavement exposed to heavy loads frequently must possess high resistance against fatigue, skid and creep. Several studies are trying to improve the performance of asphalt mix using several additives (Wang et al. 2023).

Wang et al. (2023) have reviewed the polyurethane-modified asphalt mix. Mukhtar et al. (2023) investigated the performance of an asphalt mix modified with dolomite powder and lime kiln dust and reported increased rutting index and complex modulus from modification. Amirbayev et al. (2022) investigated an asphalt mix modified with carbon powder. The addition of carbon powder decreases softening temperatures and increases resistance to penetration. Another study used graphene composite rubber as an asphalt binder and reported a decrease in penetration of 28%. It also revealed a 32% increase in ductility and a 48% softening point. The rutting factor was found to increase by 186% and 28% increase in stiffness modulus (Guo et al. 2022). Montmorillonite-nano clay-cold asphalt mix was used to investigate, and an optimum dosage of 2% of the clay was found to enhance the performance of the mix (Boateng et al. 2022). Chelovian & Shafabakhsh (2017) has investigated Al₂O₃.

There are several studies on modified asphalt mix. However, their temperature range is mostly higher in between 40-60°C. However, there is a lack of studies on asphalt mix performance in the lower range of temperature 20-40°C. Hence, the novelty of this study is to evaluate the modified asphalt mix performance in a lower temperature range. Second, no literature is available to the authors' knowledge that employed Sb₂O₃ at the lower temperature range for dynamic performance evaluation of asphalt mix. Akbas et al. (2021) evaluated Sb₂O₃ for the long-term ageing performance of bitumen and asphalt mix. However, they investigated asphalt mix performance at 40°C, 50°C, and 60°C. However, the region where the study is conducted experiences cooler temperatures throughout the year. In summer, temperatures rarely cross 30°C. Also, at night, the temperature drops between 16-20°C. In winter, the temperature is further lower. Hence, even though the range of temperature studies is higher in published studies, this study focuses on a lower temperature range. This study aims to evaluate the dynamic performance of Sb₂O₃ mixed asphalt concrete and its performance at a lower temperature range.



2. Materials and Testing

Saudi Highway Code (SHC 308) was used in this study to govern the testing procedure (Roads General Authority 2023). The wet mixing method was adopted in this study to produce a homogenous bitumen mix. The solvent used was kerosene. The bitumen was first heated to 150°C till it melted down. Then, it was mixed in high shear mixer at a speed of 4000 rpm. Gradually, 0.25%, 0.5%, 0.75% and 1% Sb₂O₃ (by weight of bitumen) were dissolved in a solvent, which was then added to bitumen to obtain the composite. The 0% Sb₂O₃ was tested to serve as the control specimen. Sb₂O₃ powder used in this is presented in Figure 1.



Fig. 1. Antimony trioxide (Sb₂O₃) nano powder used in this study

Sb₂O₃, being an inorganic semiconductor, is used in technology development. The average particle size of Sb₂O₃ lies in the 3-12 nm range. Table 1 shows the properties of Sb₂O₃ used in this study.

Table 1. Antimony trioxide properties used in this study

Specification	Result
Colour	White
Particle size	3-12 (nm)
Molecular Formula	Sb ₂ O ₃
Solubility	99.0 (g/L)
Density	5.2 (gm/cm ³)

Table 2. Aggregates properties used in this study

Sieve size	Abrasion loss	Water absorption	Specific gravity
25-4.75 (mm)	19.85%	2.91%	2.731
4.75-0.075 (mm)	–	0.131%	2.612
<0.075 (mm)	–	–	2.781

Table 3. Asphalt properties used in this study

Property	Value
Softening point	50°C
Flash point	308°C
Loss of heating	0.2%
Ductility	102 cm
Solubility	99.5%

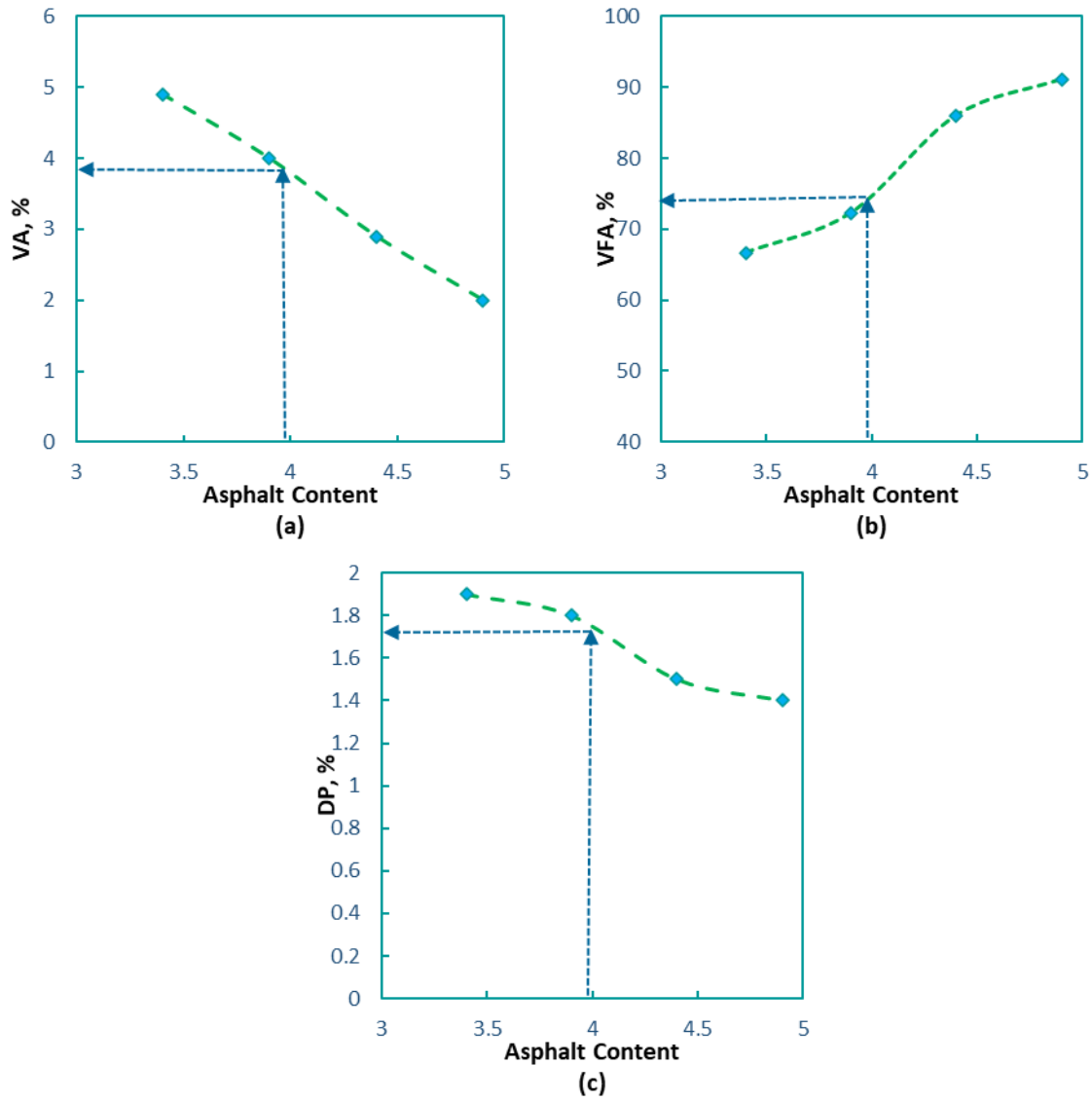


Fig. 2. Asphalt content and volumetric properties used in this study

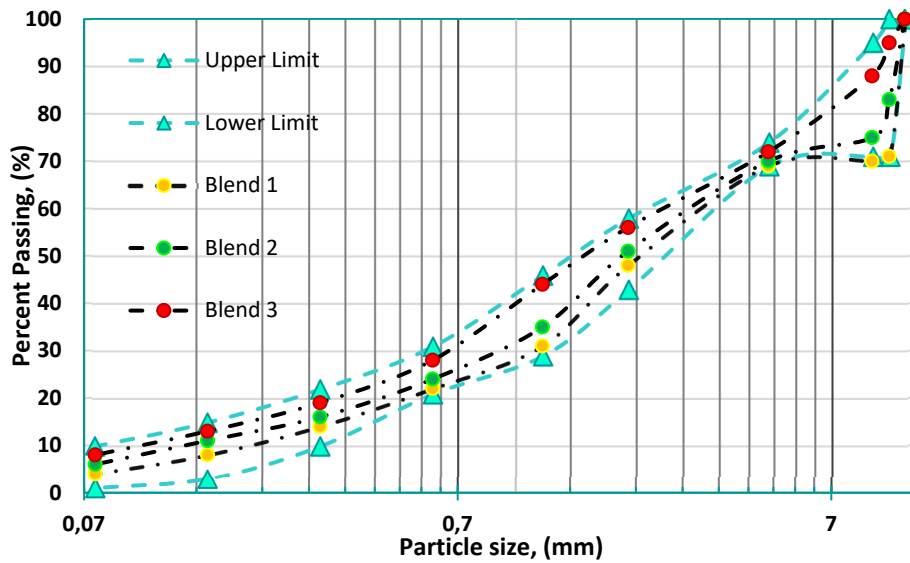


Fig. 3. Aggregate particle size distribution curve for asphalt mix

2.1. Indirect tensile fatigue test

A 100 mm x 40 mm specimen was used to perform an indirect tensile fatigue test. A 1 Hz pulse loading cycle was used to test the sample. The specimen rupture is estimated with respect to its vertical deformation. The loading condition of the specimen in the fatigue test is along the axis of the specimen and is linear in nature. The indirect tensile method estimates the fatigue life and the number of cycles required for specimen fatigue. The load applied in the fatigue test was in the range of 50-1000 kPa. The sample specimen life directly depends on the number of cycles required for specimen failure, applied load and the direction of applied load, quality of construction and weather conditions. The fatigue test was performed in 150 kPa, 250kPa, and 350 kPa loading conditions. The temperature range was selected in lieu of the range adopted by, i.e., 5°C, 15°C and 25°C. The samples were reheated to compaction temperature before they were compacted (ASTM D8225-19, 2019).

2.2. Dynamic creep test

The asphalt mix's resistance to deformation or rutting is assessed by dynamic creep test. The load is applied axially to the specimen, and deformation is measured using sensors. The test load in this study were 350 and 500 kPa for temperature ranges of 20°C, 30°C and 40°C. This temperature range was chosen based on the local climatic conditions of Abha City, in Asir Province, Saudi Arabia. The specimens were tested for 3600 cycles for comparison, and a similar value was also adopted. The results are presented as permanent deformation or strain calculated for each tested specimen.

2.3. Wheel track test

The wheel track test is devised to simulate similar loading conditions asphalt mix will experience on the roads. It is used to estimate the resistance of asphalt mix against permanent deformation for a given temperature. This study used a specimen size of 50 x 300 x 300 mm for testing. The wheel track test was performed at a temperature range of 20°C, 30°C and 40°C. The roller compactor was used to compact the test specimens according to the code (ASTM D8292-20, 2020).

3. Results and Discussion

3.1. Indirect tensile fatigue results

Figure 4-6 present the fatigue life of the asphalt mix used in this study for different dosages of nano Sb_2O_3 . The number of cycles leading to crack formation in asphalt mix is termed the fatigue life of the asphalt mix. Therefore, the results obtained from laboratory testing present the number of cycles against various loads applied on the asphalt specimen for fatigue estimation.

As per the fatigue hypothesis, life should be higher at lower temperatures and loading conditions. The obtained results validate this hypothesis. As per the results, more cycles were obtained at the lowest temperature of 5°C and in a 150 kPa loading condition. This indicates lower temperature and stress induced in asphalt specimens are directly related to their extended service life. The number of cycles decreased with an increase in temperature and load. At 25°C and 350 kPa, the number of cycles that asphalt specimens can undergo was reduced to 2900. However, in reality, these two conditions cannot be controlled by engineers as temperature is a natural phenomenon that cannot be controlled on a huge global road network. The only possible engineering solution is to develop an asphalt mix that can increase its stress and temperature-resisting capacity, for which this study has employed nano Sb_2O_3 .

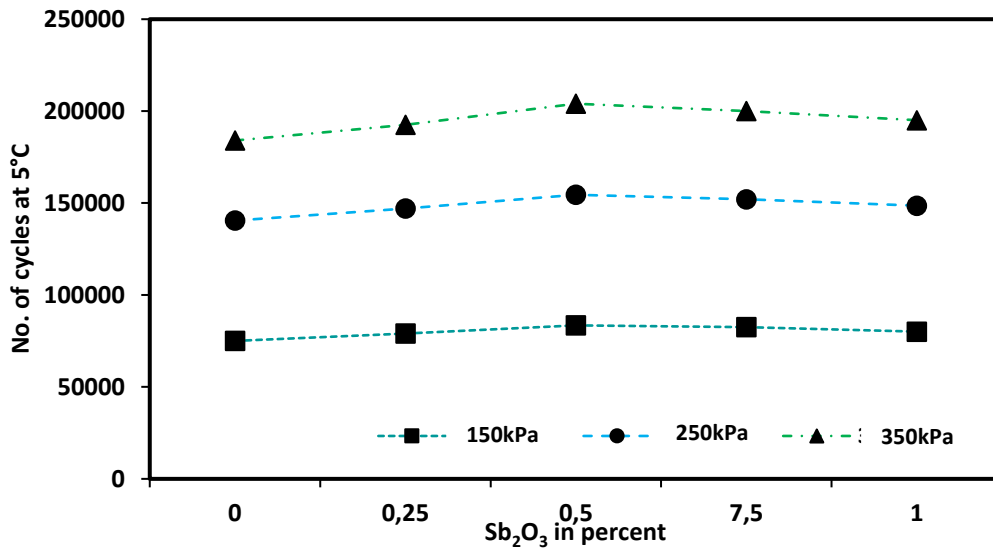


Fig. 4. Indirect tensile fatigue test results at 5°C for Sb₂O₃ modified asphalt

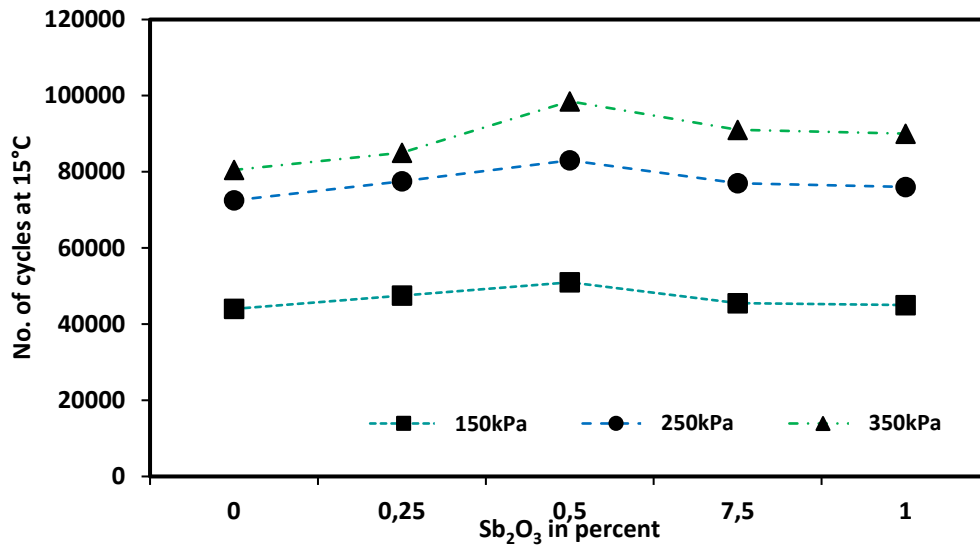


Fig. 5. Indirect tensile fatigue test results at 15°C for Sb₂O₃ modified asphalt

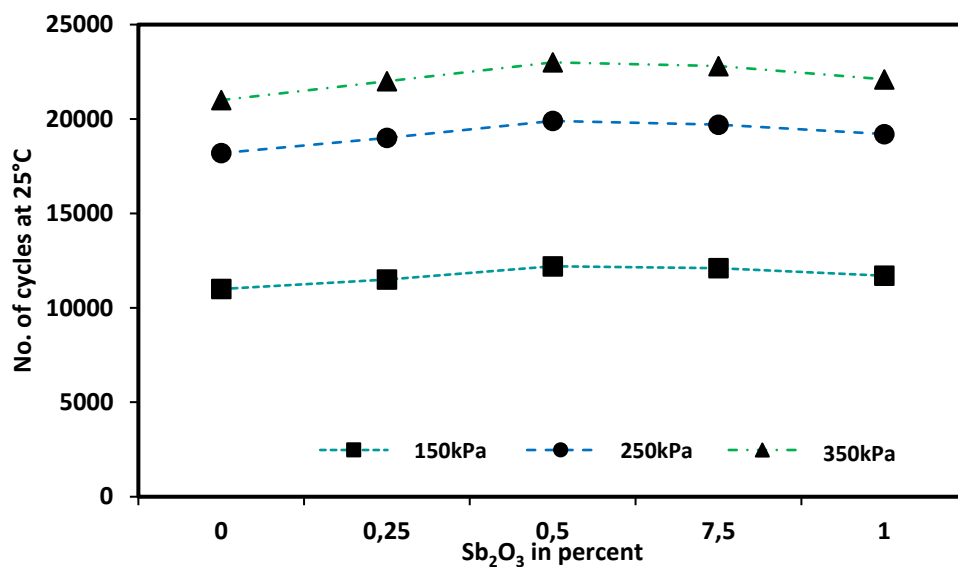


Fig. 6. Indirect tensile fatigue test results at 25°C for Sb₂O₃ modified

From the results it can be inferred that the highest number of cycles for the asphalt mix was obtained at 0.5% dose rate of Sb_2O_3 at all the temperature range of 5°C, 15°C and 25°C. All the results indicate an improvement in specimen life between 3-12% upon incorporating Sb_2O_3 into the asphalt mix. This further indicates that the crack development in asphalt mix at 0.5% dosage of Sb_2O_3 will be delayed, leading to an extended life cycle of the road pavement in reality.

3.2. Dynamic creep results

Figure 7-9 represents dynamic creep tests of the asphalt mix specimens used in this study. The results presented in the study are based on 3600 loading cycles. Chelovian & Shafabakhsh (2017) also adopted a similar loading cycle. The results here show the permanent deformation or rutting remaining after loading cycles of 3600. The final strain of the tested specimen indicates its susceptibility to rutting. Upon the addition of Sb_2O_3 , the final strain on the specimen is reduced. At 40°C and 350 kPa loading, strain was reduced by 3%, 5%, 9% and 3% for Sb_2O_3 addition to asphalt mix by 0.25%, 0.5%, 0.75% and 1% respectively.

At the temperature of 30°C and stress of 350 kPa, the decreasing trend of final strain is continued by adding different percentages of Nano Sb_2O_3 . It was observed that at 1% of nano Sb_2O_3 additive, the decrease in strain was reduced compared to previous dosages. At 650 kPa loading, the maximum reduction in strain was observed to be 26% at 0.5% Sb_2O_3 , 26% at 0.75% of Sb_2O_3 and at 1 percent it was 16%. The maximum reduction in strain was observed at 0.5% Sb_2O_3 at 350 kPa and 650 kPa.

At 20°C with load of 350 kPa Sb_2O_3 Nano mix asphalt has a maximum strain reduction of 15% compared to the control specimen. Also, at the stress of 650 kPa and temperature of 20°C, the optimum nano Sb_2O_3 dosage is 0.5% with a reduction in strain by 11%.

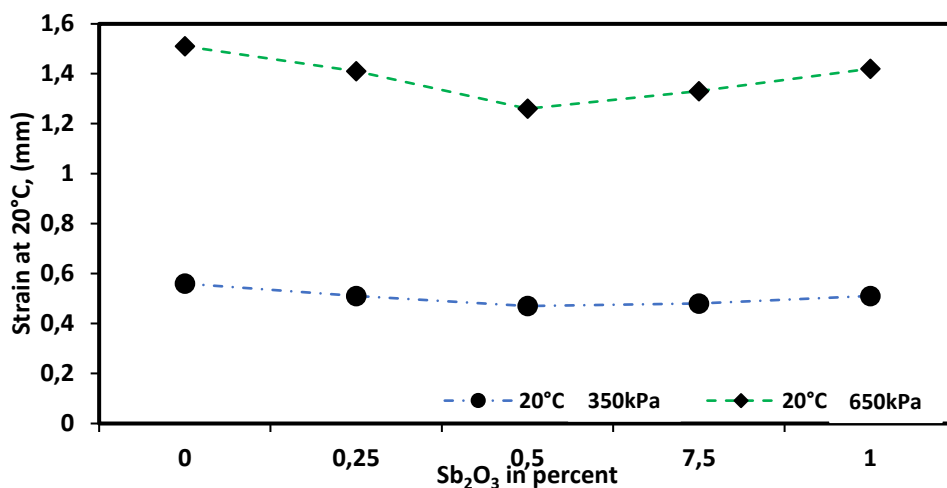


Fig. 7. Dynamics creep test results of specimen with and without Sb_2O_3 at 20°C

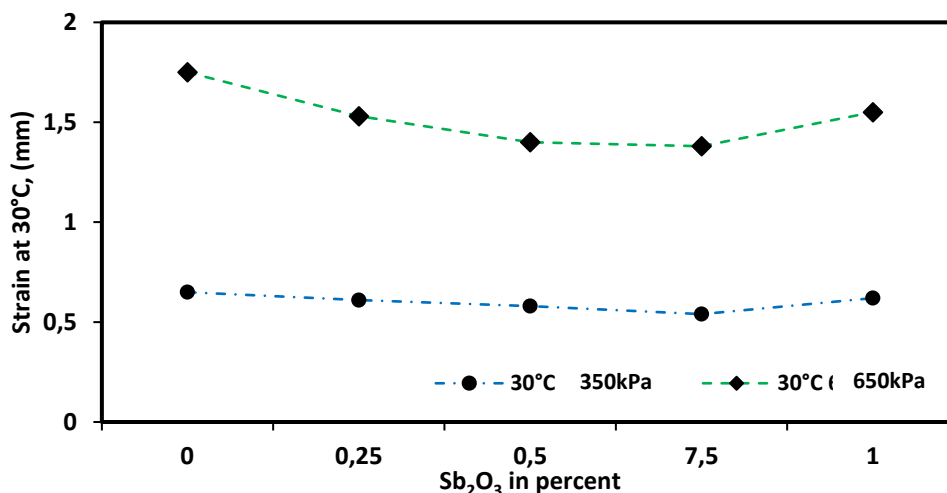


Fig. 8. Dynamics creep test results of specimen with and without Sb_2O_3 at 30°C

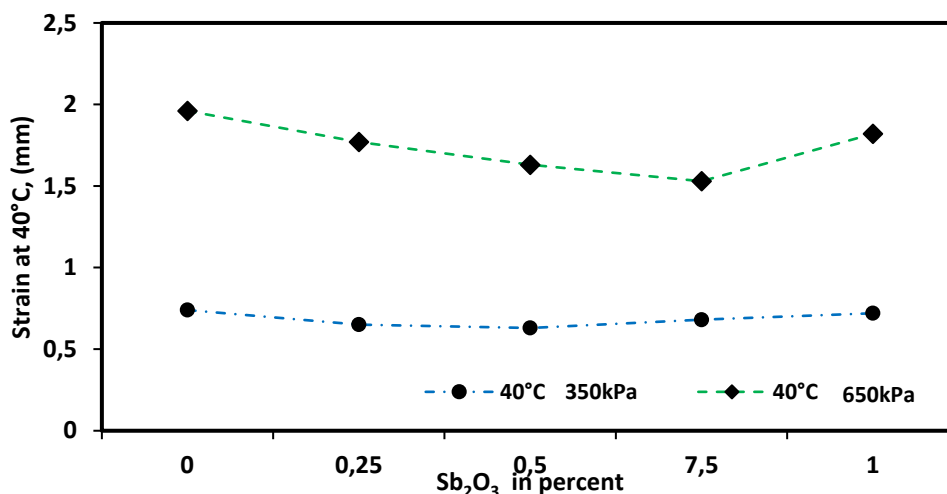


Fig. 9. Dynamics creep test results of specimen with and without Sb₂O₃ at 30°C

From the results, it can be inferred that Sb₂O₃ can induce strain reduction properties in the asphalt mix. The reduction in strain achieved over different dosages varied between 15-26%, which is significant. It can be inferred that mixing Sb₂O₃ in asphalt mix increases its adhesion property which calls for reduced maintenance. Hence, the asphalt mix has enhanced its performance against permanent deformations and creep. Bitumen performance is time-dependent as it is viscoelastic at lower temperatures. However, at a higher range of temperatures, they tend to behave as visco-elastic-plastic, which renders them susceptible to permanent deformation at high temperatures. Based on the results, it is inferred that the potential rutting is reduced by adding nano Sb₂O₃, which in turn restricts the permanent deformation in asphalt mixes.

The impact of temperature was assessed at 20°C, 30°C and 40°C in terms of creep in the specimens modified with Sb₂O₃. Several other studies have analysed the impact on asphalt mix at 40°C, 50°C and 60°C, i.e., upper temperature range (Boateng et al. 2022, Chelovian & Shafabakhsh 2017, Guo et al. 2022). However, since the study area seldom reaches 30°C, it is imperative to conduct asphalt studies at a lower temperature range, i.e., 20-40°C. The asphalt mix is susceptible to a higher degree of dynamic creep at higher temperatures as its plastic properties dominate over elastic-visco properties. This is validated by the fact that at 40°C, the creep was twice for 350 kPa as compared to what was observed at 30°C and 20°C. This is attributed to the bitumen's thermal reactivity to high temperatures, which causes these variations in results. The addition of Sb₂O₃ has reduced the thermal reactivity of the asphalt mix and thereby has enhanced the performance of the specimen as compared to the specimen with no nano additive.

3.3. Wheel track test results

The wheel track results of the asphalt mix specimen modified with Nano Sb₂O₃ are presented in Figure 10 and Figure 11. The loading forces used in the wheel track test are 500 N and 700 N. It is inferred from the results that rut depth is inversely proportional to the dosage of Nano Sb₂O₃. This arises because the high specific area of the Nano Sb₂O₃ serves as reinforcing material among the bitumen particles, increasing its resistance to external force as bitumen particles connect to each other through Nano Sb₂O₃. This can also lead to improved adhesive properties of bitumen along with viscosity. Also, the enhancement of the functional behaviour of the Nano-modified asphalt specimen is observed. Which in turn boosts its sensitivity to rutting. From the results, it can be inferred that the addition of Nano Sb₂O₃ leads to a decrease in the rutting of asphalt mix compared to the control specimen. It is derived from the fact that rutting is directly related to the type of asphalt used in it. Nevertheless, the use of nano Sb₂O₃ is in very low volume. It comprises 5.0-7.5% by weight of bitumen. If the total weight of the mix is considered, then the volume of nano Sb₂O₃ further reduces.

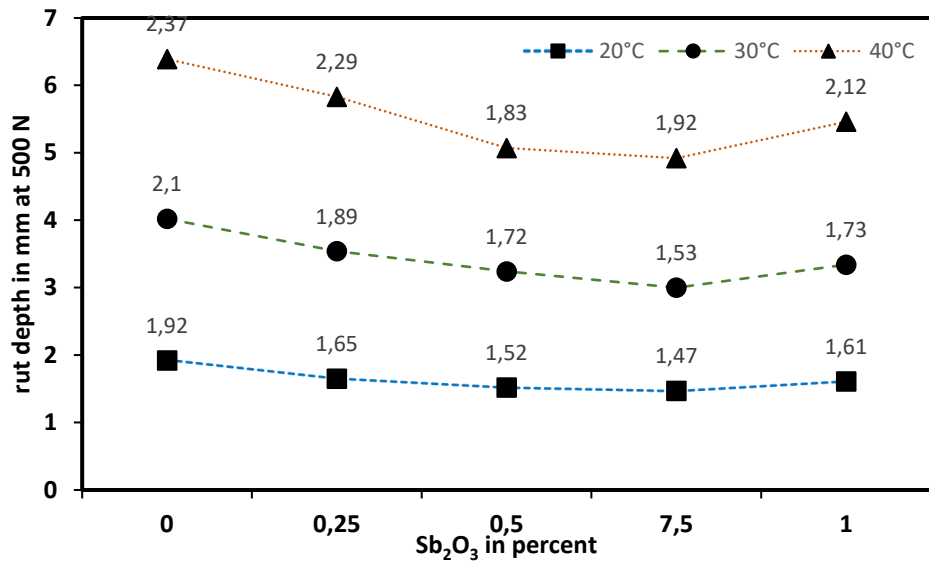


Fig. 10. Rut depth test results at 20°C, 30°C and 40°C for loading of 500 N

Upon the addition of nano Sb₂O₃, the rut depth was observed to be higher in specimens with no nanomaterial. Also, specimens with 0.25% and 1% had an increased rut depth compared to those with 0.5% and 0.75%. Based on the results, it can be deduced that adding Nano Sb₂O₃ is useful but in limited amounts. If an excess amount is used, it will deteriorate the performance of the asphalt mix. One of the hypotheses given by Chelovian & Shafabakhsh (2017) is that an excess amount of nanoparticles increases the distance between the bitumen particles. Thereby, bitumen loses its cohesive bonding force, making the asphalt mix prone to early deterioration. At this moment, this can be taken into account. However, microscopic analysis is required for validation to establish the fact, which needs further studies.

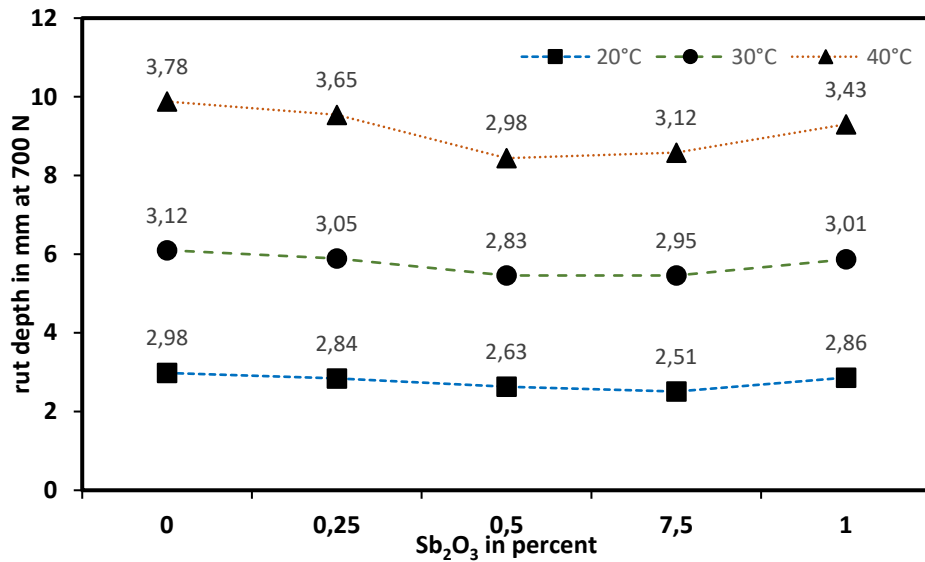


Fig. 11. Rut depth test results at 20°C, 30°C and 40°C for loading of 700 N

4. Conclusion

This study was conducted to evaluate the performance of Sb₂O₃ modified asphalt mix. The performance was evaluated using indirect tensile fatigue, creep, and wheel track tests. The specimens were prepared with a dosage of 0.25%, 0.5%, 0.75% and 1% of Sb₂O₃. A control specimen with 0% Sb₂O₃ was prepared to compare the impact of nanomaterial on the asphalt mix. The specimen was tested on a lower temperature range of 20°C, 30°C and 40°C.

Indirect tensile fatigue test of specimens with Nano Sb₂O₃ had an improved performance by 3-15% at the different dosages. The optimum dosage range was found to be 0.5%. Also, it was observed with a decrease in temperature, fatigue decreases, and asphalt life increases.

Dynamic creep test results indicated an improved Sb_2O_3 modified asphalt mix performance by 14-26%. The maximum strain reduction of 26% was observed in the specimen with nano dosages of 0.5% and 0.75%.

Instead of defining an optimum dose, this study will recommend a range of 0.5% and 0.75%, which is more feasible as the results may vary based on the quality of bitumen, asphalt, and aggregate used for the mix.

Further studies are required in terms of the lower temperature range to investigate the performance of nano-modified asphalt mix.

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