

Research Article

Environment Effect on the Rutting Resistance of Nano-SiO₂-Modified Asphalt Concrete: Temperature and Water

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Received 6 May 2021; Revised 5 July 2021; Accepted 2 August 2021; Published 12 August 2021

Academic Editor: Jiaolong Ren

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Nanoparticles have been widely adopted to improve the high-temperature performance of asphalt binder. However, the influence of moisture on high-temperature performance is not clear. Hence, the water absorption performance of the nano-SiO₂-modified asphalt concrete is investigated. Based on this, to further analyze the pavement performance of the nano-SiO₂-modified asphalt concrete, the coupled effects of high-temperature, moisture content, and nanoparticles content on the rutting resistance of the nano-SiO₂-modified asphalt concrete are tested and revealed in this study. Results show that temperature has the most significant influence on the water absorption performance of the nano-SiO₂-modified asphalt concrete. The rutting resistance of the nano-SiO₂-modified asphalt concrete decreases as temperature and moisture content increase, especially for the temperature. The dynamic stability at the same temperature condition decreases approximately linearly as moisture content increases. The effect of the nano-SiO₂ content is the most nonobvious.

1. Introduction

Since the reform and opening-up, China's highway transportation construction has been changing rapidly and has developed quickly [1, 2], but rutting has always been one of the most important diseases of China's highway asphalt pavement [3, 4]. Rutting will greatly affect driving safety and road aesthetics and have a significant negative impact on highway operations [5]. How to improve the rutting resistance of asphalt pavement is a hot topic in recent years, and enhancing the high-temperature stability of asphalt is one of the effective ways [6–8]. In recent years, nanomaterials have been widely used to improve the performance of asphalt binder because of its large specific surface area, high surface free energy, and good dispersion ability [9–12]. Hasaninia and Haddadi investigated the rutting and fatigue damage of asphalt caused by nano-SiO₂ and found the correlation between modified binder and the engineering performance of asphalt mixture [13]. Wu et al. explored the temperature sensitivity of nanoparticles to cement mortar, the influence

of nano-SiO₂ on the strength of cement asphalt mortar, and the performance of nano-SiO₂ cement asphalt mortar at different temperatures [14]. Rezaei et al. modified asphalt with nano-SiO₂ and SBS polymer and analyzed its high-temperature performance [15]. Chen and Li have carried out engineering index tests on nano-SiO₂ emulsified asphalt. It reveals that the addition of nano-SiO₂ has the effect of improving stability, permeability, and softening point [16]. Shafabakhsh and Jafari Ani found that the addition of nano-TiO₂ and nano-SiO₂ improved the rheological properties of asphalt, increasing the toughness and viscosity by 30% and 109% on average while reducing the permeability grade. In addition, the rutting resistance and fatigue life of the asphalt are improved [17]. Saltan et al. measured the rutting and fatigue properties of modified nanometer asphalt materials [18]. Chen et al. studied the effect of SiO₂ phase change composite on the internal temperature of porous asphalt concrete [19]. Shafabakhsh et al. explored the effects of nano-SiO₂ on low-temperature cracks in asphalt mixtures, using a semicircular bending test (SCB) under the loading of I/II

mixture [20]. Qian et al. showed that the anti-UV aging property of asphalt is improved obviously due to the blocking function of nano-SiO₂ and carbon black in rubber powder, and the enhancing effect of nano-SiO₂ is found to be the most significant [21]. Yang et al. investigated the effects of nano-SiO₂ content on the Engler viscosity and storage stability of asphalt emulsion as well as the performances of asphalt emulsion residue [22]. Du et al. proposed that Al₂O₃ and SiO₂ chemical components played a leading role in improving the bearing capacity and rutting performance of porous asphalt pavement [23]. Moeini et al. investigated the modification effect of two morphologically different nano-SiO₂ materials: (i) a synthesised fibrous with porous structure and (ii) a commercial spherical with nonporous structure, on asphalt binder [24]. Leiva-Villacorta and Vargas-Nordbeck carried out the dynamic shear rheological test, asphalt fatigue test, rutting test, and adhesion work analysis to explore the influence of nano-SiO₂ [25]. Wan et al. explored that ceramic fiber has a great strengthening effect on asphalt, which makes the asphalt harder and can only withstand a small strain under the same stress. The thermal insulation effect of ceramic fiber will improve temperature stability. The results of complex modulus and phase Angle show that ceramic fiber can significantly improve the high-temperature resistance of soft binder [26].

Temperature is one of the main causes of rutting on asphalt pavement [27–29]. In high-temperature areas in China, the highest temperature of asphalt pavement can be higher than 60°C. When vehicles are driving, the road is prone to rutting [11, 12, 30]. At the same time, it is usually accompanied by continuous rainfall in some high-temperature areas (such as China's southeast coastal areas and southern China), such as the "meiyu period" in China. Due to the monsoon, there will be 30–40 days of high temperature in summer (such as in Zhejiang Province and Guangdong Province), and along with continuous light to moderate rain, it is easy to make the road surface buckle under conditions of water-high temperature, and the degradation of road performance will be the result of the combined effect of water and high temperature. When water enters the asphalt pavement from cracks or other ways, it will reduce asphalt's aggregate adhesion, resulting in loosening, peeling, potholes, and other diseases of the pavement. Under the combined effect of water and high temperature, the damage to asphalt is more serious than that of water or high temperature alone.

In order to solve the above problems, this study studied the influence of water and high-temperature coupling on the rutting resistance of nano-SiO₂-modified asphalt concrete through a wheel tracking test. The laboratory tests of 48 groups with different water conditions, temperatures, and nano-SiO₂-modified asphalt concrete were designed.

2. Materials and Methods

2.1. Materials. The aggregate is limestone, and the asphalt is grade Zhonghai 70# asphalt. All technical indexes of all kinds of aggregates and asphalt meet the relevant requirements of China's aggregate technical regulations.

2.1.1. Aggregates. The technical indexes of coarse aggregates, fine aggregates, and mineral powders are shown in Tables 1–3.

2.1.2. Asphalt Mixture Composition. The aggregate gradation is given in Table 4.

2.1.3. Base Asphalt Binder. The Zhonghai 70# base asphalt binder is used in this study, of which the technical indexes are displayed in Table 5.

2.2. Methods. The test process is shown in Figure 1.

2.2.1. The Specimen Preparation. Size of specimen: 300 × 150 × 150 (mm). The test temperature is 60°C. The wheel pressure is 0.7 MPa.

(1) Add the aggregate to the mixer and stir for 90 s; then, add asphalt and stir for 90 s at 177°C. (2) The well-mixed aggregate and asphalt mixture are added to the mill. First, the asphalt mixture is preliminarily compacted, mainly from the surrounding to the middle of the mill. The compacted samples are higher in the middle than around. (3) The prepared samples were rolled on a roller, first rolled twice in one direction and then rolled 24 times after rotating 90°. (4) The prepared samples were placed at room temperature and pressure for 48 h. The operation of the rutting test was carried out after 48 hours.

2.2.2. Test Process.

- (1) The specimen shall be placed together with the test mold in a constant temperature chamber up to 60°C and 1°C for not less than 5 hours or 24 hours. On the part where the test wheel does not walk, paste a thermoelectric corner thermometer and control the temperature of the specimen to be stable at $60 \pm 0.5^\circ\text{C}$.
- (2) The specimen together with the test model was placed on the test bench of the wheel point tester. The test wheel was in the central part of the specimen, and its walking direction should be consistent with the rolling or driving direction of the specimen. Start the rut deformation automatic recorder, and then start the test machine, so that the test wheel moves back and forth to walk for about 1 h or the maximum deformation reaches 25 mm. During the test, the recorder automatically records the deformation curve and specimen temperature.

The rutting test was carried out in accordance with the specification (JTGE20-2011, 2011). Fine-grain gradation AC-13 was selected in this study. Synthetic gradation of mineral aggregate is shown in Table 6. The optimum oil-aggregate ratios of nanomodified asphalt concrete with 1%, 2%, and 3% nano-SiO₂ particles are 5.0%, 5.0%, and 5.1%, respectively.

TABLE 1: Technical indexes of coarse aggregates.

| | | | | | |
|-------------------------|--------------------------------|----------------|--------------------------------------|--------------------------------|----------------------|
| Crushed stone value (%) | Los Angeles abrasion value (%) | Ruggedness (%) | Flat-elongated particles content (%) | <0.075 mm particle content (%) | Water absorption (%) |
| 15.2 | 17.1 | 7.3 | 5.9 | 0.4 | 0.76 |

TABLE 2: Technical indexes of fine aggregates.

| | | | |
|------------------|----------------|----------------|-------------------------|
| Silt content (%) | Angularity (s) | Ruggedness (%) | Hydrophilic coefficient |
| 1 | 69 | 5.8 | 0.58 |

TABLE 3: Technical indexes of mineral powders.

| | | | | | | |
|-------------------|-------------------------|----------------------|-------------------|-------------------|----------|-----------|
| Water content (%) | Hydrophilic coefficient | Plasticity index (%) | Heating stability | Particle size (%) | | |
| | | | | <0.6 mm | <0.15 mm | <0.075 mm |
| 0.68 | 0.58 | 2.6 | Unchanged | 100 | 93.7 | 100 |

TABLE 4: Aggregate gradation.

| | |
|-------------------|----------------|
| Passing size (mm) | Mass ratio (%) |
| 19 | 100 |
| 16 | 93.5 |
| 13.2 | 79.8 |
| 9.5 | 63.8 |
| 4.75 | 45.8 |
| 2.36 | 33.1 |
| 1.18 | 22.6 |
| 0.6 | 15.4 |
| 0.3 | 9.8 |
| 0.15 | 8.1 |
| 0.075 | 6.9 |

TABLE 5: Technical indexes of base asphalt binder.

| | | | | |
|---------------------------|----------------------|---------------------|---------------------|-----------------------|
| 25°C penetration (0.1 mm) | Softening point (°C) | 10°C ductility (cm) | 15°C ductility (cm) | 60°C viscosity (Pa-s) |
| 67.0 | 48.6 | 27.6 | >100 | 216 |

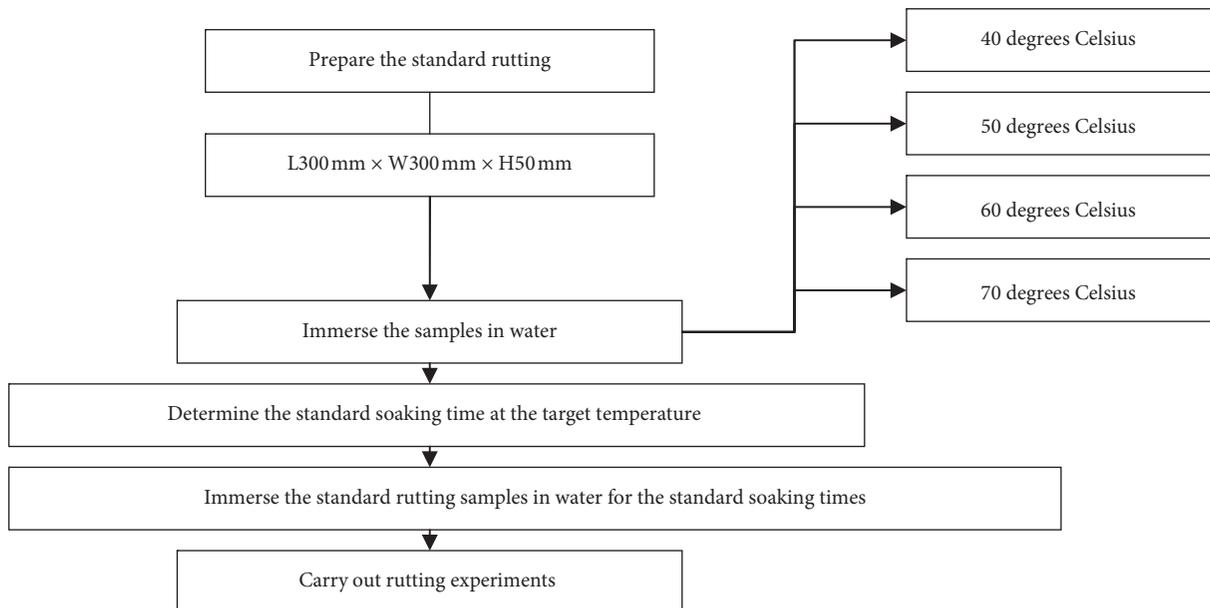


FIGURE 1: Flowchart of asphalt concrete immersion test under high temperature.

TABLE 6: Synthetic grading of mineral aggregate.

| Grading type | Pass rate (%) | | | | | | | | | | |
|--------------|---------------|-----|------|------|------|------|------|------|------|------|-------|
| | 19 | 16 | 13.2 | 9.5 | 4.75 | 2.36 | 1.18 | 0.6 | 0.3 | 0.15 | 0.075 |
| AC-13 | 100 | 100 | 91.7 | 72.3 | 49.0 | 34.8 | 23.6 | 16.0 | 10.0 | 8.2 | 6.9 |

TABLE 7: Saturated water ratios in the case of using different temperatures and content of nano-SiO₂.

| Soaking time | Saturated water ratio (%) | | | | | | | | | | | |
|--------------|---------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| | 40°C | | | 50°C | | | 60°C | | | 70°C | | |
| | 3% | 3.5% | 4% | 3% | 3.5% | 4% | 3% | 3.5% | 4% | 3% | 3.5% | 4% |
| 10 min | 26.61 | 26.67 | 26.59 | 18.68 | 18.60 | 18.71 | 15.33 | 15.32 | 15.36 | 11.87 | 11.89 | 11.89 |
| 20 min | 38.26 | 38.33 | 38.40 | 29.16 | 29.07 | 29.09 | 24.29 | 24.32 | 24.37 | 19.66 | 19.58 | 19.51 |
| 0.5 h | 48.31 | 48.33 | 48.34 | 37.15 | 37.21 | 37.16 | 31.51 | 31.53 | 31.61 | 26.45 | 26.57 | 26.55 |
| 1.5 h | 63.37 | 63.33 | 63.21 | 48.80 | 48.84 | 48.91 | 40.53 | 40.54 | 40.44 | 33.61 | 33.57 | 33.66 |
| 3.5 h | 73.29 | 73.33 | 73.55 | 55.77 | 55.81 | 55.71 | 46.69 | 46.85 | 46.60 | 39.09 | 39.16 | 39.18 |
| 5.5 h | 80.09 | 80.00 | 80.16 | 61.36 | 61.63 | 61.67 | 51.69 | 51.35 | 51.70 | 44.99 | 44.76 | 44.71 |
| 9.5 h | 86.69 | 86.67 | 86.91 | 69.62 | 69.77 | 69.83 | 60.01 | 60.36 | 60.37 | 53.01 | 53.15 | 53.09 |
| 15.5 h | 89.99 | 90.00 | 90.11 | 79.99 | 79.87 | 79.66 | 72.88 | 72.97 | 73.07 | 67.18 | 67.13 | 67.27 |
| 22.5 h | 93.19 | 93.33 | 93.38 | 89.61 | 89.53 | 89.21 | 87.41 | 87.39 | 87.16 | 79.72 | 79.81 | 79.89 |
| 30.5 h | 96.77 | 96.67 | 96.46 | 95.53 | 95.35 | 95.61 | 94.50 | 94.59 | 94.61 | 92.91 | 93.01 | 93.11 |
| 44.5 h | 98.61 | 98.33 | 98.18 | 97.72 | 97.67 | 97.99 | 97.39 | 97.30 | 97.46 | 95.70 | 95.80 | 95.91 |
| 60.5 h | 100.0 | 100.0 | 100.0 | 98.83 | 98.84 | 98.89 | 99.00 | 99.10 | 99.33 | 97.90 | 97.90 | 97.88 |
| 72.5 h | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 84.5 h | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 96.5 h | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

3. Water Absorption Characteristics of Nanomodified Asphalt Concrete under High-Temperature Conditions

The nanomodified asphalt concrete and matrix asphalt concrete with different content of nano-SiO₂ particles were tested at 40°C, 50°C, 60°C, and 70°C for the corresponding moisture content of the specimens under water immersion conditions. Each group of experiments is carried out in four parallel experiments.

The experimental temperature of the rutting test in the Chinese test specification is 60°C. To further investigate the effect of temperature on the rutting resistance of the nano-SiO₂-modified asphalt concrete, a wide range of the experimental temperature is selected in this study.

The relationship between nanomodified asphalt concrete and immersion time at different temperatures is shown in Table 7.

The change law of the nanomodified asphalt concrete with water immersion time at different temperatures is shown in Figure 2.

As shown in Figure 2 and Table 7, under the same temperature and immersion time, the difference in moisture content between nanomodified asphalt concrete and matrix asphalt concrete does not exceed 1%. Therefore, the influence of nanomodifiers on the water absorption characteristics of asphalt concrete is not significant.

From the above analysis, it can be seen that the content of nano-SiO₂ particles has no significant effect on the moisture content of asphalt concrete; that is, the same test index is selected for matrix asphalt concrete and nanomodified asphalt concrete. Therefore, for matrix asphalt and

nanomodified asphalt concrete, when conducting rutting and fatigue tests, temperature is used as the influencing factor, and moisture content is used as the controlling factor. The immersion time corresponding to the water content of 0%, 50%, 80%, and 100% is selected as the test index. The results are shown in Table 8.

4. High-Temperature Stability of Nanomodified Asphalt Concrete under the Coupling Action of Water and High Temperature

In the test, dynamic stability is used as the evaluation standard, and each group of tests is carried out in three parallel tests. See Table 9 for the rutting test results of asphalt concrete with different moisture content.

4.1. Effect of Saturated Water Ratio. Figure 3 plots the relationship between saturated water ratio and dynamic stability of modified asphalt mixture at different temperatures and different contents of nano-SiO₂ particles.

Figure 3 shows us that, with the increase of water content, the dynamic stability of nanomodified asphalt concrete decreases significantly. Under AC-13 gradation, compared with the case of 0% water content, the dynamic stability of nanomodified asphalt concrete is reduced by 37.2%, 51.1%, and 61.5% on average when the water content is 50%, 80%, and 100%. At 40°C, 50°C, 60°C, and 70°C, the total attenuation is 52.2%, 56.3%, 60.8%, and 69.5%. The analysis results show that the water in the voids of the nanoasphalt mixture will erode the asphalt film in the asphalt-aggregate interface and affect the cementation of the aggregate and asphalt. Particularly under

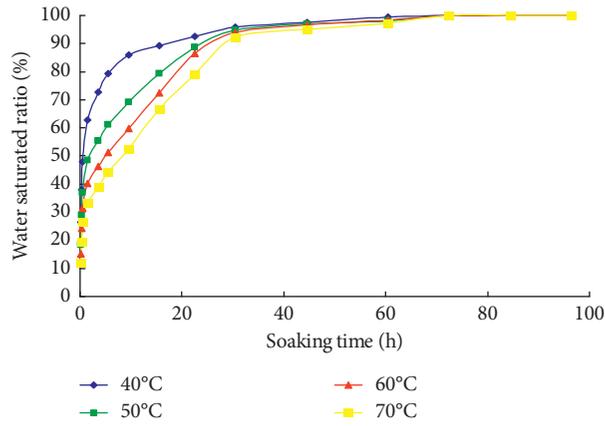


FIGURE 2: Relationship between saturated water ratio and soaking time.

TABLE 8: Time index of moisture content of asphalt concrete under AC-13 grading.

| Water absorption (%) | Temperature (°C) | Immersion time (h) |
|----------------------|------------------|--------------------|
| 0 | 40 | 0 |
| | 50 | 0 |
| | 60 | 0 |
| | 70 | 0 |
| 50 | 40 | 0.5 |
| | 50 | 1.5 |
| | 60 | 5.5 |
| | 70 | 9.5 |
| 80 | 40 | 5.5 |
| | 50 | 15.5 |
| | 60 | 19.5 |
| | 70 | 22.5 |
| 100 | 40 | 60 |
| | 50 | 72 |
| | 60 | 72 |
| | 70 | 72 |

TABLE 9: AC-13 nano-SiO₂-modified asphalt dynamic stability.

| Temperature (°C) | Water absorption (%) | Content (%) | Dynamic stability (cycles/mm) |
|------------------|----------------------|-------------|-------------------------------|
| 40 | 0 | 1 | 5625 |
| | | 2 | 6215 |
| | | 3 | 6841 |
| | 50 | 1 | 3485 |
| | | 2 | 4278 |
| | | 3 | 4521 |
| | 80 | 1 | 2805 |
| | | 2 | 3182 |
| | | 3 | 3514 |
| | 100 | 1 | 2018 |
| | | 2 | 2420 |
| | | 3 | 2655 |

TABLE 9: Continued.

| Temperature (°C) | Water absorption (%) | Content (%) | Dynamic stability (cycles/mm) | |
|------------------|----------------------|-------------|-------------------------------|------|
| 50 | 0 | 1 | 4781 | |
| | | 2 | 5283 | |
| | | 3 | 5815 | |
| | 50 | 50 | 1 | 2962 |
| | | | 2 | 3636 |
| | | | 3 | 3843 |
| | 80 | 80 | 1 | 2384 |
| | | | 2 | 2705 |
| | | | 3 | 2987 |
| | 100 | 100 | 1 | 1715 |
| | | | 2 | 2057 |
| | | | 3 | 2257 |
| 60 | 0 | 1 | 4585 | |
| | | 2 | 5162 | |
| | | 3 | 5474 | |
| | 50 | 50 | 1 | 2318 |
| | | | 2 | 2529 |
| | | | 3 | 2744 |
| | 80 | 80 | 1 | 1251 |
| | | | 2 | 1506 |
| | | | 3 | 1782 |
| | 100 | 100 | 1 | 982 |
| | | | 2 | 1123 |
| | | | 3 | 1515 |
| 70 | 0 | 1 | 3577 | |
| | | 2 | 4369 | |
| | | 3 | 4725 | |
| | 50 | 50 | 1 | 1743 |
| | | | 2 | 1710 |
| | | | 3 | 2198 |
| | 80 | 80 | 1 | 705 |
| | | | 2 | 804 |
| | | | 3 | 1141 |
| | 100 | 100 | 1 | 548 |
| | | | 2 | 649 |
| | | | 3 | 922 |

the action of the wheel pressure of the hydrodynamic pressure, the water damage will lead to the decline of the antirutting performance of the asphalt mixture and the degradation of the structural stability of the nano-SiO₂-modified asphalt concrete asphalt mixture. With the increase of water content, this negative effect of water will intensify, and rutting is apt to occur.

4.2. Effect of Temperature. Figure 4 displays the relationship between temperature and dynamic stability of modified asphalt mixture at different saturated water ratios.

Figure 4 shows the relationship between dynamic stability and temperature at different moisture contents. As the temperature increases, the dynamic stability of nanomodified asphalt concrete decreases significantly. Under AC-13 gradation, when the temperature of nanomodified asphalt concrete is 40°C, and the immersion time is 0.5 h, 5.5 h, and 44.5 h, the average dynamic stability is 2997 times/mm, 2063 times/mm, and 1571 times/mm, respectively. The dynamic stability decreased by 39.3%, 49.2%, and 57.1% for every 10°C increase in temperature.

From the above analysis, the following conclusions can be drawn: the dynamic stability of the three different contents of nanomodified asphalt concrete decreases after the temperature increases, indicating that high temperature can reduce the dynamic stability of the nanomodified asphalt concrete. Moreover, as the temperature increases, the asphalt film usually softens, and the above-mentioned effects of water will be correspondingly more significant. The results show that, under the combined action of water and high temperature, rutting is more likely to occur.

4.3. Influence of Content of Nano-SiO₂ Particles. Based on the data in Table 4, the dynamic stability curves of AC-13 nanosized modified asphalt concrete nano-SiO₂ particles with different mixing amounts at 40°C, 50°C, 60°C, and 70°C are drawn as follows:

It can be seen from Figure 5 that, as the content of nano-SiO₂ particles increases, the dynamic stability of nanomodified asphalt concrete increases and the relationship is basically linear. In consideration of economic benefits, the dynamic stability of 0.4% nano-SiO₂ particles increases by

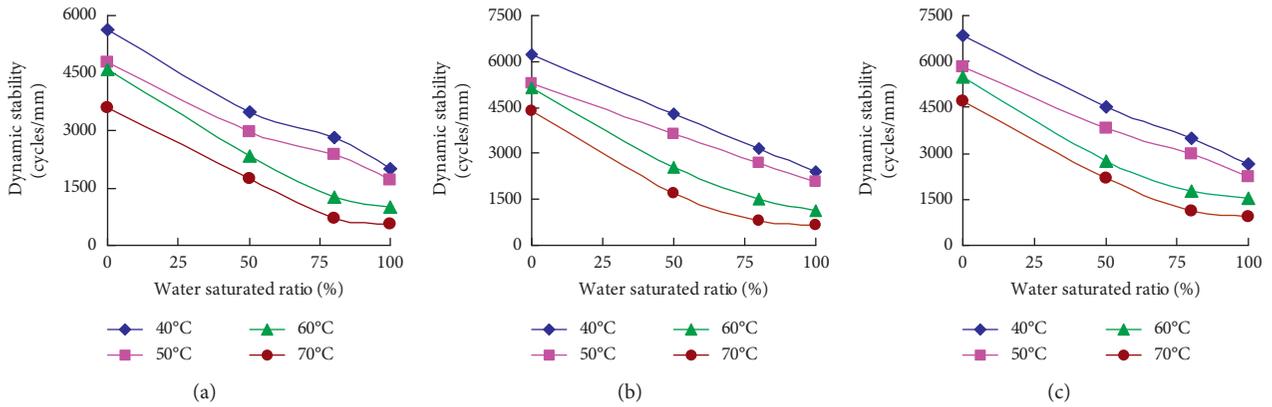


FIGURE 3: Relationship between dynamic stability and saturated water ratio at different temperatures. (a) 1% content. (b) 2% content. (c) 3% content.

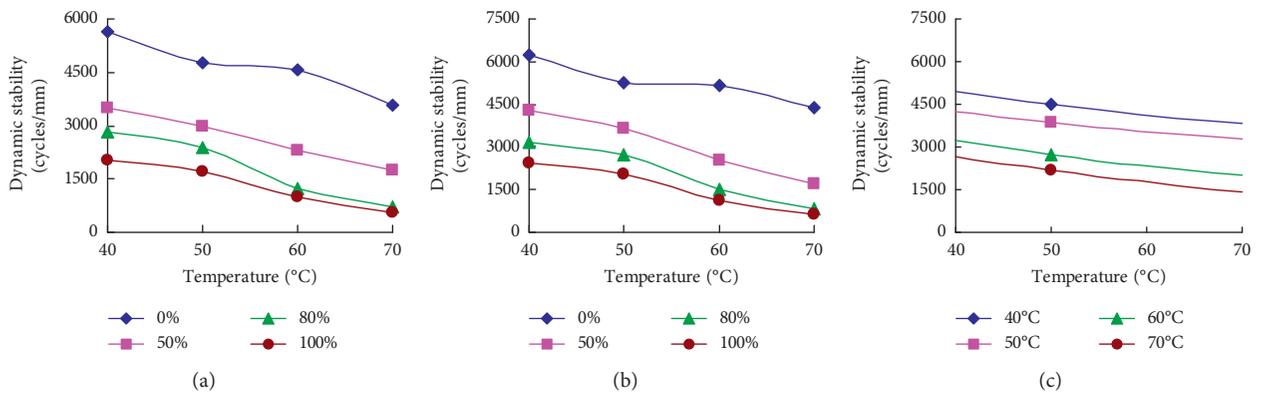


FIGURE 4: Relationship between dynamic stability and temperature at different saturated water ratios. (a) 1% content. (b) 2% content. (c) 3% content.

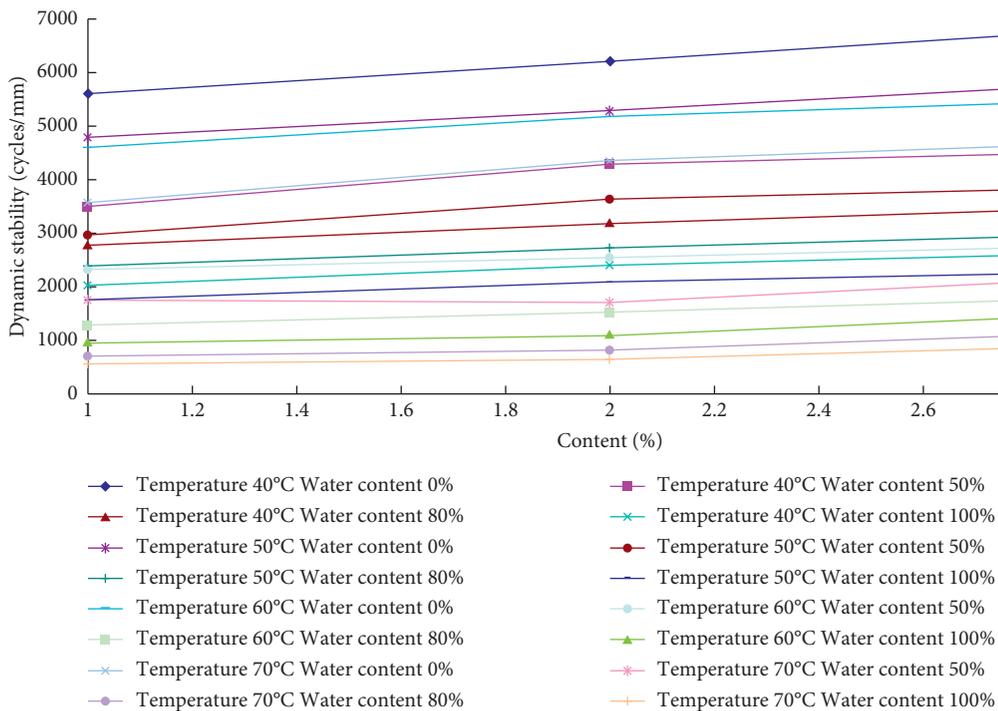


FIGURE 5: Effect of content on dynamic stability.

9.4% compared with 0.35%, and the dynamic stability only increases by 4.6% when the concentration is 0.45%. Therefore, the content of nano-SiO₂ particles is considered to be 0.4%.

5. Conclusion

This article provides a way to improve the antirutting performance of nanomodified asphalt concrete by using nano-SiO₂ particles. Research shows that the water absorption capacity and water absorption rate of nanomodified asphalt concrete are basically the same as those of matrix asphalt concrete. It shows that the addition of nano-SiO₂ particles will not affect the relationship between water absorption capacity and soaking time. This study is beneficial to design the nano-SiO₂-modified asphalt concrete during the coupled effect of high temperature and water.

- (1) According to the technical requirements of the specification, the raw materials used in asphalt concrete were tested, and the mix ratio of nanomodified asphalt concrete was designed when the raw materials met the requirements. The result shows, for AC-13 gradation, the addition of nano-SiO₂ particles will not affect the change of the optimal oil-stone ratio.
- (2) Temperature has a great influence on the water absorption performance of asphalt concrete. The higher the temperature, the longer it takes for the asphalt concrete to reach 100% moisture content. At the same time, when the moisture content reaches 100%, water absorption is higher. The dynamic stability of the three nanomodified asphalt concretes with different concentrations decreases with the increase of temperature, indicating that high temperature will reduce the dynamic stability of the nanomodified asphalt concrete. As the temperature increases, the asphalt film usually softens, and water's effect becomes correspondingly more significant. The results show that rutting is more likely to occur under the coupled action of water and high temperature.
- (3) The rutting test was carried out at 40°C, 50°C, 60°C, and 70°C, respectively. It was found that the dynamic stability under the same temperature condition decreases approximately linearly with the increase of water content. When the water content is greater than 50%, the rate of decrease gradually lessens, but with the increase of temperature, the linear trend becomes more and more obvious.

In the future, other pavement performance of the nano-SiO₂-modified asphalt concrete, for example, the fatigue behavior and skid resistance, should be addressed in the coupled effect of temperature and water.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors are very grateful for the support provided in part by the Highway Construction Science and Technology Projects of Shandong Hi-Speed Co. Ltd. (Grant no. QLTD-2019-A-FW-0036).

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