

## Article

# Experimental Study on Activated Diatomite Modified Asphalt Pavement in Deep Loess Area

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**Abstract:** In order to effectively prevent and control the rutting problem of asphalt pavement in the deep loess area of Eastern Gansu and reduce road diseases, diatomite was added into the asphalt mixture for laboratory tests. Through Marshall test and rutting test, the optimum mix proportion of the diatomite asphalt mixture, and the optimal mix amount of the diatomite in this area were determined. The pavement performance of activated diatomite asphalt pavement and SBS asphalt pavement in this area is compared and analyzed through laboratory tests and on-site road paving. The test results show that under the same ambient temperature, the activated diatomite asphalt pavement has the advantages of lower surface temperature, high stability, and low-water permeability coefficient than SBS modified asphalt pavement. In addition, by fitting the fatigue test data of these two asphalt pavements, it is found that the fatigue life of diatomite asphalt mixture is more sensitive to the change in stress level and has better fatigue resistance. Therefore, it is concluded that the use of diatomite modified asphalt pavement in the loess area can improve the temperature stability of the pavement, prolong the service life, and reduce the cost of construction, which can be popularized.

**Keywords:** asphalt modifier; activated diatomite; experimental research; road performance; mix ratio design



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## 1. Introduction

With the continuous increase in the mileage of expressways in China, pavement diseases have also appeared in varying degrees: heavy traffic, axle load, permanent deformation, such as rutting and pushing in hot seasons, low-temperature cracking in winter; reflective cracks in semi-rigid base; water damage, such as potholes, and looseness caused by rainy season and spring melting season; reduced anti-skid performance of road surface; and local cracking [1]. Faced with the pressure of modern traffic, in order to ensure that the pavement quality is in good condition for a long time, it is necessary to reduce rutting, congestion, and oil flashing on the road surface under high-temperature conditions, and avoid cracking, potholes, looseness, and other damages under the conditions of low temperature and rainfall erosion [2,3].

Early research on improving the performance of asphalt pavement mainly focused on modified asphalt or asphalt mixture and obtained a variety of asphalt modifiers, such as SBS (Styrene-butadiene-styrene block copolymer), SBR (Styrene butadiene rubber), PE (polyethylene), EVA (Ethylene vinyl acetate), and other polymer modifiers [4–7]. Diatomite is an industrial mineral with stable performance, which has the characteristics of rough surface, high hardness, acid and alkali resistance, wear resistance, anti-skid, unique microporous structure, and active ingredients. Active diatomite was widely used as a good asphalt modifier many years ago in other countries [8–11]. However, activated diatomite has only been applied in some areas and individual road sections in China. By using scanning electron microscope [12], spectral analysis [13], and other methods to study the

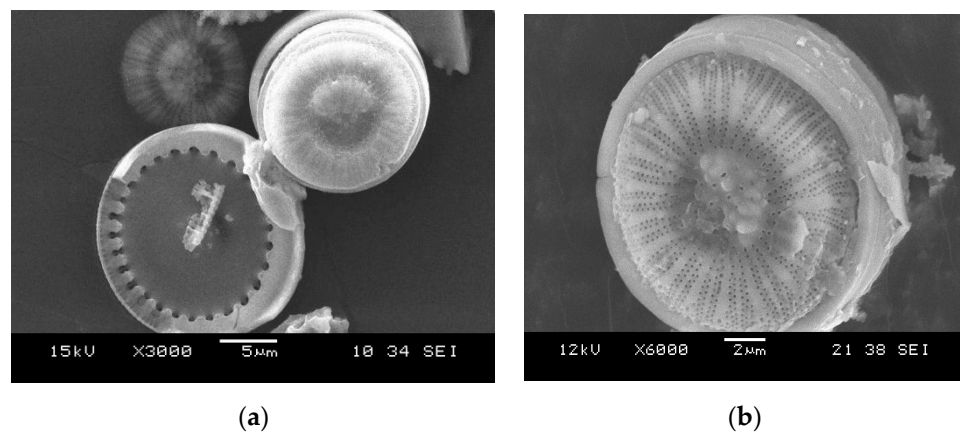
microscopic mechanism of diatomite modified asphalt, diatomite and asphalt were found to form a stable system with good compatibility when mixed. Moreover, by analyzing the chemical composition of diatomite, diatomite was found to improve the performance of asphalt by absorbing saturated and aromatic aromatics in asphalt [14,15]. The research on the influence of diatomite on the pavement performance of asphalt mixture is mainly reflected in high-temperature performance [16], low-temperature performance [17], dynamic viscoelasticity [18], water stability [19], thermal insulation performance [20], and so on. The results show that diatomite is a very good asphalt modified material, which can better improve the related performance of asphalt mixture pavement. It can increase the flow resistance of asphalt; effectively prevent the formation of oil bleeding, extrusion, and rutting; and has good wear resistance and skid resistance; the thermal insulation performance of the pavement is good, so that the asphalt does not flow in summer and does not crack in winter, reducing the harm of climate to pavement. According to the influence of diatomite on the road performance of asphalt mixture, the optimal dosage of diatomite was also obtained [21]. Recently, many composite modifiers have been used to improve the road performance of asphalt mortar, such as diatomite and glass fiber [22], basalt fiber [23], morphologically stable composite phase change material (CPCM) synthesized by stearic acid (SA) and palmitic acid (PA) [9], ceramic sand particles [24], polyethylene glycol (PEG) [10], paraffin [25], rubber [26], and other materials that are mixed together. In order to further rationally utilize the active diatomite resources and promote the development and application of new materials and technologies, the active diatomite modified asphalt mixture was used for highway construction and maintenance in the deep loess area of Qingyang City, Gansu Province, especially the highway construction under the condition of heavy traffic. It can play multiple roles, such as improving pavement performance, prolonging service life, reducing costs, etc., which will bring greater economic benefits to the development of this area. Therefore, it is of great significance to conduct research on the development and popularization of related technologies on activated diatomite modified asphalt mixtures and to fully understand the modification mechanism of activated diatomite to asphalt mixtures.

## 2. Materials and Methods

### 2.1. Diatomite

Diatomite is a kind of biogenic siliceous sedimentary rock, which is mainly composed of the remains of ancient diatoms. Its chemical composition is mainly  $\text{SiO}_2$ , with a small amount of  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$ ,  $\text{MgO}$ , etc., and organic matter. The mineral composition is opal and its variants. Figure 1 shows that under the scanning electron microscope (SEM) (JEOL JSM-7800F, Tokyo, Japan) the active silicon without purification has a high content of clay, debris, and other impurities, while the clay minerals can reduce the adhesion and water stability of the modified asphalt. Calcite and detritus minerals only play the role of filler in modified asphalt but have no modification effect. Organic matter will affect the durability of modified asphalt. Therefore, to be used as a modifier of asphalt mixture, we must go through a special purification process to remove impurities, such as clay, open diatom pores, and activate them into active silicon before it can be used as a modifier of asphalt mixture.

In Figure 1b, the activated diatomite has many ordered multilevel nanopores, which increase the specific surface area and pore volume so that it has better adsorption capacity. When the activated diatomite is added to the asphalt, there will be no chemical reaction, but the diatomite will be adsorbed in the asphalt to enhance the adhesion between the asphalt and the mineral aggregate and effectively improve the water damage resistance of the mixture. At the same time, its larger specific surface area and  $\text{SiO}_2$  content improve the high-temperature stability and low-temperature crack resistance of the asphalt mixture.



**Figure 1.** Scanning electron microscope image of diatomite. (a) Before activation. (b) After activation.

## 2.2. Asphalt

The 70# base asphalt produced by Maoming Donghai was selected for the test. The main technical indexes obtained after testing are shown in Table 1. The test results show that the asphalt meets the requirements of the specification.

**Table 1.** Test results of main technical indexes of asphalt.

Test Index		Test Result
Penetration (0.1 mm)	15 °C, 100 g, 5 s	25.7
	25 °C, 100 g, 5 s	65.9
	30 °C, 100 g, 5 s	118.9
Penetration index (PI)		0.87
Ductility (10 °C, 5 cm/min) (cm)		>100
Softening Point ( $T_{R\&B}$ ) (°C)		53.2
dynamic viscosity (Pa·s) (60 °C)		330
Solubility (%)		99.5
Density (15 °C) (g/cm <sup>3</sup> )		1.056
RTFOT (163 °C, 75 min)	mass loss (%)	0.29
	Penetration ratio (25 °C) (%)	62.55
	Ductility (10 °C) (cm)	8.93

## 2.3. Coarse Aggregates

Coarse aggregates composed of 5–10 mm and 10–20 mm crushed stones are selected for the asphalt mixture, and the technical indexes are shown in Table 2.

**Table 2.** Test results of coarse aggregates.

Test Index	Gravel (10–20 mm)	Gravel (5–10 mm)
Apparent relative density	3.049	3.074
Water absorption (%)	0.688	0.792
Needle-like content (%)		13.04
Adhesion to asphalt	Raw asphalt (boiling method)	Level 4
	Add anti-stripping agent (boiling method)	Level 5
Crushing value of stone (%)		18.62
Los Angeles attrition loss (%)		18.91

## 2.4. Fine Aggregate

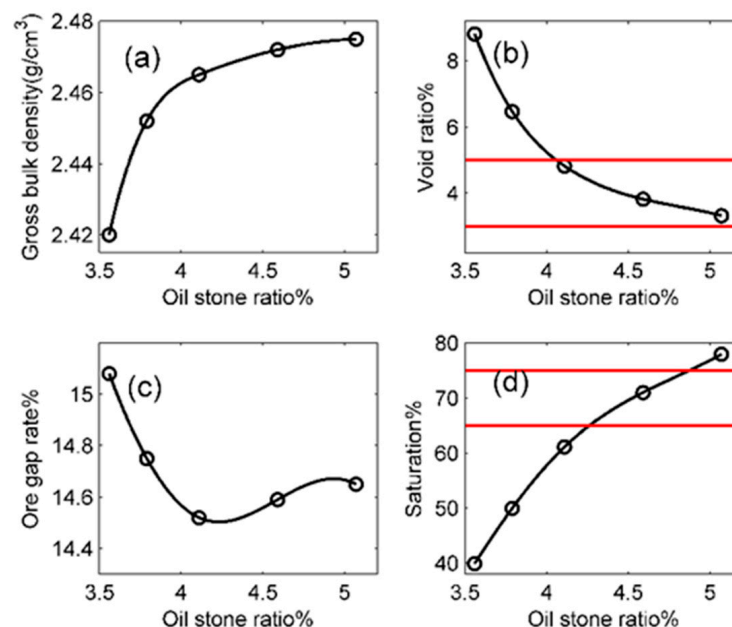
The particle size of fine aggregate used in the asphalt mixture is 0–5 mm, and the apparent relative density is 3.315. The dust content of 0–5 mm stone chips is too much,

accounting for 12% of the total mass of the material, which does not meet the specification requirements. Therefore, when using, the dust content below 0.075 mm should be controlled to be less than 7%.

### 3. Mix Proportion Design of Asphalt Mixture

#### 3.1. The Asphalt Aggregate Ratio

The Marshall test was performed indoors with the above materials, and the variation law of asphalt aggregate ratio with various indexes of Marshall test is obtained, as shown in Figure 2. Figure 2a shows that the asphalt aggregate ratio of the specimen is within the test range, and the gross bulk density does not reach the peak value. According to the method of “Technical Specification for Construction of Highway Asphalt Pavements” (JTG F40-2004),  $OAC_1$  takes the median value of the target porosity (See Figure 2b), that is,  $OAC_1 = 4.6\%$ . In Figure 2, the technical standard of the asphalt dosage range that all test indicators must meet is 4.15–4.7%, so  $OAC_2 = (OAC_{min} + OAC_{max})/2 = (4.15 + 4.7)/2 = 4.4\%$ . Take the median value of  $OAC_1$  and  $OAC_2$  as the best asphalt aggregate ratio; that is, the optimal asphalt aggregate ratio  $OAC = (OAC_1 + OAC_2)/2 = 4.5\%$ .

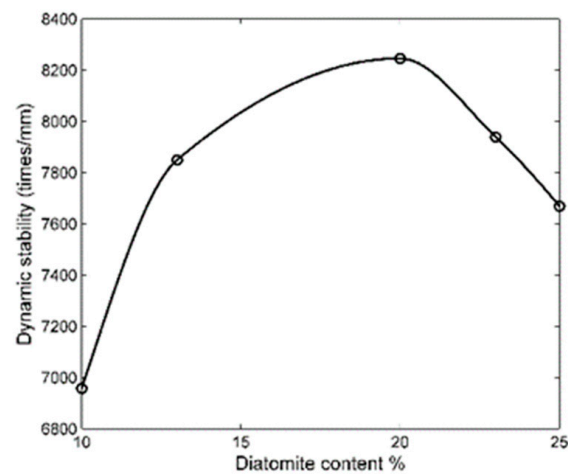


**Figure 2.** The optimum asphalt aggregate ratio. (a) The relationship between oil stone ratio and gross bulk density; (b) the relationship between oil stone ratio and void ratio; (c) the relationship between oil stone ratio and ore gap rate; (d) the relationship between oil stone ratio and saturation.

#### 3.2. Diatomite Content

We analyze the rutting test when the diatomite content (mass fraction) is 10%, 13%, 20%, 23%, and 25% of asphalt mixture, as shown in Figure 3. When the content of active diatomite is less than 20%, the dynamic stability of asphalt mixture gradually increases with the increase in the content; that is, the rutting depth has a gradually decreasing trend, indicating that the increase in active diatomite content can effectively alleviate the occurrence of rutting and reduce the possibility of rutting diseases. However, when the output exceeds 20%, the dynamic stability decreases. This shows that the proper amount of diatomite can improve the high-temperature performance of asphalt mixtures, but an excessive amount of diatomite will reduce the high-temperature performance. When the content of active diatomite is 20%, the dynamic stability is the highest, which is 8245.8 times/mm, and when the content is 13%, the dynamic stability is 7938.3 times/mm; the difference between them is small. Therefore, according to the road performance of the mixture, when the content of active diatomite is 13%, the comprehensive performance of

the mixture is the best. Therefore, the selection of the active diatomite content of 13% in this area is the best.



**Figure 3.** Rutting test results of diatomite with different content.

### 3.3. The Mixing Method of Active Diatomite

The active diatomite can be directly added into the mixing tank through the metering equipment and fully mixed with the mineral aggregate to form the asphalt mixture, that is, the dry mixing method. The asphalt also can be mixed with diatomite after heating and melting, which has good compatibility and can effectively improve the adhesion between asphalt and mineral aggregates, that is, wet mixing. A total of 13% active silicon was mixed into the asphalt mixture by dry mixing and wet mixing, respectively, and the Marshall test was performed to obtain the results as shown in Table 3. The volume index of Marshall specimens made by dry mixing and wet mixing does not change much. However, when the wet mixing is adopted, the density of diatomite is lower than that of ordinary asphalt, the storage stability is poor, it is easy to separate, and the process is more complicated. In addition, the construction is not easy to operate, which changes the properties of asphalt. If the asphalt quality is unstable in the construction process, it is easy to have quality problems. Therefore, it is finally determined that the addition method of diatomite is dry mixing.

**Table 3.** Marshall test indexes of dry mixed and wet mixed diatomite.

Add Method	Active Silicon Content (%)	Oil Stone Ratio (%)	Marshall Density	Porosity (%)	VMA (%)	Saturation (%)	Stability (kN)	Flow Value (mm)
Dry mixing	13	4.5	2.728	3.4	13.2	74.0	16.89	3.3
Wet mixing	13	4.5	2.727	3.6	13.3	73.1	16.64	3.7

### 3.4. The Best Mix Proportion

Taking the maximum density and minimum clearance rate of Marshall specimens prepared with diatomite asphalt mixture as the index, the appropriate content of diatomite and the best amount of asphalt are determined. When the active diatomite is added into the asphalt mixture, the particle content of less than 0.075 mm has the greatest impact on the asphalt mixture. In order to ensure the powder binder ratio of the asphalt mixture, it is necessary to appropriately reduce the amount of mineral powder and ensure that the asphalt aggregate ratio is consistent with that of the ordinary asphalt mixture. AC-13 (asphalt–concrete mixture of coarse aggregate with maximum nominal particle size of 13 mm) and AC-20 (asphalt–concrete mixture of coarse aggregate with maximum nominal particle size of 20 mm) asphalt mixtures commonly used in this area are selected for the test. The mineral gradation curve obtained through sieving analysis test is shown in Figure 4.

The passing rate of 0.075 mm sieve hole in the figure is 1–2% lower than the median value of the grading range recommended by the current technical specifications for asphalt pavement construction, the passing rate of 4.75 mm sieve hole is 35–38%, and the passing rate of 9.5 mm sieve hole is 52–61%; that is, the content of fixed 4.74–9.5 mm material is about 20%, and the passing rate of maximum nominal particle size sieve is 95%. The gradation curves are all distributed in “s” shape, indicating that the gradation is good. The coarse particles of AC-13 asphalt mixture are concentrated and the distribution range is narrow. The test indicators of the two asphalt mixtures under this gradation are shown in Tables 4 and 5, respectively. The pavement performance of asphalt mixture meets the specification requirements, which further indicate that this gradation is good and can guide the construction of activated diatomite asphalt pavement in the loess area.

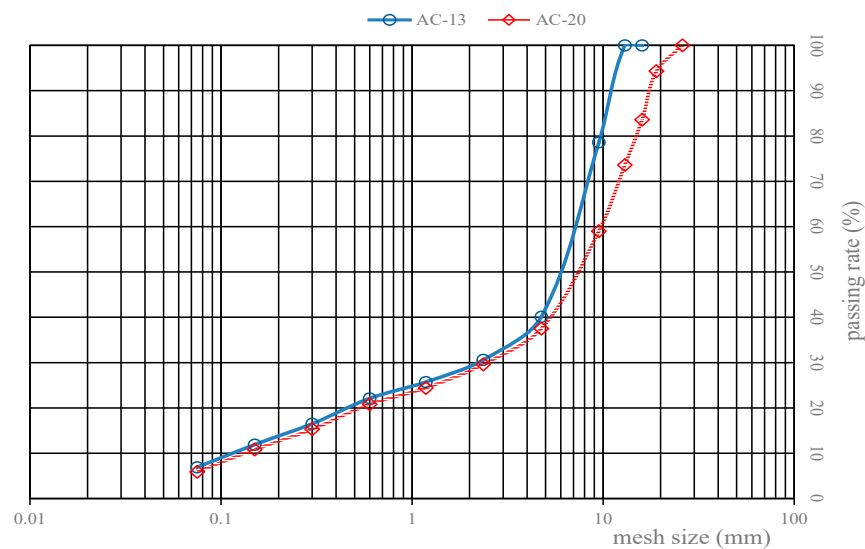


Figure 4. Gradation curve of asphalt mixture.

Table 4. Test indexes of active silicon AC-13 asphalt mixture.

Indexes	Bulk Volume Relative Density	Theoretical Maximum Relative Density	VMA (%)	Saturation (%)	Void Ratio vv (%)	Stability (KN)	Flow Value (0.1 mm)	Submerged Marshall Stability (kN)	Splitting Failure Strength (MPa)	Splitting Strength Ratio (%)	Rutting Resistance (60 °C, 0.7 MPa) (Times/(mm))
result	2.735	2.821	13.4	77.2	3.1	12.0	29	9.7	1.266	97.7	8281.5

Table 5. Test indexes of active silicon AC-20 asphalt mixture.

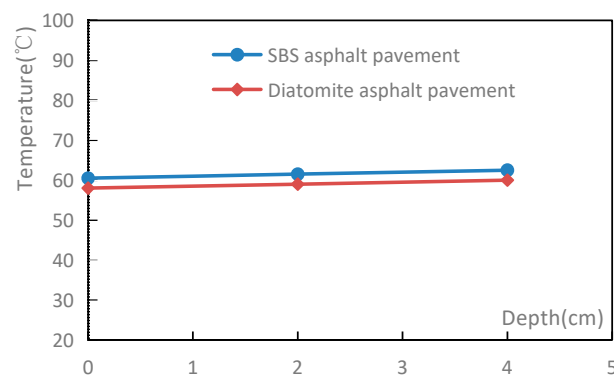
Indexes	Bulk Volume Relative Density	Theoretical Maximum Relative Density	Saturation (%)	Void Ratio Vv (%)	Stability (KN)	Flow Value (0.1 mm)	Submerged Marshall Stability (kN)	Residual Stability (%)	Splitting Failure Strength (MPa)	Splitting Strength Ratio (%)	Rutting Resistance (60 °C, 0.7 MPa) (Times/(mm))
result	2.728	2.83	73.1	3.4	9.7	30	9.4	96.3	1.119	97.2	6451

#### 4. Comparative Analysis of Pavement Performance between Activated Diatomite Modified Asphalt Pavement and SBS Modified Asphalt Pavement

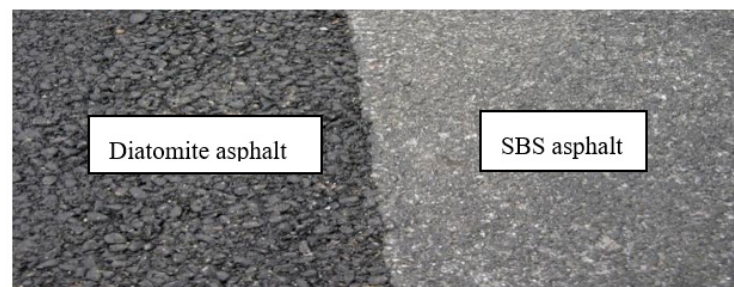
##### 4.1. Thermal Resistance and Cooling Performance

The diatomite asphalt mixture and SBS modified asphalt mixture with the same ratio prepared according to the above method are heated in the incubator for 120 min, and the temperature is set to 60 °C. The temperature change law at different depths of the two materials is measured, as shown in Figure 5. The temperature of asphalt mixture pavement mixed with SBS modifier is always maintained at the design temperature of the incubator, while the temperature of diatomite asphalt pavement is about 2 °C lower than the designed

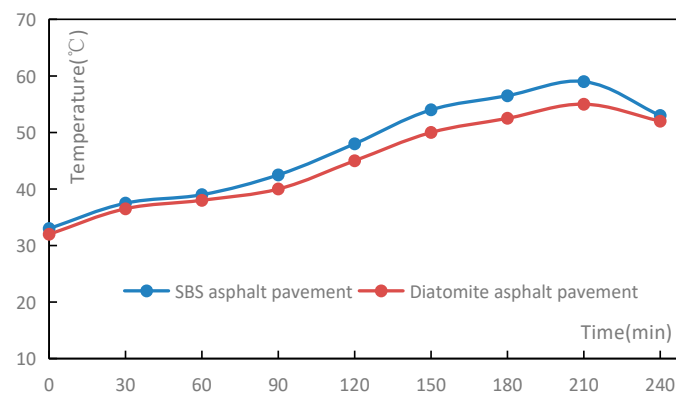
temperature of the incubator, and the difference between them does not decrease with the increase in depth. It shows that the diatomite modifier can reduce the temperature of asphalt pavement, which is lower than the surrounding ambient temperature, can adjust the pavement temperature, and has good high-temperature performance. At the same time, the outdoor test section was paved in Longdong College, Xifeng District, Qingyang City, Gansu Province, as shown in Figure 6. The active diatomite asphalt mixture pavement basically does not produce the refraction of smooth surface under the sunlight and vehicle light, which improves the safety of vehicle driving. Moreover, the annular porous structure of active diatomite can increase the scattering interface area of strong light and effectively reduce the temperature of the road surface. Therefore, the temperature variation law in Figure 5 is further verified. We measure the temperature change in the road surface of diatomite asphalt mixture pavement and SBS modified asphalt mixture pavement was measured when the ambient temperature is 38 °C, as shown in Figure 7.



**Figure 5.** Temperature variation law of different asphalt mixtures during heating.



**Figure 6.** Comparison of test sections between SBS and activated diatomite asphalt pavement.



**Figure 7.** Comparison of road surface temperature of two asphalt mixtures at ambient temperature of 38 °C.

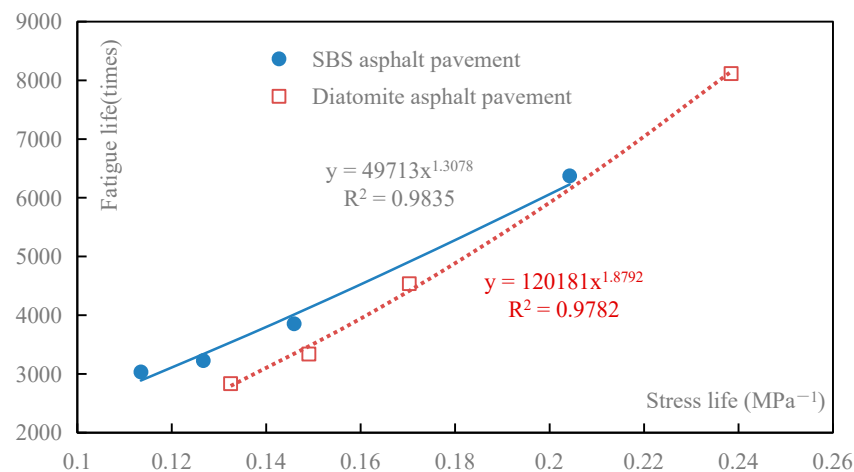
As shown in Figure 7, the road surface temperature of activated diatomite asphalt mixture is 4.2–5.1 °C, lower than that of SBS modified asphalt mixture at the same ambient temperature. The difference between them increases with the increase in ambient temperature. However, after the ambient temperature decreases, the temperature of SBS asphalt pavement decreases more than that of diatomite asphalt pavement, and the temperature of diatomite asphalt pavement decreases slowly. That is, the asphalt mixture mixed with activated diatomite can absorb the surface temperature and release the internal temperature of asphalt pavement through its own nanopores, which enhances the temperature stability of the asphalt pavement and improves the rutting resistance of asphalt pavement.

#### 4.2. Fatigue Test

The splitting fatigue test was performed on SBS modified asphalt mixture specimen and diatomite asphalt mixture specimen by means of stress control. The indoor temperature was 18 °C, and a sinusoidal load was applied vertically above the specimens with a frequency of 10 Hz. The reciprocal of the measured stress level of the specimen is the abscissa, and the action times of the load applied during fatigue failure of the specimen is the ordinate, and the regression equation is established as shown in Formula (1).

$$N_f = k \left( \frac{1}{\sigma_0} \right)^n \quad (1)$$

where  $N_f$  is load action times corresponding to the fatigue failure;  $\frac{1}{\sigma_0}$  is the splitting stress ratio; and  $k$  and  $n$  are parameters determined by the test. The test results are shown in Figure 8. Clearly,  $n = 1.8792$  in the fatigue curve of diatomite asphalt mixture is greater than  $n = 1.3078$  of SBS modified asphalt mixture, indicating that the fatigue life of diatomite asphalt mixture is sensitive to the change in stress level. At the same time,  $k = 12 \times 10^4$  in the fatigue curve of diatomite asphalt mixture is much larger than that of SBS modified asphalt mixture, which shows that the fatigue resistance of diatomite asphalt mixture is much better than that of SBS modified asphalt mixture.



**Figure 8.** Fatigue test results of pavement with different asphalt mixtures.

#### 4.3. Road Performance

The diatomite asphalt mixture and SBS modified asphalt mixture with the same proportions were made into standard Marshall specimens. The road performance of the two kinds of pavement is compared and analyzed through the test, as shown in Table 6.



**Table 6.** Performance comparison of SBS and activated diatomite modified asphalt pavement.

Pilot Project	SBS	Activated Diatomite
Void ratio (%)	4.0	3.8
VMA (%)	16.5	15.6
VFA (%)	68.8	66.5
Stability (kN)	12.5	13.7
Flow value (mm)	2.6	2.8
Dynamic stability (times/mm)	8770	7193
Low temperature bending ( $\mu\epsilon$ )	2635	2750
Water permeability coefficient (mL/min)	68	56
Residual stability (%)	86.5	90.2
Cost per kilometer (million)	96.5	87.9

As shown in Table 6, the performance indexes of diatomite asphalt pavement all meet and greatly exceed the national technical requirements for modified asphalt, in which the stability, dynamic stability, low-temperature bending deformation, water permeability coefficient, and residual stability are better than SBS modified asphalt. Therefore, compared with ordinary asphalt, it can greatly improve the pavement performance and prolong the service life by three to five times. At the same time, compared with SBS modified asphalt pavement, the material cost per kilometer can be reduced by 25–50%, and the carbon-dioxide emission can be reduced by 105 tons. It can be recycled; conforms to the trend of green energy; meets the requirements of energy conservation and environmental protection; and has obvious economic, social, and environmental benefits. It is undoubtedly the best cost-effective road asphalt modifier in the loess area.

## 5. Conclusions

In this study, the diatomite modifier was added to the asphalt mixture, and the addition method and optimal dosage of diatomite were obtained through experiments. The optimal gradation suitable for the loess region was analyzed at the same time. The pavement performance of SBS modified asphalt pavement and diatomite asphalt pavement was compared and analyzed through laboratory test and field test, and the advantages of diatomite in improving asphalt pavement in the loess area were obtained. Based on this study, the following main conclusions are drawn:

- (1) The Marshall test was conducted indoors to obtain the relationship among the density, void ratio, mineral interstitial ratio and saturation, and the asphalt aggregate ratio. When using diatomite modified asphalt pavement in the loess area, the optimal asphalt aggregate ratio can be calculated at about 4.5%. According to the relationship between the different content of diatomite and the dynamic stability of the asphalt mixture, the optimal content of diatomite is 13% of the asphalt mixture. The performance of diatomite asphalt mixture made by wet mixing and dry mixing was also compared and analyzed. The high-temperature performance of the pavement was found to be the best when diatomite was added by dry mixing.
- (2) In order to optimize the gradation of diatomite asphalt mixture, it is necessary to ensure its powder-to-binder ratio. Therefore, through the gradation curve of asphalt mixture, the passing rate of 0.075 mm sieve hole is 1–2% lower than the median value of the grading range recommended in the current technical specification for asphalt pavement construction. The content of 4.75–9.5 mm material is about 20%. At this time, the pavement performance of asphalt mixture meets the specification requirements, and the gradation is good.
- (3) The heat resistance and temperature-reduction performance in diatomite asphalt pavement and SBS modified asphalt pavement were analyzed through laboratory tests and on-site paving test sections. The surface cooling of active diatomite asphalt mixture is up to 4.2–5.1 °C compared with SBS modified asphalt mixture. Moreover, with the increase in air temperature, the difference of road surface temperature between

activated diatomite asphalt mixture and SBS modified asphalt mixture is greater. After the temperature decreases, the temperature of diatomite asphalt pavement decreases slightly, indicating that diatomite can enhance the temperature stability of asphalt pavement and improve the rutting resistance of asphalt pavement.

- (4) The splitting fatigue tests of SBS modified asphalt mixture and diatomite asphalt mixture were performed. The regression equation was established to show that the fatigue resistance of diatomite asphalt mixture was better than that of SBS modified asphalt mixture.
- (5) By comparing and analyzing the performance of SBS modified asphalt pavement and diatomite asphalt pavement, we found the stability, dynamic stability, low-temperature bending deformation, water permeability coefficient, residual stability, and construction cost of activated diatomite modified asphalt pavement are obviously better than those of SBS modified asphalt pavement. Therefore, we concluded that the use of diatomite modified asphalt pavement in the loess area can resist high temperature, low temperature, fatigue, water, oil, ultraviolet radiation, etc., to delay the aging of pavement, and the cost is low, which is suitable for popularization and application.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Zhang, R.; Zhang, W.; Shen, S.; Wu, S.; Zhang, Y. Evaluation of the correlations between laboratory measured material properties with field cracking performance for asphalt pavement. *Constr. Build. Mater.* **2021**, *301*, 124126. [\[CrossRef\]](#)
2. Zhu, M. Application of phase change temperature-regulating material in road design and construction. *Res. Urban Constr. Theory* **2018**, *33*, 118.
3. McNally, T. *Polymer Modified Bitumen: Properties and Characterization*; Woodhead Publishing Limited: Cambridge, UK, 2011; pp. 10–11.
4. Zhou, X.; Ma, B.; Ren, Y.; Wang, X. Study on temperature control performance of composite shaped phase change material for asphalt pavement. *Bull. Chin. Ceram. Soc.* **2018**, *37*, 3611–3616.
5. Zhang, D.; Chen, M.; Wu, S.; Riara, M.; Wan, J.; Li, Y. Thermal and rheological performance of asphalt binders modified with expanded graphite/polyethylene glycol composite phase change material (EP-CPCM). *Constr. Build. Mater.* **2018**, *194*, 83–91. [\[CrossRef\]](#)
6. Kakar, M.R.; Refaa, Z.; Worlitschek, J.; Stamatiou, A.; Partl, M.N.; Bueno, M. Thermal and rheological characterization of bitumen modified with microencapsulated phase change materials. *Constr. Build. Mater.* **2019**, *215*, 171–179. [\[CrossRef\]](#)
7. Ruien, Y.; Xijing, Z.; Maorong, Z.; Changqing, F. Properties and mechanism of graphene oxide/polyurethane composite modified asphalt mixture. *Sci. Technol. Eng.* **2018**, *33*, 209–214.
8. Liu, Z.; Yanmin, W.; Jia, J.; Sun, H.; Wang, H.; Qiao, H. Preparation and Characterization of Temperature-Adjusting Asphalt with Diatomite-Supported PEG as an Additive. *J. Mater. Civ. Eng.* **2020**, *32*, 04020019. [\[CrossRef\]](#)

9. Jin, J.; Liu, L.; Liu, R.; Wei, H.; Qian, G.; Zheng, J.; Xie, W.; Lin, F.; Xie, J. Preparation and thermal performance of binary fatty acid with diatomite as form-stable composite phase change material for cooling asphalt pavements. *Constr. Build. Mater.* **2019**, *226*, 616–624. [[CrossRef](#)]
10. Qian, T.; Li, J.; Deng, Y. Pore structure modified diatomite-supported PEG composites for thermal energy storage. *Sci. Rep.* **2016**, *6*, 32392. [[CrossRef](#)]
11. Karaman, S.; Karaipekli, A.; Sari, A.; Biçer, A. Polyethylene glycol (PEG)/diatomite composite as a novel form-stable phase change material for thermal energy storage. *Sol. Energy Mater. Sol. Cells* **2011**, *95*, 1647–1653. [[CrossRef](#)]
12. Zhang, X.Y.; Tan, Y.Q.; Wang, Z.R. Influence of diatomite on temperature stability of asphalt. *Highway* **2005**, *6*, 149–152.
13. Xu, J.P.; Bao, Y.N. Modification mechanism of silicon modified asphalt based on microscopic test. *J. Chang. Univ. Nat. Sci. Ed.* **2005**, *25*, 14–17.
14. Zhang, X.Y.; Tan, Y.Q.; Wang, Z.R. Analysis of influence factors of diatomite chemical composition on high temperature performance of asphalt. *J. Highw. Transp. Res. Dev.* **2005**, *22*, 18–20.
15. Zhang, X.Y.; Hu, G.Y.; Song, Y.R. Study on absorption of asphalt components by diatomite. *J. Jilin Inst. Archit. Civ. Eng.* **2008**, *25*, 47–50.
16. Wang, G.A.; Zhu, H.Z.; Chen, T.J.; Tang, B.M. High temperature performance evaluation of diatomite modified asphalt mortar. *Highw. Eng.* **2010**, *35*, 150–154.
17. Yiqiu, T.; Liyan, S.; Jun, F.; Xingyou, Z. Antil-cracking mechanism of diatomite asphalt and diatomite asphalt mixture at low temperature. *J. Southeast Univ. (Engl. Ed.)* **2009**, *25*, 74–78.
18. Li, X.M.; Zhang, X.N.; Li, Z. Analysis of dynamic viscoelastic characteristics of diatomite modified asphalt mortar. *Highway* **2006**, *10*, 145–149.
19. Li, G.F.; Bian, J.; Wang, L.G. Experimental study on water stability of diatomite modified asphalt mixture. *Pet. Asph.* **2007**, *21*, 10–13.
20. Hu, G.S.; Liu, Q.; Song, D.G.; Wang, S.J. Study on thermal insulation and heat resistance technology of diatomite asphalt mixture. *J. Highw. Transp. Res. Dev.* **2016**, *12*, 23–24.
21. Lv, H.W. Research on road performance of diatomite modified asphalt mixture. *Highw. Eng.* **2018**, *43*, 241–246.
22. Guo, Q.; Li, L.; Cheng, Y.; Jiao, Y.; Xu, C. Laboratory evaluation on performance of diatomite and glass fiber compound modified asphalt mixture. *Mater. Des.* **2015**, *66*, 51–59. [[CrossRef](#)]
23. Song, S.B. Experimental study on performance of diatomite/basalt fiber composite modified asphalt mixture. *Synth. Mater. Aging Appl.* **2021**, *50*, 59–61.
24. Bian, X.; Tan, Y.Q.; Lv, J.F.; Shan, L.Y. Preparation of Latent Heat Materials Used in Asphalt Pavement and Theirs' Controlling Temperature Performance. *Adv. Eng. Forum* **2012**, *5*, 322–327. [[CrossRef](#)]
25. Xu, B.; Li, Z. Paraffin/diatomite composite phase change material incorporated cement-based composite for thermal energy storage. *Appl. Energy* **2013**, *105*, 229–237. [[CrossRef](#)]
26. Jin, J.; Tan, Y.; Liu, R.; Zheng, J. Synergy effect of attapulgite, rubber, and diatomite on organic montmorillonite-modified asphalt. *J. Mater. Civ. Eng.* **2018**, *31*, 04018388. [[CrossRef](#)]