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Laboratory Investigation of Brucite Fiber in Stabilizing and Reinforcing Asphalt Binder

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Abstract: The purpose of this study is to evaluate brucite fiber's properties, stabilizing and reinforcing effects, and corresponding mechanism when used for asphalt binder. Commonly used fibers such as lignin fiber, basalt fiber, and polyester fiber were chosen for comparative studies. Laboratory tests of water absorption, oven heating, and mesh-basket draindown were designed and performed to evaluate their wettability, thermostability, asphalt absorption, and stabilization, respectively. The cone penetration test was applied to study the resistance to shear of fiber modified asphalt; the standard dynamic shear rheometer test was conducted to evaluate the rheological properties and rutting resistance of fiber modified asphalt; and Scanning Electron Microscopy(SEM) analyses was introduced to observe fiber's microstructure characteristic and its spatial network in asphalt binder. The results indicate that brucite fiber has improved the moisture susceptibility property and thermostability more than lignin fiber. It has better asphalt absorption and stabilization effects than basalt fiber and polyester fiber. Meanwhile, brucite fibers can effectively improve asphalt binder's resistance to rutting and shear, and dynamic shear modulus. Brucite fiber can effectively reinforce the asphalt matrix through its functions of spatial networking, adhesion and stabilization of asphalt binder.

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Key words*: Asphalt binder; Brucite fiber; Mechanical property; Network effect; Rheology.*

Introduction

Asphalt pavement is the most prevalent type of highway pavement because of its advantages such as low noise, good skid resistance, improved comfort, convenience of maintenance, and recyclability. Asphalt mixture has been widely used in road pavement. However, asphalt pavements are subjected to distresses of cracking and rutting (permanent deformation) under the effects of repeated vehicle loading and freeze-thaw cycles [1-3]. Accordingly, fibers have been used in asphalt mixture to improve pavement performance. Previous researchers have reported fiber's reinforcing effects in asphalt mixture and pavement. Fibers can not only modify asphalt binder just like organic polymers (e.g., SBS, SBR, and PE) or prevent asphalt leakage in asphalt mixture especially for the OGFC and SMA mixtures effectively [4-6], but also improve the engineering properties of asphalt mixture including viscoelasticity, dynamic modulus, moisture susceptibility, creep compliance, rutting resistance, and anti-reflective cracking, which all prolong the service life of asphalt pavement [7-13]. At present, several fibers are usually added into the asphalt mixture, such as lignin fiber, basalt fiber, and polyester fiber. However, lignin fiber has objective shortcomings because it is prone to be affected by damp conditions, which results in poor dispersion property in the asphalt mixture as well as low tensile strength. Although the basalt fiber and polyester fiber can improve the road performance of asphalt concrete, their prices are so high that they cannot to be applied widely. Therefore, it is important to find the appropriate fiber to overcome these shortcomings and provide an innovative way to satisfy the asphalt pavement engineering needs.

As a naturally fibrous mineral abundant in world, brucite fiber has notable deposits existing in China, the United States, Italy, Russia, and so on. It is quite different from asbestos in chemical compositions, crystal structures, and chemical properties [14]. Brucite fiber is a magnesium hydroxide mineral, $Mg(OH)_2$, crystallizing in the trigonal system. Its tensile strength and Young's modulus can reach more than 900MPa and 13.8GPa respectively [15]. After a series of the systematic tests, including an animal test, investigation of people's epidemics, solubility of the mineral, and the organism durability, etc., it has been proved that brucite fiber does not harm the human body [16]. The application of brucite fiber as a kind of reinforced material in asphalt mixture has not been studied in past.

This paper aims to investigate the brucite fiber's properties, stabilizing and reinforcing effect, and corresponding mechanism for asphalt binder. Many tests, including water absorption test, oven heating test, and mesh-basket draindown test are conducted to evaluate the properties of fibers, and Scanning Electron Microscopy (SEM) is used to observe the microstructure of fiber and its spatial network in asphalt binder in order to provide an deeper insight into the fiber reinforcing mechanism. Mechanical tests for brucite fiber modified asphalt are conducted to evaluate its reinforcing effect. Based on comparative experiments, the feasibility of brucite fiber used in asphalt binder is assessed compared with control specimens and the other fibers (lignin fiber, basalt fiber, and polyester fiber).

Materials and Methods

Materials

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Table 1. Physical Properties of Asphalt Binder.

Material	Test Items	Unit	Value	Specification
Original Asphalt Binder	Penetration at 25°C	0.1 mm	83.1	ASTM D5-97
	Ductility at 15°C	cm	120	ASTM D113-99
	Softening Point	°C	47.4	ASTM D36-06
	Wax Content	%	1.86	ASTM D3344-90
	Flash Point	°C	271	ASTM D92-02
	Specific Gravity	Non	0.982	ASTM D70-76
RTFO Binder*	Mass Loss	%	-0.05	ASTM D2872-04
	Penetration Ratio at 25 °C	%	82.7	ASTM D5-97
	Ductility at 15 °C	cm	29.3	ASTM D113-99

*Note: * Rolling thin film oven (RTFO) aged, according to ASTM D2872-04.*

Table 2. Physical Properties of Fibers (Provided by Manufacturers).

Items	Brucite Fiber	Lignin Fiber	Basalt Fiber	Polyester Fiber	Specification
Diameter (mm)	0.020*	0.045*	0.013	0.020	ASTM D2130
Length (mm)	2.50*	1.10	6.00	6.00	ASTM D204
Length/Diameter Ratio (mean)	125	24	462	300	N/A
Specific Surface Area ($10^{-3}m^2/g$)	150.3	118.1	74.7	14.8	N/A
Tensile Strength (MPa)	932	N/A	2000	531	ASTM D2256
Specific Gravity	2.300-2.600	1.280	2.817	1.360	ASTM D3800
Melt Temperature (°C)	>400	>200	1500	>250	ASTM D276

*Note: * Mean value.*

Asphalt

The asphalt type of A-90 was used for all experiments. The physical properties of asphalt binder were measured following the ASTM standards, and presented in Table 1.

Fibers

Four fibers were studied in this paper. They are the brucite fiber, the lignin fiber, the basalt fiber, and the polyester fiber. The basic physical properties of fibers are presented in Table 2 (provided by the manufacturers).

Test Methods

Testing Physical Properties of Fibers

Water Absorption

Fiber's absorption of water during storage will make it more moist, susceptible to coagulation and harder to be evenly distributed when being mixed with aggregates and asphalt binders in construction. In this laboratory test, a fiber sample weighing 30 g was prepared and placed in a dry beaker, and its weight was measured with a precision of ±0.001 g. Consequently, the beaker with fibers was placed in a curing chamber filled with air at a relative humidity of 90% at 20°C for 5 days. Afterwards, the total weight was continuously measured at 5-h intervals. The absorbed water can be calculated from the weight changes. This procedure was continued for five days, and three samples were tested for each fiber type.

Oven Heating Test

Fiber may coalesce and even decompose under high temperature when being mixed with asphalt mixture. Therefore, in order to evaluate fibers' thermostability in this study, a simple laboratory oven heating experiment was designed as follows. Three samples of each fiber (50 g per sample) were put in a beaker and then placed in an oven at 163°C (it is similar to the compacting temperature)for 5 h. The weight variations of fibers were observed and recorded continuously.

Mesh-basket Draindown Experiment

Fibers can easily absorb the saturates in asphalt due to the function of surface physical absorption, resulting in the change of the rheological properties of asphalt binder and the optimum asphalt content for the mixture design [17]. Accordingly, a mesh-basket draindown experiment was designed to evaluate fibers' absorption and stabilization of asphalt binder, described as follows. A 6% fiber content by mass of asphalt binder (about 0.3% fiber by mass of AC mixture including aggregates) according to the engineering practice was widely utilized. Consequently, a mix sample weighing 40 g was uniformly placed into a designed steel mesh basket with a sieve size of 0.25 mm, and maintained at 25°C for 2 h. Afterwards, the basket was heated in an environmental chamber at 163°C for 30 min, and some asphalt binder would melt, flow, and drop out under the heating effect. The sample weight was measured, to determine the weight loss of asphalt binder. Less loss and flowing of asphalt indicates the fiber's greater ability to absorb and stabilize asphalt. Three replicate specimens were used for each fiber [1].

Scanning Electron Microscopy (SEM) Analyses

In order to observe fiber's microstructure characteristic and its spatial network in asphalt binder, the SEM analyses was conducted on fibers and fiber modified asphalts using the SEM EPMA (S-4800).

Testing Physical and Mechanical Properties of Fiber Modified Asphalt

Cone Penetration Test

In order to evaluate the fiber modified asphalt's resistance to shear, a cone penetration test was designed to measure. As shown in Fig. 1 [1], an asphalt sample weighting 500 g and a fiber sample weighting 30 g were mixed at 150°C. Subsequently, the uniform fiber-asphalt mix was filled in a funnel, which was then slightly oscillated to pour the mix into an iron vessel. The prepared sample was maintained under room temperature for 40 min until it cooled and solidated, and then conditioned underwater at 30°C for more than 1 h. Afterwards, the sample was taken out of water, and an iron cone weighing 195 g was released from the mix surface. The cone would gradually penetrate into the fiber-asphalt mix until being stable, at which the sink depth was measured and recorded. It should be noted that the cone would not completely penetrate into the mix. Based on the force balance (see Fig. 1), the shear stress τ (kPa) of fiber modified asphalt at the direction tangential to the cone surface can be determined as follows:

$$\tau = \left[981Q\cos^2(\alpha/2)\right] \Big/ \left[\pi h^2 \tan(\alpha/2)\right] \tag{1}$$

where Q is the cone's quality (195 g), h is the sink depth (0.1mm), and α is the cone angle (30°). Three replicate specimens were used for each fiber type. Here the cone sink depth and calculated shear stress according to the force balance are used to evaluate fiber modified asphalt's resistance to shear force.

Rheological Experiments

Rheological measurement is the basic method to study the viscoelasticity of materials. In this paper, the Dynamic Shear Rheometer (DSR) test was conducted to measure the shear modulus and phase angle of asphalt binder, and evaluate its rheological properties and rutting resistance, following the standardized method described by ASTM P246. The test temperature was set at 82°C according to the asphalt performance-grading (PG) system in order to evaluate the high temperature performance of asphalt mortar and asphalt mixture. In this test, the asphalt film sample with a diameter of 25 mm and a thickness of 2 mm was sandwiched between a fixed steel plate and an oscillating plate which oscillated with an angular frequency of 10 rad/s under a constant torque. The material's shear modulus G^* and phase angle δ (shear lag of strain to stress) can be determined as follows:

$$G^* = \sigma(t)/\gamma(t) = i\omega\int_0^\infty \varphi(\xi)\exp(-i\omega\xi)\,d\xi = G' + iG'' \tag{2}$$

$$tg\delta = G''/G'$$

where i is the imaginary unit, ω is the angular frequency, σ is the shear stress, γ is the shear strain, G' is the elastic part and G'' is the viscous part of G^*. G^*/(1-1/sinδtanδ) is proposed as an improved performance index instead of G^*/sinδ to evaluate asphalt binder's rutting resistance [18]. A higher G^*/(1-1/sinδ tanδ) value indicates a higher elasticity and rutting resistance of asphalt.

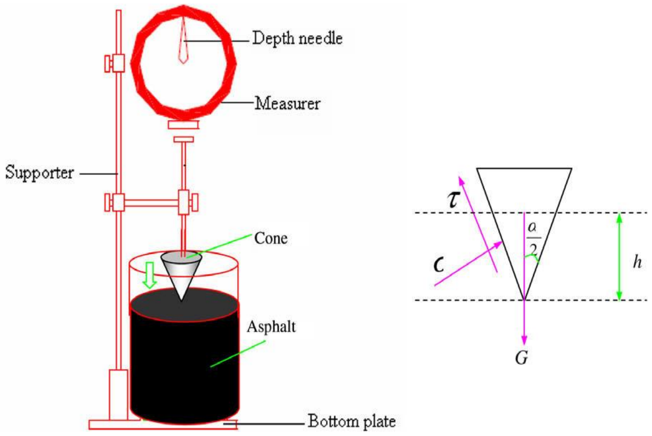


Fig. 1. Cone Penetration Test.

Table 3. Water Absorption of Fibers.

Fiber Type	Dry Weight (g)	Wet Weight (g)	Average Water Absorption(%)
Brucite Fiber	30.01	30.33	1.07
Lignin Fiber	30.02	34.67	15.49
Basalt Fiber	30.02	30.37	1.17
Polyester Fiber	30.01	30.74	2.43

Results and Discussion

Fiber Properties

Water Absorption

The results of water absorption of fibers are shown in Table 3, which shows that the lignin fiber absorbed much more water than other fibers after 5 days in a curing chamber. Its absorbed moisture can be detected by a touch of finger. In this test, brucite fiber, basalt fiber, and polyester fiber have poor water absorption ability. The water absorption ratios for the brucite fiber, basalt fiber, and polyester fiber are 1.07%, 1.17%, and 2.43%, respectively. The water absorption ability of brucite fiber is similar as basalt fiber, and it is lower than polyester fiber. Therefore, these three types of fiber have better states of preservation in humid environment.

Thermostability

Table 4 presents the oven heating test results of fibers. It can be seen that mass loss of lignin fiber is more than other fibers, and this fiber is most susceptible to coagulation. Basalt fibers have the highest thermostability among the four fibers. Fibers have obvious changes in color. The color of lignin fiber becomes brown from light gray. Polyester fiber changes its color from white to light yellow. Brucite fiber and basalt fiber do not have obvious color changes. Because these fibers are composed of different material,

Table 4. Thermostability of Fibers.

Fiber Type	Before Oven Heating(g)	After Oven Heating(g)	Mass Loss (%)
Brucite Fiber	30.02	29.80	0.72
Lignin Fiber	30.01	29.46	1.84
Basalt Fiber	30.03	29.86	0.56
Polyester Fiber	30.01	29.73	0.95

Table 5. Experiment Results of Mesh-basket Draindown.

Fiber Type	Asphalt Separation (%)
Brucite Fiber	8.17
Lignin Fiber	3.04
Basalt Fiber	12.32
Polyester Fiber	18.13

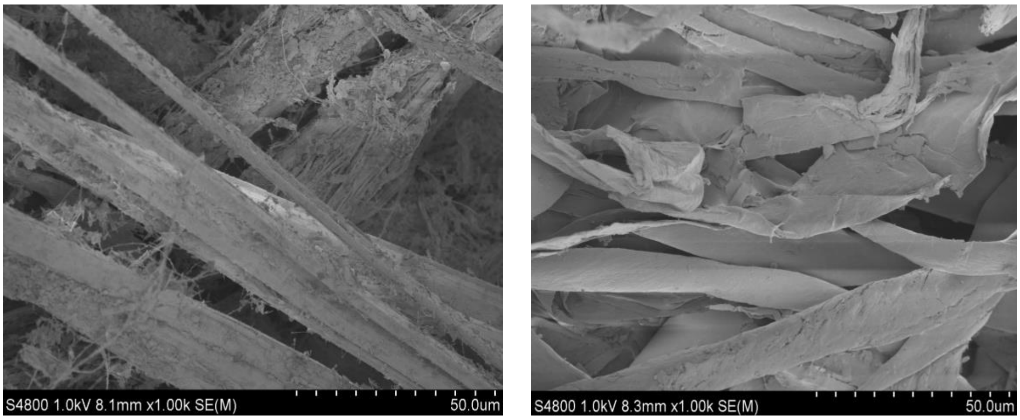
their thermostability is different. Lignin fiber is made from wood and other plants, so its thermostability is the worst. Polyester fiber, which is organic, has worse thermostability than brucite fiber and basalt fiber, which are inorganic. It indicates that brucite fiber and basalt fiber are more stable in high construction temperatures than the other fibers.

Absorption and Adhesion of Asphalt

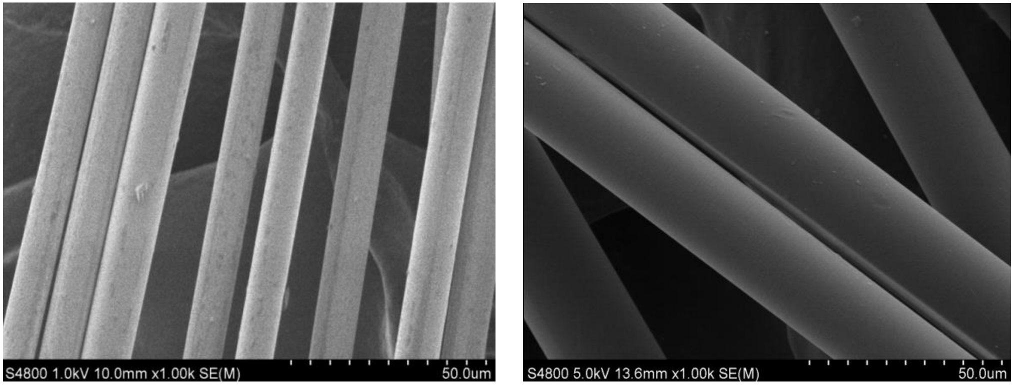
The results of the mesh-basket draindown experiment are shown in Table 5. From Table 5, it can be clearly seen that the lignin fiber has the lowest asphalt drop and separation, or highest asphalt absorption and stabilization, followed by brucite fiber, basalt fiber, polyester fiber. According to the physical properties of fibers, basalt fiber has larger specific surface; however, it has poor absorption and adhesion of asphalt. The main reason is that surface texture is an important factor affecting the bonding strength between asphalt and fiber. The rougher surface texture is, the higher the bonding strength. Surface textures of the artificially synthesized basalt fiber and polyester fiber are smoother than the natural brucite fiber and lignin fiber observed by SEM. Brucite fiber and lignin fiber have higher bonding strength between asphalt and fiber. Fiber's absorption of asphalt results in increasing asphalt's viscosity, improving interface adhesion between asphalt and fiber and increasing the asphalt film thickness. As a result, the flexibility, anti-cracking effect, and resistances to aging and fatigue property of asphalt matrix or asphalt mixture can be improved effectively [1]. In this test, brucite fiber is better than basalt fiber and polyester fiber.

Microstructure Characteristics

Fig. 2 shows the Microstructure characteristics of fibers by SEM. It shows that compared with other fibers, the appearance of brucite fiber is different. The grade 7 of brucite fiber is produced in bundles. Fiber bundles are formed by a number of single fiber whose diameter can reach nanometer level, and it has a rough surface texture without uniform sizes. Lignin fiber is an irregularly shaped fiber, which has plenty of interweaved branches with rough surface texture. Because basalt fiber and polyester fiber are customized in

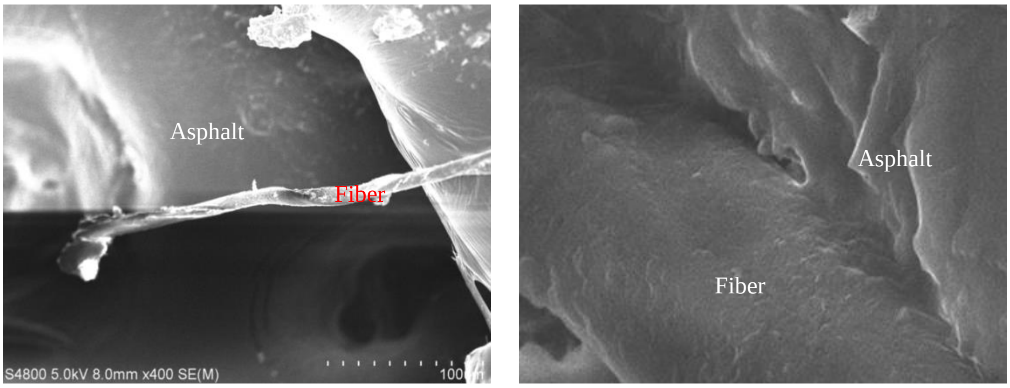


(a) Brucite Fiber (b) Lignin Fiber

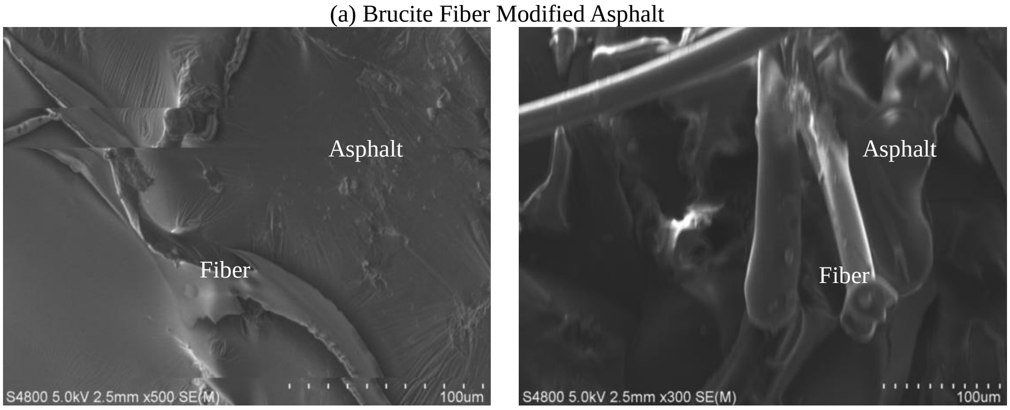


(c) Basalt Fiber (d) Polyester Fiber

Fig. 2. SEM Microstructure of Fibers.



(a) Brucite Fiber Modified Asphalt



(b) Lignin Fiber Modified Asphalt (c) Polyester Fiber Modified Asphalt

Fig. 3. SEM Microstructure of Fiber Modified Asphalt.

the factory, they are regularly cylindrical shaped fiber and their surface is smooth. Table 2 shows that the brucite fiber and lignin fiber have larger specific surface area, which plays a key role in the absorption and adhesion of asphalts. Therefore, combined with the micro-structural characteristics of the fiber surface, the two fibers have better ability to stabilize asphalt.

Fig. 3 shows fibers' spatial distribution in asphalt binder (note that the SEM experiment on basalt fiber modified asphalts was not successful due to the experimental equipment). For the brucite fiber, its alkali component and rough surface texture make its ability to stabilize asphalt good. Besides, the fiber can form a three-dimensional multi-directional spatial network in asphalt and possess good bridging and reinforcing effects combining with its higher tensile strength. For the lignin fiber, its ability to stabilize asphalt is very good, while its reinforcing effect for asphalt binder is low due to its raw materials and manufacturing technique. The polyester fiber also has good asphalt stabilization and great interface adhesion, which may be explained by the solubility law, as it is a product produced from petroleum as is asphalt. Some researchers have confirmed that fiber's three-directional network reinforcing effect stabilizes asphalt binder at high temperatures, resists cracking propagation and aggregate-asphalt interface's sliding, and reduces stress concentration [1]. Therefore, it is promising to use the brucite fiber to improve the mechanical properties of asphalt binder, which will be discussed in the next section.

Fiber Modified Asphalt Properties

Resistance to Shear

Table 6 shows the cone penetration test results of fiber modified asphalts, including the measured cone sink depths and calculated shear stresses. The cone sink depths of fiber modified asphalts can be ranked in a decreased order or increased order for shear stress as follows: the lignin fiber, brucite fiber, basalt fiber, and polyester fiber. Fibers increase the shear strength of asphalt through contrast test with the unmodified asphalt. The reason is that some fibers can perform the three-dimensional spatial networking effect such as brucite fiber, basalt fiber, and polyester fiber, and fibers absorb the light components of asphalt and increase the viscosity and stiffness of asphalts. The polyester fiber has the greatest effect on reducing the cone sink depth and improving the shear stress among the four fibers, which would be due to its great asphalt stabilization and spatial networking effect. Generally, the fiber with higher tensile strength can more effectively resist asphalt flow and cracking propagation. Table 2 shows that the basalt fiber has the highest tensile strength, while it also has the largest density among the fibers. As a result, its effect for improving asphalt's shear strength is influenced by its sinking even segregation in asphalt binder inevitably. The brucite fiber has an improvement effect approximately equal to the basalt fiber due to its physical properties. Its tensile strength is lower than basalt fiber while its surface texture is rougher than basalt fiber. Furthermore, because its larger specific surface area and more absorption of asphalt components to improve the viscosity and stiffness of asphalt binder, the lignin fiber can also reinforce the shear strength of asphalt binder.

Table 6. Cone Sink Depth and Shear Stress of Fiber Modified Asphalts.

Fiber Type	No Fiber	Brucite Fiber	Lignin Fiber	Basalt Fiber	Polyester Fiber
Cone Sink Depth (0.1mm)	160.6	96.2	118.2	92.4	73.0
Shear Stress (kPa)	8.23	22.93	15.20	24.85	39.88

Table 7. DSR Test Results of Fiber Modified Asphalts (82°C).

Fiber Type	G^*(kPa)	Phase Angleδ(°)	$G^*/(1\text{-}1/\sin\delta\tan\delta)$ (kPa)
No Fiber	0.476	89.3	0.482
Brucite Fiber	1.020	83.1	1.163
Lignin Fiber	1.545	75.6	2.105
Basalt Fiber	0.921	84.9	1.012
Polyester Fiber	1.112	81.4	1.314

Rheological Property and Rutting Resistance

Table 7 illustrates the DSR test results of the unmodified asphalt and the fiber modified asphalt. It shows fibers have significantly improved asphalt binder's dynamic shear modulus G^* and the $G^*/(1\text{-}1/\sin\delta\tan\delta)$ value, which represents the rutting resistance of asphalt binder. The lignin fiber has the highest $G^*/(1\text{-}1/\sin\delta\tan\delta)$ value, which would be due to its highest absorption of light components of asphalt binder to improve the viscosity and stiffness of asphalt binder. It is followed by the polyester fiber, brucite fiber, and basalt fiber. The basalt fiber has the lowest $G^*/(1\text{-}1/\sin\delta\tan\delta)$ value which could be due to its smooth surface texture. It is worth noting that brucite fiber possesses good effect for improving the asphalt binder's high temperature performance compared with unmodified asphalt (improved by 141.29%), which could be attributed to its higher ability of stabilizing asphalt and networking effect.

Conclusions

The effects of brucite fiber in stabilizing and reinforcing asphalt binder were investigated through laboratory experiments in the paper. The following conclusions can be drawn:

- Brucite fiber has a better state of preservation in humid environment and thermostability than lignin fiber, and its ability of absorption and adhesion of asphalt is better than that of basalt fiber and polyester fiber.
- Brucite fiber forms a three-dimensional spatial network in asphalt and possesses good bridging and reinforcing effects.
- Brucite fiber shows to have better networking function than the lignin fiber and greater rutting resistance of fiber modified asphalt than basalt fiber.
- Brucite fiber can reinforce the asphalt binder's resistance to shear and high temperature performance effectively due to its microstructure characteristics and physical properties, including the size, shape, and tensile strength and its effects of stabilizing and reinforcing asphalt binder.

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