

Research Article

Study on the Construction Performance of Zeolite Asphalt Mixture Based on Macro-Micro Scale

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In order to explore the construction performance of zeolite asphalt mixture, the microproperties of zeolite and the macroproperties of zeolite asphalt mixture were studied. The structure composition, surface properties, and pore characteristics of zeolite were analyzed by infrared spectroscopy and pressure pump method. The structure, composition, and thermal stability of zeolite were analyzed by differential scanning calorimetry and thermogravimetry, the mechanism of moisture absorption and loss of water was explored, and the properties of moisture absorption and loss of water were studied. The effect of the type and amount of zeolite on the viscosity of asphalt was studied by the viscosity test. According to the mixing current and the compaction void ratio, the influence of zeolite on the construction performance of zeolite asphalt mixture was studied. The results show that zeolite contains special zeolite water and the pore content of zeolite is much higher than that of mineral powder. Zeolite loses water at 90°C~120°C, which is the necessary condition for zeolite to be used in warm mix asphalt mixture. The water absorption and loss capacity of zeolite mainly depend on pore volume. The larger the pore volume is, the stronger the water holding capacity of zeolite is. Meanwhile, the water holding capacity and loss capacity of zeolite are related to pore size distribution. According to the viscosity temperature equation, the mixing and compaction temperature of the asphalt mixture are determined. The mixing and initial pressure temperature of the zeolite asphalt mixture are lower than those of the hot asphalt mixture. Based on the principle of mixing current equivalence, the mixing temperature of zeolite asphalt mixture can be reduced by 20°C compared with that of hot asphalt mixture. The better the water loss performance of zeolite is, the easier the mixture is to be compacted. For the base asphalt mixture, the compaction temperature of the mixture is 120–130°C, and, for the modified asphalt mixture, the compaction temperature is 130–140°C.

1. Introduction

Under the premise of ensuring the mechanical performance and durability, warm mix asphalt mixture can effectively reduce the construction temperature and mixing temperature, reduce the emission of harmful gases in the construction process, the energy consumption in the construction, and reduce the aging of asphalt. Therefore, warm mix asphalt mixture conforms to the green traffic concept and is widely used in road construction [1–3]. In the aspect of construction characteristics of warm mix asphalt mixture, Ulmgren et al. [4] suggest that the method of evaluating the working performance of cold mix asphalt

mixture and the method of rotating compaction of mixture should be used to evaluate the working performance of zeolite asphalt mortar under certain temperature conditions. These two methods are helpful to analyze the mixing characteristics of warm mix asphalt mixture to some extent, so as to distinguish the performance of mixture. Vaiana et al. [5] evaluated the volume and mechanical properties of warm mix asphalt mixture and discussed the influence of foaming time (between mixing and compaction) on mixture workability. Sengoz et al. [6] found that the penetration of zeolite asphalt decreased, but the softening point increased. Kutay and Ozturk [7] studied the dissipation process of bubble water in zeolite asphalt system by X-ray

microchromatography. It was found that the dissipation speed of bubble water in hard asphalt was slower than that in soft asphalt and the volume of bubble in different asphalt was different. Wozzuk et al. [8, 9] investigated the foam effect through the dynamic viscosity of synthetic zeolite and clinoptilolite and further analyzed the relationship between the foam effect and the physical and chemical properties of the two kinds of zeolite. It was found that the foam effect had a very important relationship with the water content in the zeolite, the release mode of water with time, and the type of exchangeable cation. Sengoz et al. [10] compared the asphalt with natural zeolite and different types of warm mix agent and determined the basic properties and rheological properties of different types of warm additive asphalt samples by conventional asphalt test method and dynamic shear rheometer (DSR). Dubravský and Mandula [11] studied the mixing ability of natural zeolite in the subbase asphalt layer and studied the performance of asphalt mixture before and after adding natural zeolite. Wozzuk et al. [12] analyzed the influence of zeolite and other fillers on the performance of asphalt mastic and found that clinoptilolite can partially replace the traditional lime fillers, without negative impact on the performance of asphalt mastic. Vaiana et al. [13] studied the volumetric and mechanical properties of zeolite mixtures under laboratory conditions and also studied the effect of foaming time (mixing and compaction) on the workability of the mixture. Leo et al. [14] concluded that the asphalt mixture with synthetic zeolite can be prepared at a temperature lower than 30°C of the mixing and compaction temperature of the hot mixture, and, through Marshall test, when the zeolite content is 0.3% of the total weight of the mixture, the characteristic value of the asphalt mixture still meets the requirements of the use specification. Wozzuk et al. [15] studied the performance of the water filled zeolite foam asphalt added with waste oil. It was found that the addition of waste oil reduced the viscosity and softening point of asphalt and increased penetration. Handayani et al. [16] studied the performance of asphalt mixture with natural zeolite. Through the Marshall test, it was found that when the content of natural zeolite was 1%, the mixing temperature and compaction temperature of polymer modified asphalt mixture could be reduced by 30°C, which was lower than the mixing temperature of zeolite-free polymer modified asphalt mixture. Wozzuk and Franus [17] reviewed the research results of zeolite asphalt mixture technology at home and abroad, including the influence of zeolite on asphalt performance and mixture asphalt performance, as well as the related environmental, economic, and technical benefits. Sanchez-Alonso et al. [18] evaluated the feasibility of preparing warm mix asphalt mixture by adding rap based on natural zeolite through SEM, fluorescence, and Marshall parameters. Sol-Sánchez [19] prepared two kinds of warm mix asphalt with two different types of zeolite waste as additives and compared with the mechanical properties of conventional warm mix asphalt and hot mix asphalt; it was found that the zeolite waste with lower particle size has higher water absorption capacity and 0.3% of the content allows the production of warm mix asphalt at 145°C and has the same workability as traditional

HMA at 165°C and compactness, without reducing its bearing capacity, fatigue life, and water damage resistance. de Castro Amoni et al. [20] synthesized NaA zeolite with fly ash as the main raw material and fly ash from different sources. Through dynamic shear rheometer (DSR), the mechanical tests of tensile strength (TS), resilient modulus (RM), dynamic creep (DC), and tensile strength (POTS) of modified asphalt mixture showed slight positive difference. It can be seen from the above research that zeolite, as a kind of warm mixture, plays a significant role in reducing the construction temperature. At present, the research on the performance of zeolite asphalt mixture at home and abroad mainly focuses on the construction performance verification and road performance analysis of zeolite asphalt mixture, while the research on the microcosmic of zeolite and zeolite asphalt mixture is less.

Therefore, this paper starts from the microperformance of zeolite, analyzes the structure and performance differences between zeolite and mineral powder, and then analyzes the construction performance differences between zeolite asphalt, zeolite asphalt mixture, and hot mix asphalt mixture.

2. Materials and Methods

2.1. Selection of Zeolite and Mineral Powder Materials. Zeolite is a general term for a group of rack like hydrous aluminosilicate minerals, including natural zeolite generated in nature, as well as synthetic crystals. The properties of zeolite and mineral powder used in this paper are shown in Table 1.

2.2. Selection of Asphalt Materials. The asphalt and modified asphalt used in this study are 70# road petroleum asphalt and SBS modified asphalt, and their performance indexes are shown in Tables 2 and 3, respectively.

3. Results and Discussion

3.1. Microproperties of Zeolite

3.1.1. Infrared Spectrum of Zeolite. Infrared spectrum analysis uses the structure analysis of the selective absorption of infrared electromagnetic radiation by objects. Due to the different infrared spectra of different substances, different substances have their own infrared spectrum, and different molecular groups and chemical bonds also have their own vibration frequency, peak shape, and peak strength. Therefore, the identification and analysis of material composition can be carried out by infrared spectrogram [21].

The infrared spectrum data of three kinds of zeolites were analyzed by using the infrared spectrum analysis software OMNIC. The infrared spectrum of three kinds of zeolites is shown in Figure 1.

The absorption band of zeolite infrared spectrum is mainly composed of four parts [22, 23]:

TABLE 1: Apparent density of zeolites and mineral filler.

Sample	Apparent density (g/cm ³)
1# natural zeolite	2.145
2# natural zeolite	2.623
3# synthetic zeolite	2.297
4# limestone powder	2.811

- (1) 3700–1600 cm⁻¹ is the absorption band of combined water in zeolite
- (2) 1200–400 cm⁻¹ is the framework vibration absorption band of zeolite
- (3) 700–500 cm⁻¹ is the vibration absorption band of zeolite structure unit
- (4) 500–400 cm⁻¹ is the bending vibration band of Si-O or Al-O

Taking 1# zeolite as an example, the hydroxyl band and lattice water absorption peak appeared near 1636.50 cm⁻¹ and 3455.08 cm⁻¹, indicating the existence of water molecules with different orientations and forces. The 1066.29 cm⁻¹ strong absorption band is the skeleton vibration of Si-O-Si, 793.52 cm⁻¹ has the external expansion vibration peak of tetrahedron, the absorption at 606.04 cm⁻¹ is caused by the expansion vibration of tetrahedron internal structure, and the absorption at 469.58 cm⁻¹ is caused by the bending vibration of Si-O or Al-O [24, 25].

Compared with them, the absorption peaks at 530.54 cm⁻¹ and 647.96 cm⁻¹ are quite different in the 2# zeolite spectrum, which are mainly caused by the stretching vibration of tetrahedron structure, and the absorption peaks at 758.44 cm⁻¹ are Si-O-Si or Al-O-Si.

There are some differences between 3# zeolite and natural zeolite. The main reason is that there is a small peak at 1383 cm⁻¹ of synthetic zeolite. The peak of 1383 cm⁻¹ may be from the original materials of synthetic zeolite, or the peak of some materials adsorbed on the surface of zeolite, but no chemical bond is formed.

Through the analysis of the infrared spectrum of the above-mentioned zeolite, it can be seen that the three kinds of zeolite have wide and strong absorption band of binding water in the approximate vibration range of 3400⁻¹~3600 cm⁻¹ and there are wave peaks near 1600 cm⁻¹. These two wave peaks indicate that there are water molecules with different forces and orientations in the zeolite, which is unique to the zeolite.

3.2. Pore Structure Characteristics. There are a lot of pores in zeolite, which is one of the most typical and basic physical properties of zeolite.

In this paper, the micropore iv9500 mercury porosimeter of micromeritics company in the United States is used to determine the pore content and pore distribution of zeolite by continuous pressure boosting. The maximum pressure of the mercury porosimeter is 228 MPa, the radius of the measurable hole is 3 nm~360 μm, the surface tension of mercury is 0.485 n/m, the angle of immersion is 130°, and the density is 13.5325 g/ml.

After drying and pretreatment of zeolite samples at 105°C, mercury injection test is carried out. The mercury injection curve of each zeolite is shown in Figure 2.

Figure 2 is the pore size distribution curve of zeolite. The peak value of the curve represents the maximum volume pore in zeolite and its corresponding pore size. The width of the curve represents the range of pore size distribution, that is, the dispersion degree and dispersion degree of different pore sizes of zeolite [26–28]. The pore size distribution curves of three kinds of zeolites are different; among them, the pore size distribution area of 3# synthetic zeolites is the smallest, and its pore size distribution is more uniform.

The pore characteristic parameters of zeolite are analyzed. Figure 3 shows the distribution proportion of various pores in zeolite, and Figure 4 shows the comparison of pore parameters of zeolite.

It can be seen from Figures 3 and 4 that different zeolites have different pore distribution. According to the pore volume, the order is 3# > 1# > 2# > mineral powder; according to the internal specific area, the order is 1# > 2# > 3# > mineral powder.

In general, the pore content of zeolite is much higher than that of mineral powder. Among the three kinds of zeolite, 3# synthetic zeolite has the largest pore volume and the smallest internal specific surface area, which indicates that the pores in synthetic zeolite are mainly macropores. In natural zeolite, 1# in pore size distribution, pore size distribution is more uniform.

3.3. Moisture Absorption and Water Loss Characteristics of Zeolite

3.3.1. Thermal Analysis of Zeolite. The physical and chemical properties of zeolite are heat-related. According to the infrared spectrum analysis of zeolite, it is found that there is crystal water in the zeolite. Therefore, the thermal analysis of zeolite is carried out in this section.

(1) DSC Analysis. DSC analysis is differential scanning calorimetry. By measuring the heat difference between the sample and the reference at the same temperature at the same heating or cooling rate, the DSC curve with the temperature as the abscissa and the heat difference as the ordinate is obtained. The heat flow difference can reflect the enthalpy change of the sample with the temperature change [29, 30].

Mettler Toledo heat flow DSC analyzer was used to analyze zeolite, and the heat curve of zeolite was shown in Figure 5.

In DSC diagram, the melting of crystalline components and the change of phase state of amorphous components will produce endothermic peak. The size and position of the peak can reflect the phase state change of different components. The area surrounded by endothermic peak is large, which shows that there are many components changed and the stability is poor in macroscopic observation. From the DSC curve of Figure 5 zeolite, the curve is relatively flat, indicating that the overall thermal stability of zeolite is good. However,

TABLE 2: Properties of AH-70 asphalt.

Project	Unit	Technical requirements	Test results	Test method
Penetration (25°C)	0.1 mm	60~80	71.9	T0604
Ductility (10°C)	cm	≥20	23.4	T0605
Softening point (R&B)	°C	≥46	47.0	T0606

TABLE 3: Properties of modified asphalt.

Project	Unit	Technical requirements	Test results	Test method
Penetration (25°C)	0.1 mm	60~80	63.6	T0604
Ductility (10°C)	cm	≥30	37.7	T0605
Softening point (R&B)	°C	≥70	72.2	T0606

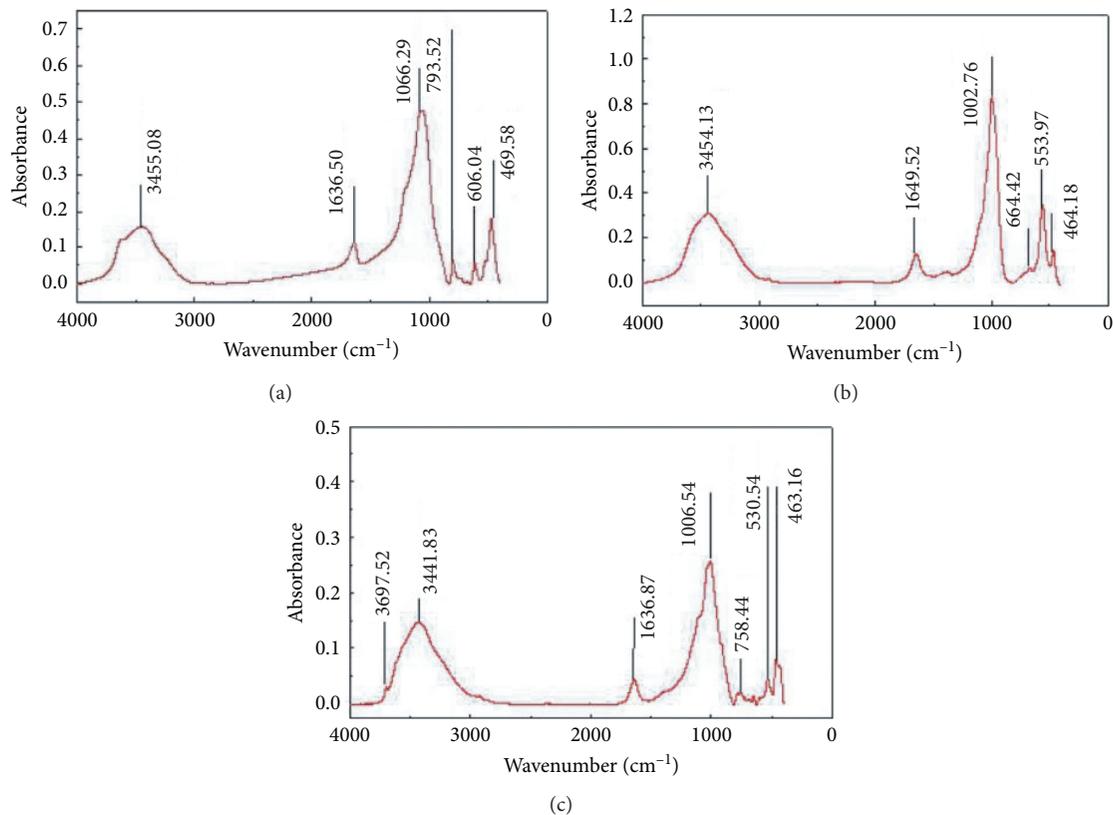


FIGURE 1: Spectra of zeolites. (a) 1# zeolite. (b) 2# zeolite. (c) 3# zeolite.

with the increase of temperature, there is an endothermic peak on the DSC curve of zeolite, which indicates that the phase state changes. The positions of the endothermic peaks of the three kinds of zeolites are different, and the temperatures of phase transformation are different. The DSC data are summarized in Table 4.

In Table 4, the water loss starting point of 2# zeolite is higher; the zeolite loses water at a higher temperature (120°C) or above, while the other two kinds of zeolite basically begin to lose water at 90°C. This is because the density of zeolites 1# and 3# is close to and less than that of zeolite 2#; this shows that the volume number of 1# and 3# is more than that of 2# under the same conditions, and, according to the analysis of pore characteristics of zeolites, the median pore

sizes are 3# > 1# > 2#. The results show that, under the same conditions, the number of mesoporous pores of zeolite 2# is less than that of zeolites 1# and 3#. The more the pores are, the more favourable the phase change of zeolite water is. Therefore, the phase change temperature of zeolite 2# is required to be higher than that of zeolites 1# and 3#, and the phase change temperature of 1# and 3# is close since the density of 1# and 3# is almost equal.

(2) *Thermogravimetric Analysis*. Thermogravimetric analysis (TGA) is to analyze the thermal stability of materials by measuring the change of the mass of objects with the temperature. Its basic principle is that the mass changes when the objects vaporize, decompose, or lose the crystal

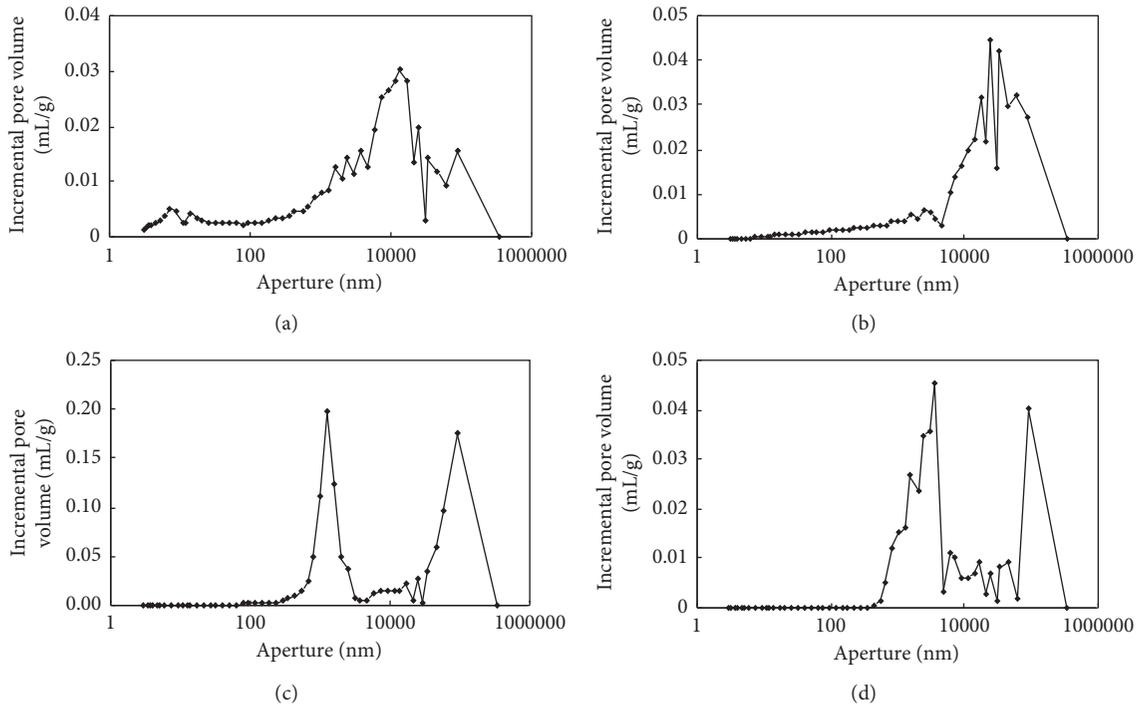


FIGURE 2: Pore distribution of zeolites and mineral filler. (a) 1# zeolite. (b) 2# zeolite. (c) 3# zeolite. (d) 4# mineral filler.

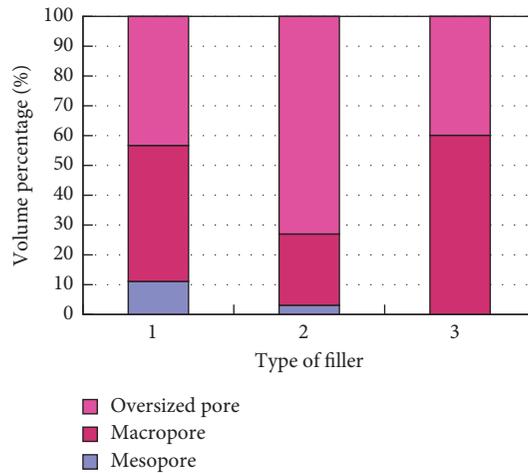


FIGURE 3: Pore distribution of zeolites.

water. Through the mass temperature curve (TGA curve), quantitative information such as the composition and thermal stability of materials can be analyzed [31, 32].

The thermogravimetric analysis of zeolite was carried out on the star system thermogravimetric analyzer. The test temperature range is 30–800°C, and the thermogravimetric curve of zeolite is shown in Figure 6.

Zeolite is used in asphalt mixture, and its working temperature is lower than 200°C. Therefore, when analyzing its heat and weight loss, it focuses on analyzing the quality change within the temperature range of 30–200°C, as shown in Table 5.

From the TGA curves of the three types of zeolites in Figure 6, it can be seen that the decomposition temperature

and the heat weight loss of zeolites are different. The heat weight loss curves of 1# and 3# zeolites are steeper, while the curves of 2# zeolites are relatively flat, indicating that the water loss rate of zeolites is different. 2# zeolite loses water at 70°C and 120–160°C; the rate of water loss is slow, while the decomposition temperature of 3# zeolite and 1# zeolite is low, which is basically consistent with DSC test results. In terms of heat and weight loss, the mass loss of 3# zeolite is the most, and that of 2# zeolite is the least; that is to say, the water loss of 3# zeolite is the most, while that of 2# zeolite is the least.

Through the above analysis, it is found that the zeolite will show endothermic peak with the rise of temperature, which indicates that there is a phase transformation process

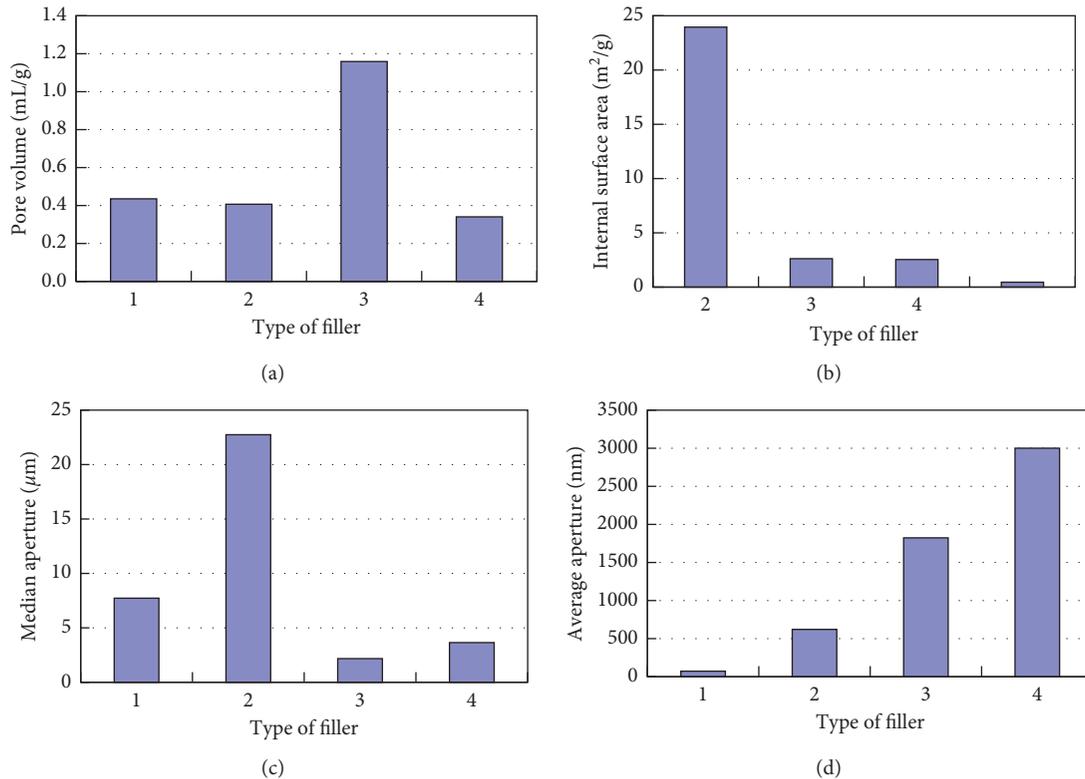


FIGURE 4: Pore parameters of zeolites and mineral filler. (a) Pore volume. (b) Internal surface area. (c) Median pore diameter. (d) Average pore diameter.

of water in the zeolite and the thermal stability of different zeolites is different. As temperature mixing additives, these kinds of zeolites can start to absorb heat and lose water in the temperature range of 90~120°C. The gasification of zeolite water in this temperature range is consistent with the working temperature range of asphalt in the construction process, which can affect the flow characteristics of asphalt and meet the requirements of asphalt mixture for temperature mixing additives.

3.3.2. Water Absorption of Zeolite. In the framework structure of zeolite, there are two forms of water, adsorbed water and free water, which are called zeolite crystal water or zeolite water. Under the condition of natural storage, the natural water content of different zeolites is different, and the zeolites water in the pores of zeolites skeleton is in a relatively stable state. This relative balance will change due to the change of temperature and humidity conditions. In order to understand the water content and the amount of water loss during heating of zeolite under natural storage conditions, this paper analyzes the water loss rate of different zeolites under different heating temperatures.

When determining the heating temperature, the production and construction of asphalt mixture are mainly considered. The different temperatures are encountered by zeolite in different processes, such as those under 105°C; the free water in zeolite is separated out, which is also the commonly used temperature for measuring the moisture

content of mineral materials. 120~140°C is the heating temperature of asphalt, 120~160°C is the mixing temperature of asphalt mixture, and the mixing temperature of modified SMA asphalt mixture can reach 180°C. In the above temperature range, the water of different properties in zeolite overlaps and loses, which continuously makes the asphalt mixture microfoaming in the process of heating, mixing, storage, and construction. In this way, the mixture has good workability in the above construction processes. Figure 7 shows the comparison of water loss rate between zeolite and mineral powder.

It can be seen from Figure 7 that the water loss rate of zeolite at different temperatures is much higher than that of limestone powder, indicating that the water content of zeolite is much higher than that of limestone powder. The water loss rate of different zeolites is very different, the highest is 3# synthetic zeolites, and the lowest is 2# synthetic zeolites. The water content of zeolites mainly depends on the composition of zeolites, diagenesis process, and storage conditions.

Under heating conditions, zeolite water with different properties escapes from different heating temperatures. Free water and capillary water are mainly lost at 105°C, capillary water and adsorbed water are mainly lost between 100~200°C, and adsorbed water is lost at 300~400°C [33]. In asphalt mixture, the state change of zeolite water under 200°C is studied. For mineral materials, the water loss rate under certain conditions can reflect their water content and properties, and the water loss rate of zeolite under specific

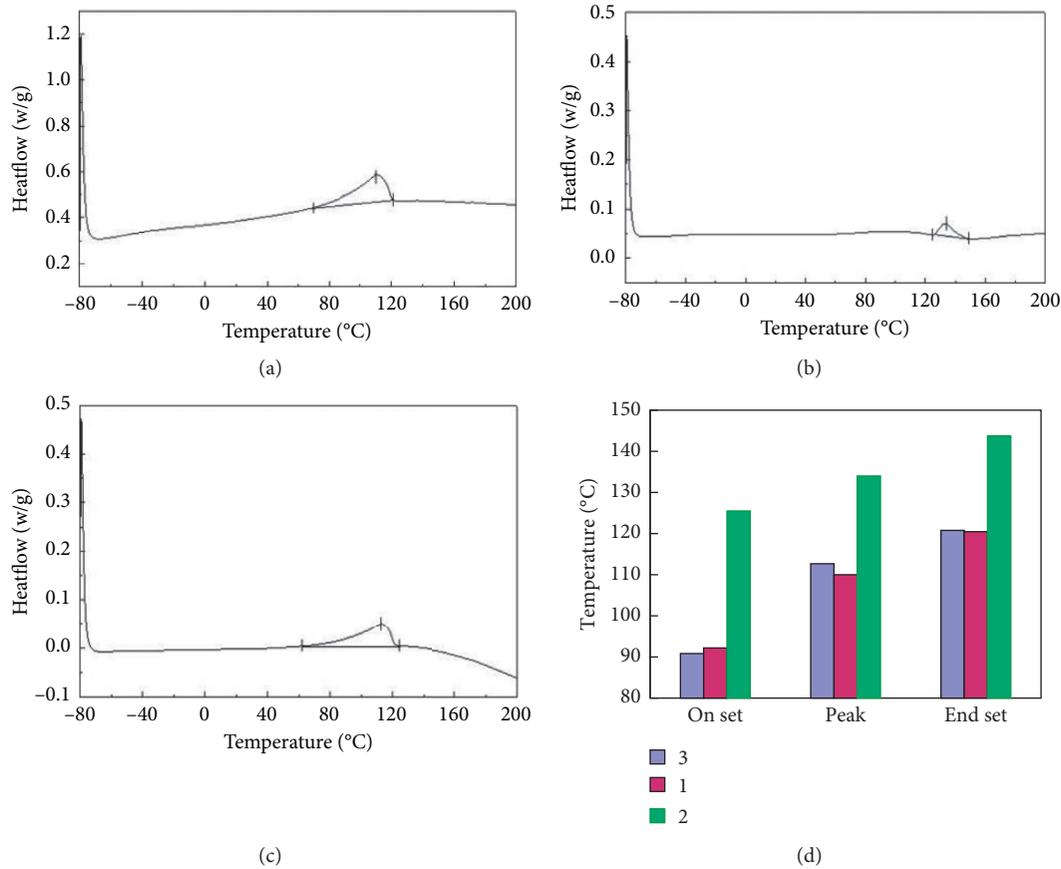


FIGURE 5: DSC curve of zeolites. (a) 1# zeolite. (b) 2# zeolite. (c) 3# zeolite. (d) Temperature comparison of zeolites.

TABLE 4: Summary of DSC data.

Zeolite	Starting temperature (°C)	Peak temperature (°C)	End temperature (°C)
1#	92.19	110.00	120.46
2#	125.50	134.00	143.75
3#	90.83	112.67	120.78

temperature can reflect their water holding capacity. It can be found that, with the increase of temperature, the water loss rate of zeolite gradually increases, but the growth range is different. The water loss rate of limestone powder is basically kept at 105°C, which indicates that the water in limestone powder is completely separated out at 105°C and the water is mainly free water. The water loss rate of 2# zeolite did not increase obviously with the increase of temperature. However, for 1# and 3# zeolites, they show different water loss properties. With the increase of temperature, the water loss rate increases to a certain extent, and the water loss rate continues to increase with the increase of temperature, which can better realize the continuous water loss and foaming in the hot asphalt.

Through the analysis of the water loss rate of zeolite, the water loss track of zeolite can be described, thus reflecting the water holding capacity of zeolite and the nature of zeolite water. The water holding capacity of three kinds of zeolites is in the order of 3# > 1# >> 2# > mineral powder. The comparison shows that 3# zeolite has the largest water holding

capacity and its water loss process is more balanced. With the increase of temperature, the water in it gradually volatilizes.

Zeolite water exists in the pores of zeolite, and the pore structure has a certain impact on the water release of zeolite. Figure 8 shows the relationship between the water loss rate of zeolite and pore volume. From the change trend of the water loss rate of zeolite with the pore volume, the larger the pore volume is, the greater the water loss rate of zeolite is.

3.3.3. Moisture Absorption Capacity and Water Loss Mechanism. The existence of a large number of pores in porous materials makes them have the characteristics of water absorption. The pore structure and the distribution and diffusion of water molecules in the pores determine their water absorption and loss behavior. For zeolite, the zeolite water in the pores can be adsorbed and discharged freely without affecting the mineral skeleton, which is a major feature of zeolite. This water absorption and loss feature is

TABLE 5: Summary of TG data.

Zeolite	Decomposition temperature (°C)	Decomposition temperature (°C)	Thermal weight (%)
1#	80	—	94.3
2#	70	120-160	95.2
3#	80	100	91.8

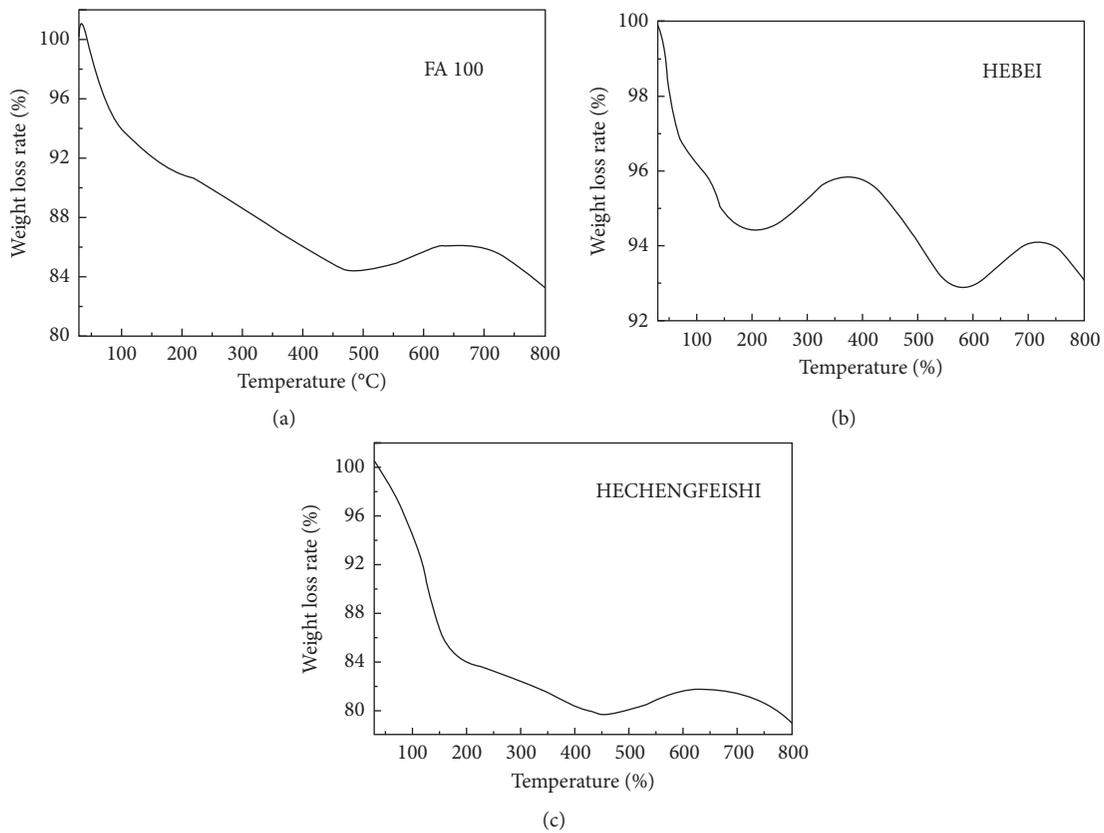


FIGURE 6: TGA curve of zeolites. (a) No. 1 zeolite. (b) No. 2 zeolite. (c) No. 3 zeolite.

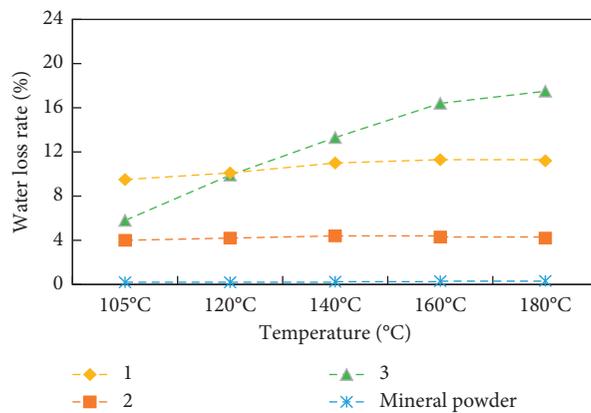


FIGURE 7: Comparison of water loss of zeolites and mineral filler.

mainly due to the skeleton pore structure of zeolite. Porous zeolites have affinity for water molecules with strong polarity, which makes zeolites have certain water absorption.

The mechanism of water absorption can be analyzed by capillary condensation principle and solid surface adsorption.

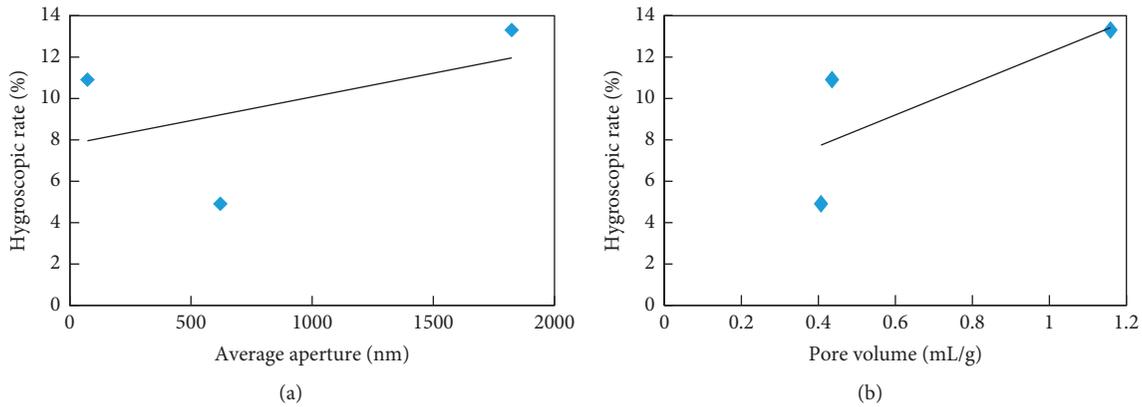


FIGURE 8: Relationship between water loss and porosity. (a) 120°C water loss. (b) 140°C water loss.

(1) *Moisture Absorption Capacity.* For zeolite minerals, the rich internal channels make the capillary phenomenon have an important impact on the moisture absorption capacity of zeolite. For the analysis of the moisture absorption capacity of the internal channels of zeolite based on the capillary condensation principle, Kelvin formula [34, 35] is used to calculate the critical pore size of zeolite under different temperature and humidity conditions, as shown in Table 6.

It can be seen from Table 6 that the critical pore size of zeolite varies a little under different temperatures. However, with the increase of humidity, the critical pore size increases significantly. Therefore, the critical pore size of zeolite is mainly related to the ambient temperature and humidity.

According to the distribution characteristics of zeolite pores, it can be analyzed that there are three situations of water in zeolite, as shown in Figures 8(a) and 8(b), respectively. When the pore size is less than or equal to the critical pore size, the water absorption is as shown in Figure 8(a); mainly, due to the capillary action, the adsorbed water molecules condense in the pore wall to form zeolite water. When the pore size is larger than the critical pore size, the pore water absorption is as shown at C in Figure 9, and the surface water absorption of zeolite is as shown at B.

Only micropores can adsorb pore water through capillary action. Comparing the critical pore size distribution of Table 6 with that of Figure 3, it is found that the proportion of micropores (3–50 nm) in zeolite is below 11% and the number and volume of pores smaller than the critical pore size are less. It can be inferred that there is relatively less capillary water in zeolite. When the pore size of zeolite is larger than the critical pore size, zeolite can form pore water or surface water through physical adsorption, so there are relatively less capillary water, more pore water, and surface water in zeolite, and the escape temperature of this water is lower. It is because of the above pore characteristics and the characteristics of adsorbed water that the evaporation and migration of zeolite water are different from those of general adsorbed water. The properties of zeolite water are between adsorbed water and crystal water, which also explains the reason why zeolite begins to lose water at low temperature.

(2) *Water Loss Performance.* Hydrous zeolite is a composite medium composed of solid skeleton and fluid. Under

the high temperature conditions of asphalt mixture production and construction, the water in hydrous zeolite volatilizes to the outside of zeolite skeleton through the interference of external thermal energy. In this rapid heating process, zeolite undergoes a complex heat transfer process. Free water is discharged in the form of liquid water diffusion or seepage, and combined water is discharged in the form of evaporation [36].

In the process of heating, the evaporation of zeolite water is first carried out on the surface of zeolite, which is similar to the evaporation process of pure water. Due to the different adsorption degree of zeolite water and particles, the difficulty and ease of desorption are also different. With the increase of temperature, the water in the capillary moves. The smaller the capillary radius R is, the slower the water evaporation rate is, and the more difficult it is for zeolite to lose water [37–39].

Structure of zeolite is loose and the channels and cavities are well developed, which provides a place for the existence of zeolite water. The existing state of zeolite water and the characteristics of its loss in the heating process are the material basis for the use of zeolite in warm mix asphalt mixture. As the water carrying medium of warm mix asphalt mixture, the characteristics of water holding and loss of zeolite are particularly important. Only with proper water holding performance and continuous water loss in mixing, compaction, and other construction processes, zeolite can play a real role as a warm mix additive. Next, the moisture absorption and water loss properties of zeolite are analyzed through experiments.

3.3.4. Moisture Absorption and Water Loss Performance of Zeolite

(1) *Hygroscopic Properties of Zeolite.* The zeolite sample is dried at 105°C and placed in a humidity regulating box. The temperature in the box is set at 20°C, and the relative humidity is 60%, 70%, 80%, and 90%, respectively. The isothermal moisture absorption capacity of the zeolite is tested under different humidity conditions until the mass of the sample no longer increases. At this time, the sample is

TABLE 6: Critical aperture at different temperature and humidity (nm).

Humidity (%)	0°C	20°C	30°C	40°C
20	0.74	0.67	0.64	0.62
30	1.00	0.89	0.86	0.82
40	1.31	1.17	1.13	1.08
50	1.72	1.55	1.49	1.43
60	2.36	2.11	2.03	1.94
70	3.36	3.01	2.91	2.78
80	5.37	4.82	4.65	4.44
90	11.37	10.2	9.84	9.40
95	23.36	20.9	20.22	19.30

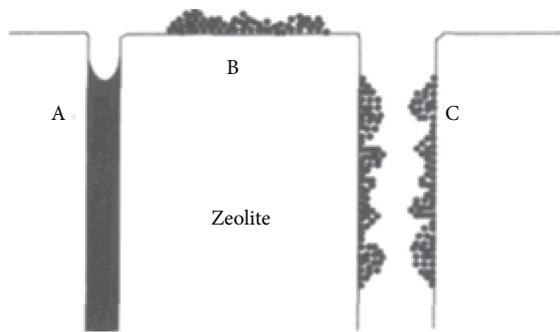


FIGURE 9: Water absorption of zeolite.

considered to reach the equilibrium state under the corresponding humidity [40–43]. Figure 10 shows the change of moisture absorption rate of zeolite with time, and Figure 11 shows the comparison of moisture absorption rate of zeolite under different humidity.

According to the change curve of zeolite moisture absorption performance in Figure 10, the moisture absorption capacity of zeolite increases gradually with the extension of time and increases greatly before 10h. Then, the moisture absorption rate increases slowly and basically reaches the relative moisture balance. In Figure 11, the hygroscopic rate of zeolite is related to the environmental humidity. The higher the environmental humidity is, the higher the hygroscopic rate of zeolite will be, which also verifies the mechanism of zeolite water absorption. When the relative saturation state is reached, the hygroscopic rate of different zeolites is very different; the largest the 3# synthetic zeolites are, the smallest the 2# zeolites become.

The relationship between the hygroscopic capacity and pore structure of zeolite is analyzed, as shown in Figure 12.

Figure 12 shows the relationship between the hygroscopic rate of zeolite and pore structure characteristics. It can be found that the hygroscopic rate of zeolite increases with the increase of pore volume. There are enough pores in zeolite to provide space for zeolite water. The larger the pore volume is, the stronger the moisture absorption capacity of zeolite is. 3# zeolite has the largest pore volume and the largest moisture absorption rate; 2# zeolite has the smallest pore volume and its moisture absorption rate is also small. Therefore, from the perspective of water absorption, the pore

volume is large; that is, the pore is more conducive to zeolite water absorption.

It is related to pore structure characteristics, as shown in Figure 12(b); with the increase of average pore size, the water absorption of zeolite shows an increasing trend. The water absorption performance of different zeolites is also related to the pore distribution. For natural zeolites, the larger the pore size is, the larger the water absorption is, but the larger the proportion of super pores is, the smaller the water absorption is, as shown in Figure 12(c). Therefore, the pores of zeolite are mainly macropores with the strongest water absorption capacity. For synthetic zeolites, the pores of 3# zeolites are mainly macropores with the largest water absorption. Therefore, the water absorption capacity of zeolite is related to the pore distribution, and the super pore is not conducive to water absorption, while the middle pore and the large pore are easier to absorb water.

(2) *Water Loss Performance of Zeolite.* The mixing and rolling of asphalt mixture are carried out under certain high temperature conditions. In order to study the water loss performance of zeolite, it is necessary to simulate the water loss track of zeolite under high temperature conditions. In this paper, the water loss of absorbent zeolite in the temperature range of 50°C~180°C is tested to simulate the water loss of asphalt mixture in the process of mixing and rolling, as shown in Figures 13 and 14.

In the water loss curve of Figure 13, with the increase of temperature, zeolite shows the characteristics of gradual water loss. At lower temperature (lower than 70°C), the water absorption of zeolite has little difference, and the water loss curve is relatively flat. With the increase of temperature, the water loss rate of zeolite increases gradually, and the difference of water loss rate of different zeolites becomes larger. The change range of water loss rate of different zeolites is different. Except for 3# zeolites, the water loss rate is basically stable at 125°C~135°C.

In Figure 14, of the three kinds of zeolites, the most water loss rate is 3# zeolite, and the least is 2# zeolite. From the above analysis of zeolite water loss rate, it can be seen that the volatilization of zeolite water is a continuous process, which is related to temperature and duration. With the increase of temperature, zeolite water is gradually discharged, which makes its foaming effect in asphalt last for a certain period of time, thus ensuring the workability of asphalt mixture in a certain period of time.

See Figure 15 for comparison with water absorption. It can be seen that zeolite has the characteristics of “energy absorption and energy loss,” with high water absorption and water loss. 3# zeolite has the largest water loss rate, while 2# zeolite has the smallest water loss rate. Comparing the water loss rate of zeolite with the pore distribution characteristics of zeolite, as shown in Figure 16(b), the water loss rate of zeolite is related to the pore volume. The larger the pore volume is, the more easily the zeolite loses water. Taking 3# synthetic zeolite as an example, it has the largest pore volume and relatively concentrated pore size distribution, and it has the largest water loss rate. 2# zeolites have the smallest pore volume and a wide range of particle size distribution.

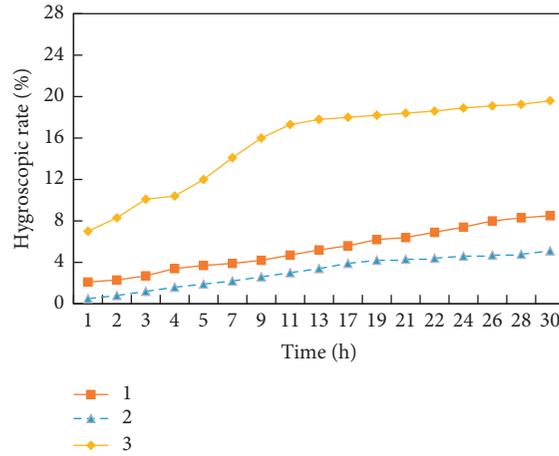


FIGURE 10: Moisture absorption of zeolites at 90% humidity.

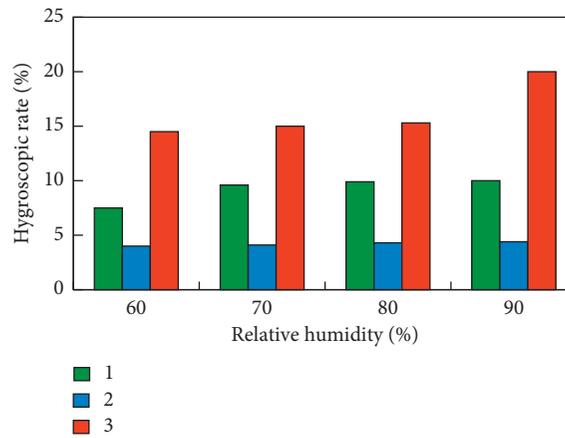


FIGURE 11: Comparison of moisture absorption of zeolite.

Therefore, the water loss rate of zeolite mainly depends on water content and pore volume.

4. Effect of Zeolite on Viscosity of Asphalt

4.1. *Viscosity Temperature Relationship.* As a viscoelastic material, temperature is the most important factor affecting the viscosity of asphalt. The viscosity temperature relationship of asphalt reflects the degree of change of asphalt viscosity with temperature, which is an important factor affecting the performance and service quality of asphalt. Under the construction temperature, asphalt should have a smaller viscosity to facilitate the mixing and compaction of asphalt mixture, while, under the used temperature, asphalt should have a higher viscosity to prevent the pavement from flowing deformation and improve its durability. For zeolite asphalt mixture, the following focuses on the viscosity characteristics of asphalt in the process of high temperature construction. See Figure 16 for the influence of zeolite on the apparent viscosity of matrix asphalt.

The effect of zeolite on the viscosity of asphalt is mainly at a lower temperature. From Figure 16, it can be seen that, at 100°C, the viscosity of different zeolites varies greatly, while,

at 140°C, the viscosity of zeolites asphalt varies a little. In other words, the effect of zeolite on the viscosity of asphalt is significant at lower temperature. Zeolite has a great influence on the low temperature viscosity of asphalt. This result is because zeolite contains zeolite water which can move freely or enter and exit the pore channel under specific temperature conditions. According to the thermal analysis of zeolite, zeolite begins to absorb heat and lose water in a lower temperature range. Within this temperature range, the zeolite water will generate gas and then influence the viscosity of asphalt. In order to further describe the viscosity temperature relationship of zeolite asphalt, the viscosity temperature equation of zeolite asphalt is established according to Saal formula:

$$\log(\eta \times 10^3) = a - b \log(T + 273.13), \quad (1)$$

where a and b are regression coefficients; η is viscosity of asphalt (Pa · s); T is temperature (°C).

The regression coefficient of viscosity temperature equation of asphalt zeolite is determined through regression analysis, and the mixing and compaction temperature of each zeolite asphalt mixture are determined, as shown in Table 7.

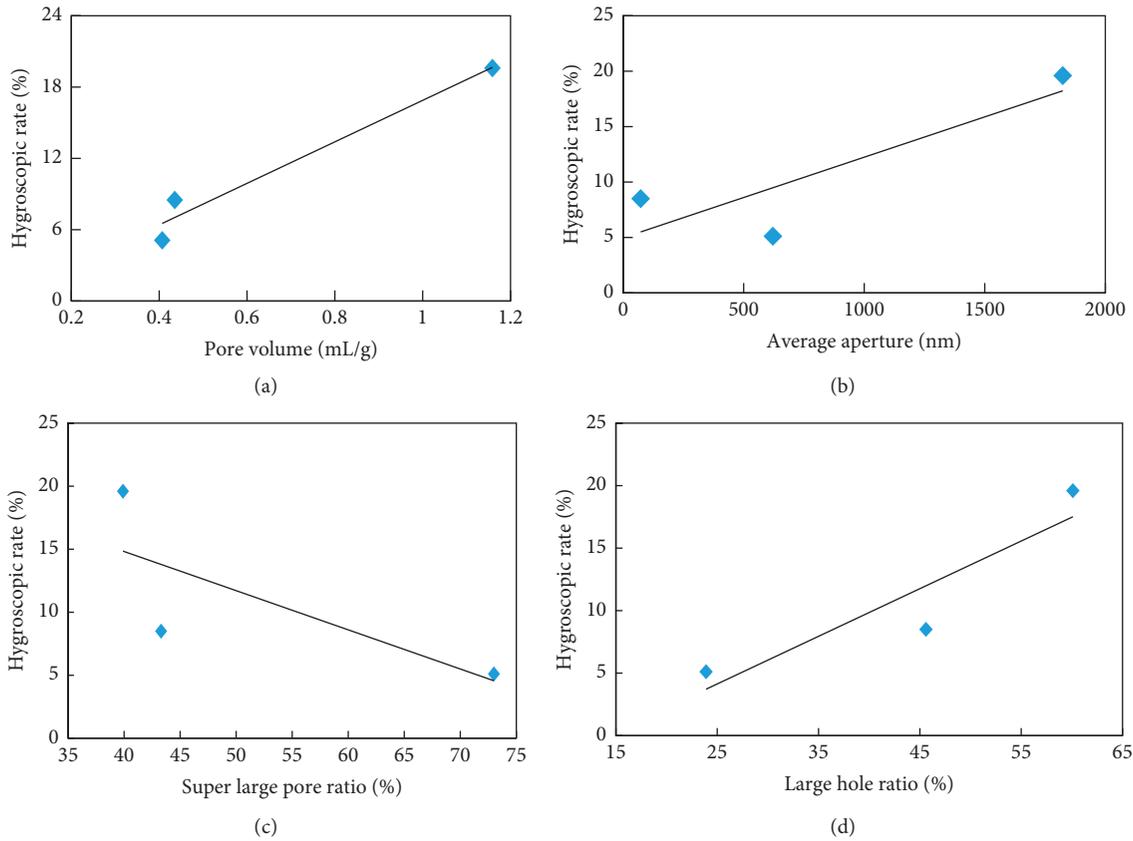


FIGURE 12: Influence of pore structure on moisture absorption. (a) Porosity. (b) Average pore diameter. (c) Proportion of super pore. (d) Proportion of big pore.

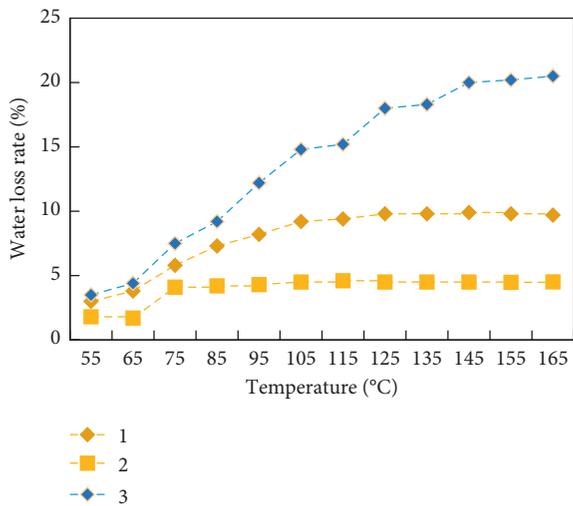


FIGURE 13: Water loss of zeolites.

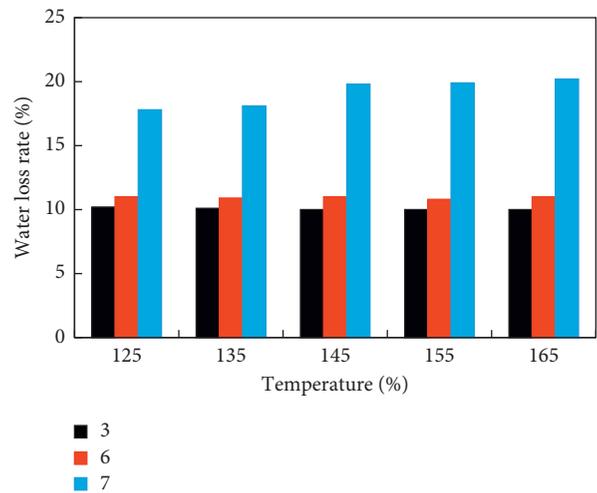


FIGURE 14: Comparison of water losses at different temperatures.

From the coefficient of viscosity temperature equation in Table 7, the influence trend and degree of zeolite on the viscosity change of asphalt can be analyzed. Compared with matrix asphalt, the addition of zeolite makes the b value increase; that is, the sensitivity of asphalt viscosity to temperature increases. According to the viscosity temperature equation, the mixing and compaction temperature of the

asphalt mixture are determined. The mixing and initial pressure temperature of the zeolite asphalt mixture are lower than those of the hot asphalt mixture.

4.2. *Viscosity Time Relationship.* In order to analyze the influence of zeolite hydration on the viscosity of asphalt, three kinds of zeolites were added to the asphalt and placed

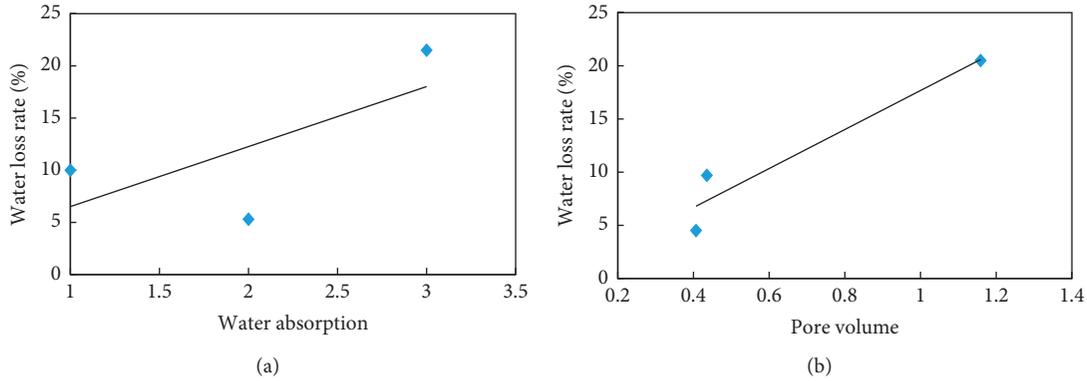


FIGURE 15: Relationship of water losses with absorption and porosity. (a) Water absorption. (b) Porosity.

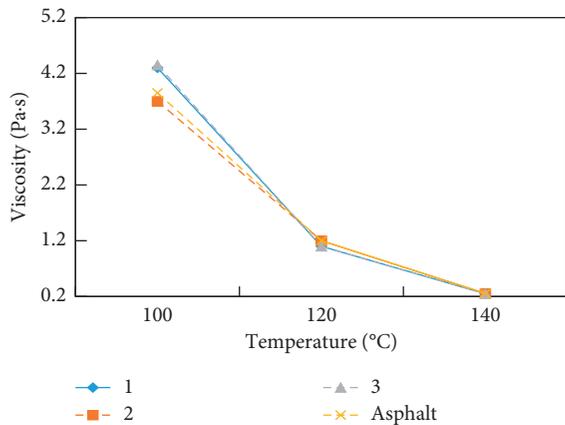


FIGURE 16: Viscosity change of asphalt at different temperatures.

in a 120°C incubator for curing. After curing for different times (1 h–4 h), the viscosity of asphalt at 120°C was measured, respectively. The curve of the viscosity of each zeolite with time was fitted by quadratic polynomial, as shown in Figure 17.

From the viscosity time curve of zeolite in Figure 17, it can be seen that, in asphalt zeolite, the viscosity of asphalt changes with time, which is different from the viscosity change characteristics of matrix asphalt. The viscosity of base asphalt is basically horizontal with the extension of curing time; that is to say, the viscosity of asphalt is basically constant at a certain temperature and shear rate. The addition of zeolite changes the viscosity of asphalt. From the viscosity change of each zeolite asphalt, it can be seen that the viscosity of asphalt is higher at the initial stage of adding zeolite into asphalt. With a long period of time, the viscosity began to decline. When the minimum value was relatively stable, the viscosity of asphalt increased and finally tended to be stable. According to the change characteristics of viscosity, the change of viscosity of zeolite asphalt can be divided into three stages: decline stage, stability stage, and growth stage. In these three different stages, the viscosity shows different change properties. The different change characteristics of viscosity in these three stages reflect the change process of zeolite water: volatilization stage, stability stage, and decay stage. Therefore, the change of asphalt

viscosity with time can reflect the volatilization process of zeolite water on the other hand. At the initial stage of adding zeolite into asphalt, the viscosity of asphalt is relatively large because the zeolite water has not yet fully escaped. With the volatilization and foaming of water, the concentration of bubbles in asphalt increases, and the viscosity of asphalt decreases. When zeolite water foams at a relatively uniform rate, the viscosity of asphalt remains stable. With the continuous precipitation of zeolite water, the bubble concentration in asphalt began to decrease, and the viscosity of asphalt began to increase. Finally, when the water in the zeolite is separated out and the pores in the zeolite absorb a certain amount of asphalt, the viscosity of the asphalt reaches a stable state.

In Figure 17, 2# zeolite viscosity has the smallest change with time. The analysis of viscosity curve with time can reflect the change track of zeolite water and provide basis for determining mixing temperature and time. In order to evaluate the effect of zeolite on the viscosity of asphalt, considering the different materials and compositions of zeolite, the relative index is adopted, and the viscosity change rate when the viscosity of asphalt is the lowest and reaches the final stable state is taken as the index to investigate the effect of zeolite on the viscosity, which is defined as the viscosity change rate. When the viscosity of asphalt reaches the final stable state, the evaporation of water in zeolite is completed, and the viscosity is the viscosity of zeolite particles and asphalt. Using this index to compare the influence of zeolite on asphalt viscosity, we can eliminate the influence of the density, particle size, and pore of zeolite itself and only consider the influence of zeolite water escaping and bubbling process:

$$\eta' = \frac{\eta_0 - \eta_{\min}}{\eta_0} \times 100\%, \quad (2)$$

where η' is the viscosity change rate (%); η_0 is the viscosity of zeolite asphalt without bubbles (Pa·s); η_{\min} is the minimum viscosity of zeolite asphalt (Pa·s).

After three kinds of zeolites are added into asphalt, the relationship between the water loss rate of zeolites and the viscosity change rate of asphalt is analyzed, as shown in Figure 18.

TABLE 7: Coefficient of viscosity temperature equation.

Sample	a	b	Mixing temperature (°C)	Compaction temperature (°C)
Base asphalt	8.889	3.240	156.3~162.4	144.6~149.6
1	9.541	3.492	153.2~158.9	142.5~147.1
2	9.297	3.400	152.6~158.5	141.6~146.3
3	9.527	3.487	152.9~158.5	142.1~146.7

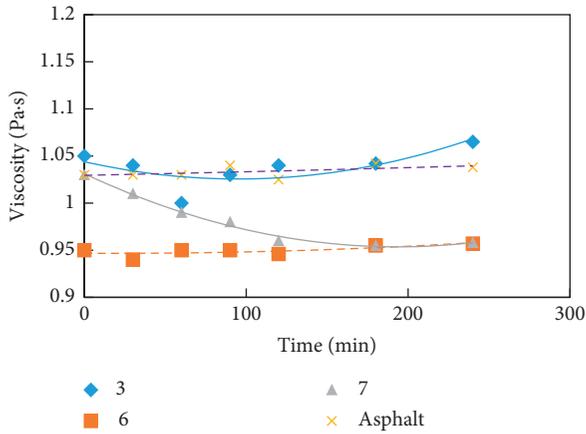


FIGURE 17: Viscosity development of asphalt with different zeolites.

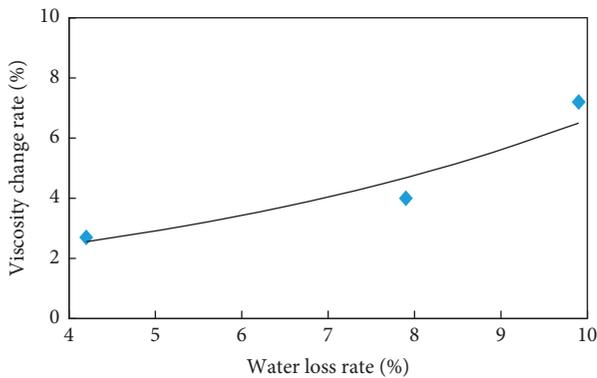


FIGURE 18: Relationship of viscosity change rate with water loss.

In Figure 18, the correlation between the viscosity change rate of asphalt and the water loss rate of zeolite is analyzed by quadratic polynomial regression, and the correlation coefficient $R^2 = 0.9103$, which shows that the viscosity change rate has a good correlation with the water loss rate of zeolite at this temperature.

The time when the viscosity of asphalt reaches the lowest value after adding zeolite is taken as the effective time to characterize the effect of zeolite on the viscosity of asphalt:

$$T = t_0 - t_{\min}, \quad (3)$$

where T is effective time of zeolite viscosity (min); t_0 is initial time (min); t_{\min} is minimum viscosity time (min).

Therefore, the influence degree of zeolite on asphalt viscosity is reflected by viscosity change rate index, and the influence time is reflected by effective action time of zeolite.

These two indexes can reflect the degree and time range of asphalt viscosity change. At the same time, according to the requirements of asphalt mixture on viscosity, the applicability of zeolite as temperature mixing additive of asphalt mixture can be analyzed.

4.3. Influence of Zeolite Varieties. Different kinds of zeolites have different structure and material composition, and their water content and pore characteristics are also very different. These differences will have a certain impact on the viscosity of asphalt. Add three kinds of zeolites into asphalt, respectively, and test the viscosity of asphalt at different temperatures (100°C, 120°C, and 140°C), as shown in Figure 19.

In Figure 19, the influence of zeolite varieties on asphalt viscosity shows different regularity at different temperatures. At the temperature of 100°C, except that the viscosity of asphalt decreased with the addition of 2# zeolite, the viscosity of asphalt increased with the addition of other zeolites; that is to say, zeolite did not play a role in reducing the viscosity of asphalt. At 140°C, the addition of zeolite makes the viscosity of asphalt decrease in varying degrees. This phenomenon can be explained as follows: zeolite water precipitates in hot asphalt to produce microbubbles, which makes the viscosity of asphalt decrease; on the other hand, zeolite particles also play a role of volume enhancement, resulting in the increase of asphalt viscosity. The mutual counteraction of the two effects of viscosity reduction and stiffening is the change of asphalt viscosity. Due to the difference of density and moisture content of different zeolites, the effect of zeolites on the strength and viscosity reduction of asphalt is different. At 140°C, a large number of zeolite particles precipitate, so it has a strong drag reduction effect, the viscosity reduction effect is greater than that of zeolite particles, which shows that the viscosity of asphalt decreases. Taking 2# zeolite as an example, the density of the two kinds of zeolites is the largest. Under the same dosage, the volume of the two zeolites in asphalt is smaller, the viscosity increasing effect is weaker, and the viscosity of asphalt is reduced.

4.4. Effect of Zeolite Dosage. The effect of zeolite dosage on viscosity is shown in Figure 20. At 140°C, the viscosity of three kinds of zeolites in asphalt is lower than that of base asphalt. With the increase of zeolites content from 4% to 8%, the viscosity of asphalt increases in varying degrees. At 120°C, the viscosity of asphalt increases with the increase of zeolite content from 4% to 8%. The variation of asphalt viscosity with the amount of zeolite is not significant, which is related to the factors such as water volatilization rate,

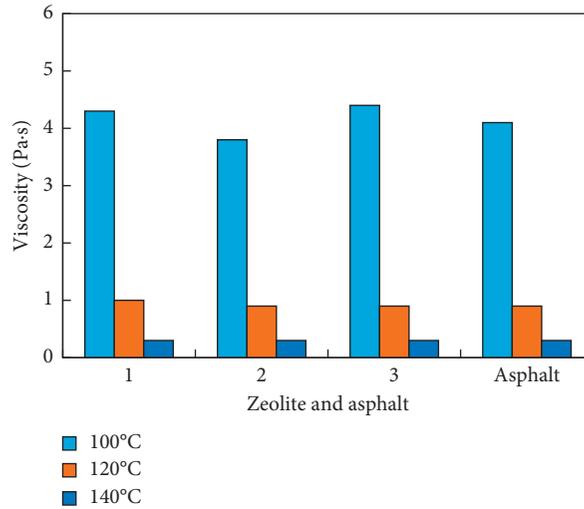


FIGURE 19: Viscosity of asphalt with different zeolites.

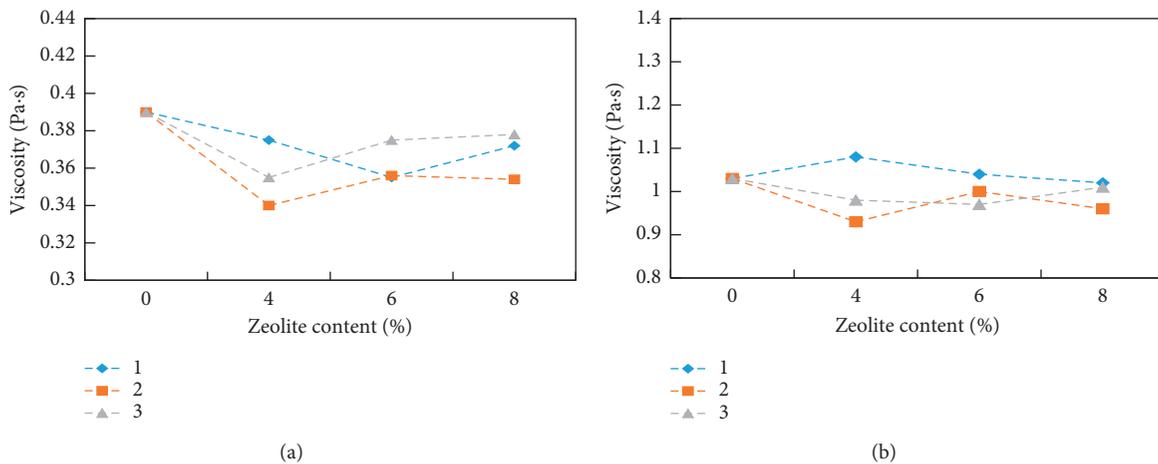


FIGURE 20: Influence of zeolite content on viscosity. (a) 140°C viscosity. (b) 120°C viscosity.

zeolite density, and testing time. The interaction of these factors makes the variation of asphalt viscosity less regular.

5. Effect of Zeolite Water on Construction Performance of Asphalt Mixture

In this paper, the construction performance of the commonly used AC-20 mineral aggregate grade matching zeolite asphalt mixture is analyzed, and the grading of the used AC-20 mineral aggregate is shown in Table 8.

The best ratio of oil to stone is 4.4%, the corresponding void ratio and mineral aggregate void ratio are 4.4% and 14.0%, the corresponding powder to binder ratio is 1.3, and the effective thickness of asphalt membrane is 9.0 μm . For the convenience of comparison, zeolite asphalt mixture

adopts the same gradation and oil stone ratio as hot mix asphalt mixture.

5.1. Mixing Performance. As a warm mix asphalt mixture, it should be able to mix at a lower temperature, which requires the workability and workability of the mixture. On the premise that the voltage remains unchanged, the electric power consumed is directly proportional to the current in the circuit; the power consumption of mixing paddle of asphalt mixing pot in laboratory test is closely related to the resistance; then, the resistance of the mixing paddle can be characterized by electric current to evaluate the workability of asphalt mixture. Obviously, the greater the internal friction and the cohesion of the mixture are, the greater the resistance of mixing is, and the more the energy support is

TABLE 8: Gradation of AC-20.

Sieve hole (mm)	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.60	0.30	0.15	0.075
Design grading (%)	100	95.0	83.0	72.0	57.0	38.0	26.0	18.0	13.0	9.0	6.5	5.0
Grading range (%)	100	90–100	76–90	64–80	50–64	33–43	21–31	13–23	9–17	6–12	4–9	3–7

needed in the mixing process. Therefore, the mixing power can be used to evaluate the difficulty of mixing asphalt mixture. When the voltage is fixed, comparing the difference of electric power with the index of mixing current can indirectly reflect the workability of warm mix asphalt mixture.

Use clamp ammeter to measure the current of zeolite asphalt mixture in the mixing process and compare it with hot asphalt mixture, as shown in Figures 21 and 22.

Figure 21 shows the mixing current of base asphalt mixture and Figure 22 shows the mixing current of modified asphalt mixture. It can be seen that, for the same asphalt mixture, the mixing current decreases with the increase of temperature, which indicates that the mixing temperature increases and the mixing resistance decreases, which is related to the decrease of asphalt viscosity and the increase of asphalt mortar fluidity under high temperature.

Compared with hot mix asphalt mixture, the mixing current of zeolite asphalt mixture is less than that of hot mix asphalt mixture at the same temperature, which shows that zeolite can improve the workability of mixture when used in asphalt mixture. Taking the mixing current as the index, for the base asphalt mixture, the mixing current at 130°C is slightly lower than that at 150°C, so it can be inferred that the mixing resistance of zeolite asphalt mixture at 130°C is equivalent to that at 150°C; that is to say, under the same mixing effect, the mixing temperature of zeolite asphalt mixture can be reduced by 20°C. For the modified asphalt mixture, the mixing temperature of zeolite asphalt mixture can be reduced to 20°C. Different types of zeolite have certain influence on the mixing current of the mixture.

5.2. Compaction Performance. Due to the different flow characteristics of asphalt at different temperatures, the compaction energy required to overcome the cohesion of asphalt is temperature dependent [40, 41]. In order to understand the response of zeolite asphalt mixture under different compaction methods, this paper uses SGC, which is more close to the compaction situation of the open project, to make an experimental analysis of the compaction effect of zeolite asphalt mixture. Using the rotary compactor, rotate at the rate of 1.25° and 30 R/min under the vertical pressure of 60 kPa and evaluate the volume index of the zeolite asphalt mixture after compaction. Figure 23 shows the compaction curve of the matrix asphalt mixture, and Figure 24 shows the compaction curve of the modified asphalt mixture.

As shown in Figures 23 and 24, the compaction curve of zeolite asphalt mixture is under the hot mix asphalt mixture, which indicates that zeolite asphalt mixture is easier to be compacted under the same compaction temperature and compaction work.

From the point of view of similar void ratio, the void ratio of zeolite asphalt mixture at 120°C can reach the void

ratio level of 140°C of hot mix asphalt mixture, so the compaction temperature of zeolite asphalt mixture can be reduced to 120°C.

For modified asphalt mixture, the porosity of zeolite asphalt mixture decreases with the increase of temperature by rotary compaction. Taking the void ratio as the evaluation index, the hot mix asphalt mixture can meet the design requirements at 160°C, and the zeolite asphalt mixture can basically reach the same level at 140°C, but the void ratio of 2# zeolite is high.

According to the above compaction curve of asphalt mixture, the compactness of asphalt mixture is less than 4% when the compaction temperature of matrix asphalt mixture is 140°C and modified asphalt mixture is 160°C. Therefore, in order to ensure that the mixture has a reasonable void ratio, in addition to the lower limit of compaction temperature, the upper limit of compaction temperature should be controlled to avoid excessive compaction of the mixture resulting in low void ratio.

5.3. Compaction Curve and Compaction Energy Index

5.3.1. Compaction Curve of Asphalt Mixture. In the process of rotary compaction, the height change of asphalt mixture can be collected in real time, so as to describe the change track of compactness in the process of mixture compaction, which provides the possibility to study the compaction characteristics of asphalt mixture. From the analysis of the physical meaning of the compaction curve, the slope of the compaction curve can relatively evaluate the compaction rate of the mixture. The larger the slope is, the greater the compaction rate of the mixture is, and the easier the mixture is to be compacted [44–46].

In the semilogarithmic coordinate system, a straight line is used to fit the change of compaction density of the mixture, as shown in Figure 25. The fitted compaction equation is

$$K = a \ln N + b, \quad (4)$$

where K is density of mixture (%); N is times of rotary compaction (times); and a and b are coefficients.

For various zeolite asphalt mixtures and hot mix asphalt mixtures, the change of a and b coefficients is shown in Figure 26.

In Figure 26, the coefficients a and b represent different physical meanings, a reflects the compaction speed of asphalt mixture, and b reflects the initial compaction degree of mixture. According to the compaction fitting equation of each asphalt mixture, the compaction speed of zeolite asphalt mixture is higher than that of hot asphalt mixture at lower temperature (100°C). However, with the increase of

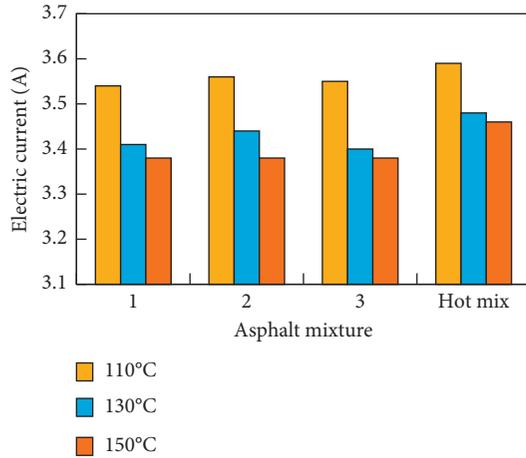


FIGURE 21: Electric current of mixture.

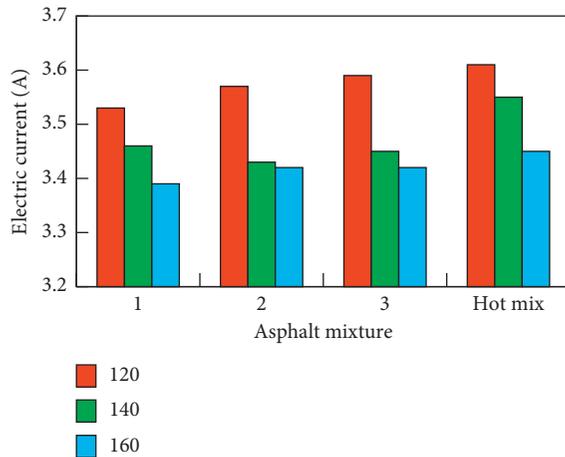


FIGURE 22: Electric current of modified mixture.

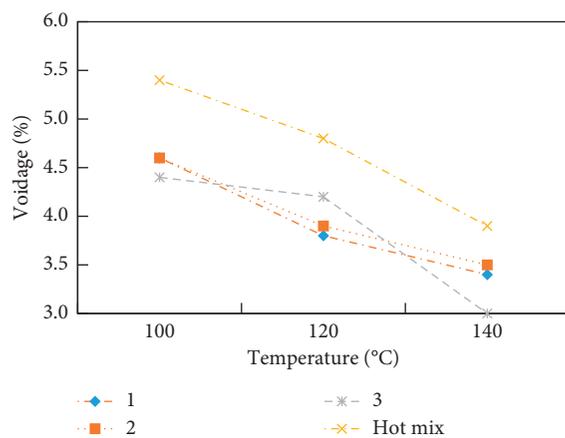


FIGURE 23: Air void of gyratory compacted asphalt mixtures.

temperature, the compaction speed of the two has little difference.

The difference of b value in the mixture compaction equation is not big, which shows that the zeolite type has little influence on the initial compactness of the mixture. For

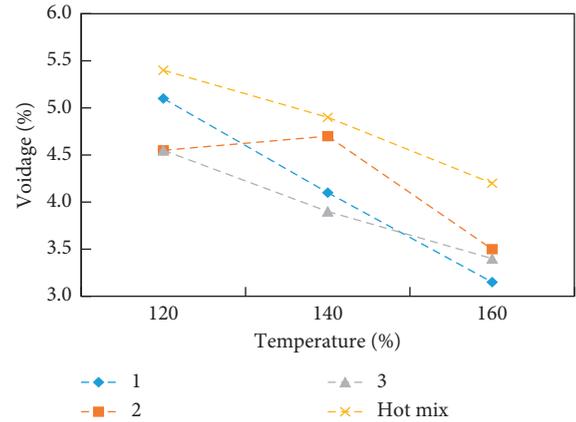


FIGURE 24: Air void of gyratory compacted modified asphalt mixtures.

hot mix asphalt mixture and zeolite asphalt mixture, the initial compactness fluctuates with the increase of temperature to a certain extent.

5.3.2. Compaction Energy Index. The coefficients a and b of the above fitting compaction curve can relatively evaluate the compaction speed and initial compaction degree of asphalt mixture but cannot accurately evaluate the compaction energy and compaction work of the mixture. In order to evaluate the compaction and workability of asphalt mixture, it is necessary to study the energy demand in the process of mixture compaction. Because of the difficulty of energy testing, the concept of compaction energy index in Superpave design method is used for [47, 48].

In this study, when calculating the compaction energy index, the initial state of asphalt mixture adopts the compactness of the mixture after 8 times of rotation, because the 8% void ratio is the lowest standard of the mixture compaction.

The compaction curve of asphalt mixture is as shown in Figure 26(b). The power function is used to fit the compaction curve of asphalt mixture. Assuming that the function is continuous, the envelope area of the curve between any two points of the compaction curve can be obtained by integrating the equation. As the compaction energy index (CEI) of asphalt mixture, it indicates the difficulty of compaction of mixture.

(1) *Base Asphalt Mixture.* The compaction energy index of various asphalt mixtures is shown in Figure 27.

It can be seen from Figure 27 that the asphalt mixture at different temperatures has different rotary compaction energy index. Compared with the hot mix asphalt mixture, the energy index of zeolite asphalt mixture is lower, indicating that it has good workability and is easy to compact. At 100°C, 3# zeolite has the minimum energy index, and the zeolite asphalt mixture is easy to compact at this temperature. At this temperature, the order of compaction of three kinds of zeolite asphalt mixture is 3# > 1# > 2# > hot mix.

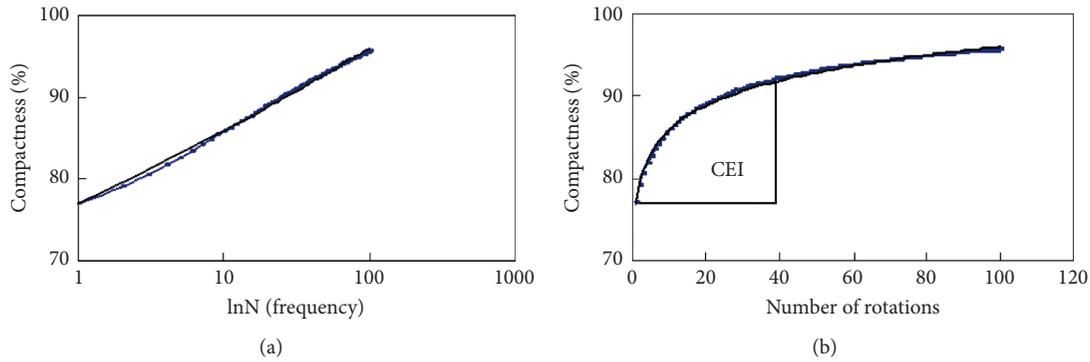


FIGURE 25: Gyratory compacting curve of asphalt mixture. (a) Semilogarithmic coordinate. (b) Rectangular coordinate.

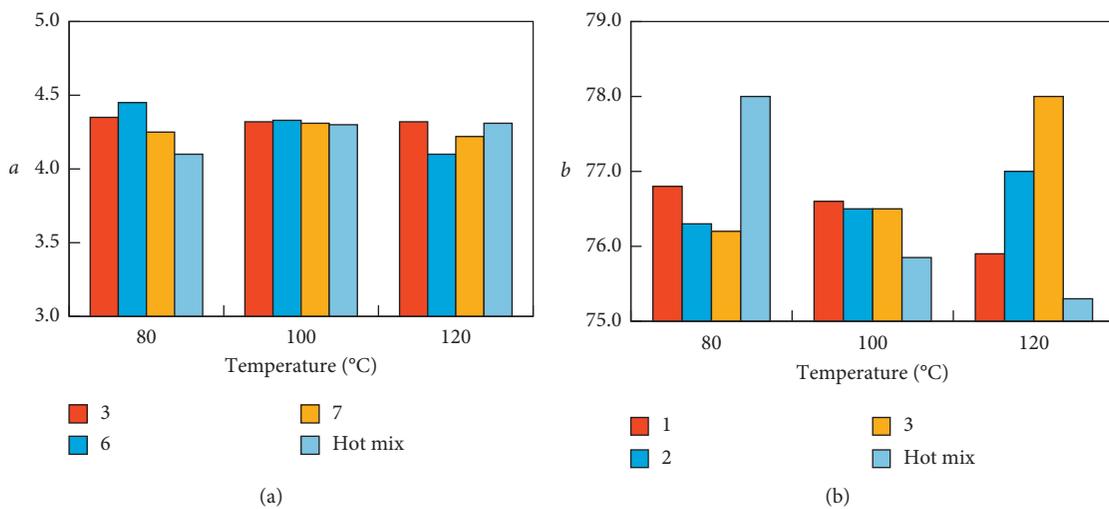


FIGURE 26: Coefficients of gyratory compaction. (a) Coefficient *a*. (b) Coefficient *b*.

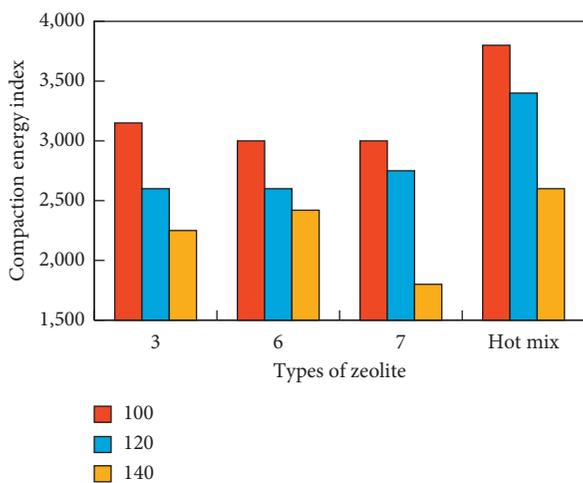


FIGURE 27: Compact energy index of asphalt mixtures.

It can be seen from the energy index comparison between zeolite and hot mix asphalt that the energy index of hot mix asphalt at 120°C is higher than that of zeolite asphalt

at 100°C, indicating that the workability of hot mix asphalt at 120°C is lower than that of zeolite asphalt at 100°C. At 140°C, the energy index of hot mix asphalt is slightly higher than that of zeolite asphalt at 120°C, which also proves that zeolite asphalt has good workability.

(2) *Modified Asphalt Mixture.* The compaction energy index of the mixture with modified asphalt is analyzed, as shown in Figure 28.

Similarly, for the modified asphalt mixture, the compaction energy index of the asphalt mixture is temperature dependent. In addition to 2#, the energy index of zeolite asphalt mixture at 140°C is lower than that of hot asphalt mixture at 160°C, which indicates that zeolite asphalt mixture has good compactability.

(3) *Influence of Zeolite Characteristics on Compaction Energy Index.* As mentioned before, zeolite has a certain impact on compaction energy index. The relationship between water loss performance of zeolite and compaction energy index is analyzed. Figure 29 shows the relationship between compaction energy index of matrix asphalt mixture and modified asphalt mixture and water loss rate of zeolite.

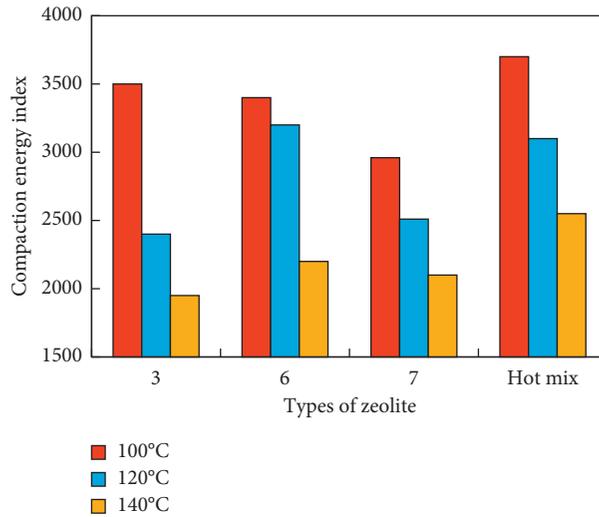


FIGURE 28: Compact energy index of modified asphalt mixtures.

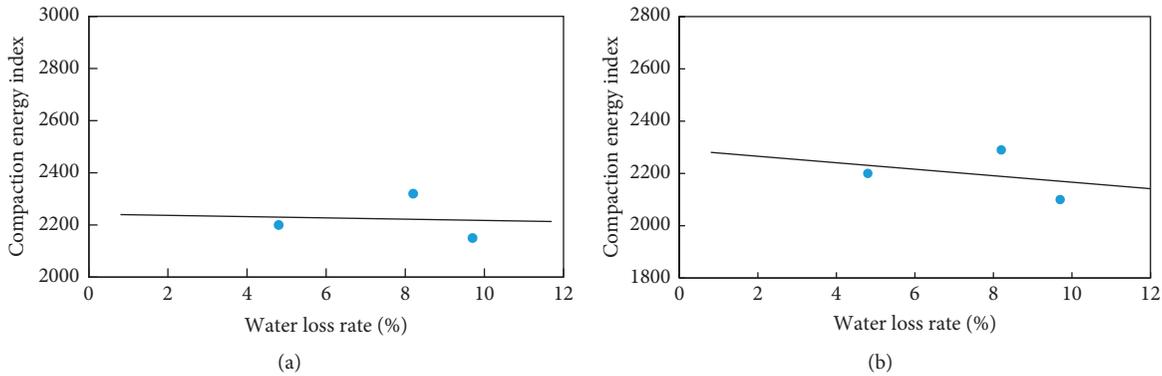


FIGURE 29: Influence of water loss on compact energy index.

It can be seen from Figure 28 that the compaction energy index of asphalt mixture decreases with the increase of zeolite water loss rate, indicating that the water loss performance of zeolite directly affects the compaction energy index of asphalt mixture. The more the water loss of zeolite, the more the bubbles formed, the greater the reduction of compaction friction, and the easier the compaction of mixture.

6. Conclusions

- (1) The results show that there are water molecules with different forces and orientations in the zeolite, which is unique to zeolite.
- (2) Through SEM observation and pore structure analysis, it is found that natural zeolite particles have different shapes and uneven size distribution and the pore content of zeolite is far greater than that of mineral powder.
- (3) TGA and DSC were used to analyze the zeolite. Under certain conditions, the water loss of zeolite was different. The three types of zeolite had the property of water loss at 90°C~120°C, which was the necessary condition for zeolite to be used in the warm mix asphalt mixture.
- (4) The water absorption and loss performance of zeolite mainly depend on pore volume. The larger the pore volume is, the stronger the water holding capacity of zeolite is. At the same time, the water holding capacity and water loss capacity of zeolite are related to the pore size distribution, and the appropriate pore size is conducive to the volatilization of water.
- (5) The effect of zeolite on the viscosity of asphalt is time-dependent. As time extends, the viscosity of zeolite asphalt changes dynamically, which can be characterized by viscosity change rate and effective action time. The former reflects the degree of influence of zeolite on the viscosity of asphalt, and the latter reflects the time range of change.
- (6) The mixing resistance is characterized by the mixing current. The comparison between zeolite asphalt mixture and hot asphalt mixture shows that, under the same temperature, the mixing current of zeolite asphalt mixture is less than that of hot asphalt

mixture, which shows that zeolite can improve the workability of asphalt mixture.

- (7) This paper studies the compaction behavior of zeolite asphalt mixture, analyzes the influence of temperature and zeolite on the compaction performance of asphalt mixture, and indicates that zeolite asphalt mixture has good compaction performance. There is a flat area on Marshall compaction curve, in which the mixture is easy to compact. The compaction temperature of zeolite asphalt mixture can be reduced by 20~30°C.
- (8) Comprehensive analysis of the influence of zeolite on the voidage of asphalt mixture shows that the better the water loss performance of zeolite is, the easier the mixture is to be compacted. For the base asphalt mixture, the compaction temperature of the mixture is 120–130°C, and, for the modified asphalt mixture, the compaction temperature is 130–140°C.

Data Availability

The data in this paper are given in the tables and figures within the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Zhuolin Li and Junda Ren conceived and designed the experiments; Wei Li performed the experiments; Xingsheng Fu and Liying Yang analyzed the data; Zhuolin Li and Junda Ren wrote the paper.

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