Laboratory Evaluation on the Road Performance of Diatomite Modified Porous Asphalt Mixture

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Abstract. Porous asphalt mixture (PAM) is an indispensable pavement material for the construction of sponge city with low-cost and environment friendly characteristics, which conducive to replenishing urban groundwater and alleviating the heat island effect. The main purpose of this article is to explore the change of road performance and water permeability of PAM under different diatomite dosage, and determine the optimal amount of diatomite content. First, the volume characteristics of diatomite permeable asphalt mixture (D-PAM) were measured by Darcy's law, the void of D-PAM decreased slightly according to the test results. Furthermore, based on the water damage Marshall test and freeze-thaw splitting test, the water stability of D-PAM increases significantly with the increase of diatomite content. At last, the low-temperature anti-cracking performance and ductility of D-PAM were carried out based on the acoustic emission (AE) detector and the Low temperature universal mechanics testing machine. According to the experimental results, it is recommended that the content of diatomite is 10%.

Keywords: Porous Asphalt Mixture; Diatomite; Water Stability; Permeability; Low Temperature Performance; Acoustic Emission Technology

1. Introduction
Asphalt pavement has the characteristics of better driving comfort and construction convenience, and has long been developed into the higher utilization of urban road construction pavement type. The materials used in the current asphalt pavement surface layer are mostly dense-graded asphalt mixtures with low porosity. If the rainfall exceeds the bearing limit of the pavement, it will cause water on the road area, and water mist will be produced when the vehicles drive by, which will increase the incidence of traffic accidents. In addition, the rapid increase of runoff during rainstorm will increase the burden of urban drainage system and even cause floods disasters [1]. Road researchers have proposed a new structure with high porosity, which called permeable asphalt (PA) pavement, and PA pavement is classified as open-grade asphalt pavement. PAM has higher porosity compared with ordinary dense graded asphalt [2]. High porosity makes the PAM has better permeability and sound absorption and noise reduction function [3], which can effectively alleviate the current urban ecological system's drainage blockage, heat island effect and other disadvantages, and it can also restore the urban water ecology, conserve water resources, and enhance the city's ability to prevent water logging. However, due to the internal porous structure of the PAM, its low temperature crack resistance and durability are poor, it is difficult to apply to high-latitude cold regions [4,5]. Therefore, how to improve the road performance of PAM as much as possible without affecting the permeability is also a hotspot in this field.
In recent years, the research direction prefers to study the diatomite modified asphalt. Through the research on the properties of modified asphalt, the fillers have a significant effect on the properties of asphalt mortar [6, 7]. Researchers have researched the performance of such fillers as limestone, basalt fiber, slaked lime and fly ash in asphalt mixture in the hope of improving the low temperature performance and durability of the mixture [8,9]. However, these materials do not perform well in PAM through tests. Diatomite is a kind of nonmetallic mineral material with high air gap and low cost. Guo et al. [10] study the basic properties of diatomite modified asphalt binder. The experimental results show that the permeability and ductility of the asphalt binder decrease with the increase of diatomite content; In addition, when the diatomite content exceeds a certain value, the low temperature performance of D-PAM will decrease. Cheng et al. [11] pointed out that a certain amount of diatomite can significantly improve the high and low temperature performance of asphalt mortar, kietzman et al. [12] studied that diatomite mixed with mixture can improve the durability of asphalt pavement. Guo et al. [10] through rutting test, indirect tensile fatigue test (ITFT), low temperature indirect tensile test and indirect tensile stiffness modulus test (ITSM), conclude that the diatomite has a significant effect on the stiffness modulus of asphalt mixtures, which can improve the anti-rutting and anti-fatigue performance of asphalt mixtures. In conclusion, diatomite, as a new inorganic modifier, has greatly improved the various properties of asphalt mixtures. However, the above studies are based on dense graded asphalt mixtures, while the research on open graded mixture is less.

When the stress exceeds the tensile and compression limit or the internal cumulative fatigue damage exceeds the threshold, the mixture will occur cracks [13,14]. Cracks will seriously affect the performance of roads and may cause traffic accidents. The unpredictability and serious consequences of cracks are the main problems that plague the field of highway engineering. In order to better grasp the occurrence of cracks and better understand the fracture behavior and mechanism of asphalt materials, others have done a lot of research, including semi-circular bend (SCB) test, single edge notched bead beam (SENB) test, disc shape compact tension (DCT) test, and edge notched disc bend (ENDB) test, etc [15,16,17]. The above method is not only troublesome, but also can’t monitor the cracks in real time [18]. Acoustic emission technology has the advantages of dynamic measurement and non-destructive testing and can monitor the sudden energy release in the material in real time. It is widely used in bridge testing, concrete and other fields, but it is rarely used in the field of asphalt mixture [19]. Jiao et al. [20,21] realized the classification of the fracture process of PA based on AE parameters, Khosla and Goetz [22] used AE parameters to monitor and evaluate the low temperature fracture behavior of asphalt mixtures, Seo and Kim [23] used AE to evaluate the damage accumulation and strength recovery of asphalt mixture under uniaxial cyclic loading. The subject of the above study using AE is also dense graded asphalt mixture. In this article, AE is used to record the whole cracking process of PAM under low temperature conditions, and it was also applied for monitor the energy value change of PAM in the split process and made the energy-load analysis correlation diagram, the influence of the diatomite on the fracture process of PAM was studied.

2. Materials and Methods

2.1. Materials
This article used SBS-modified asphalt, obtained from Changchun. The basic performance is shown in Table 1. SBS modified asphalt has the highest utilization rate in pavement construction, because it has higher viscosity and can significantly improve the anti-fatigue cracking performance [24].

| Properties                  | Test Values | Specification |
|-----------------------------|-------------|---------------|
| Penetration (25 °C, 0.1 mm) | 65.2        | 60-80         |
| Softening point (°C)        | 64.2        | ≥55           |
| Ductility (5 °C, cm)        | 34.5        | ≥30           |
| Density (15 °C, g/cm³)      | 1,068       | Measured data |
| Flash Point (°C)            | 264         | ≥230          |
| Elastic recovery(5 °C, %)   | 90.9        | ≥65           |
Permeable asphalt mixture is typical skeleton void structure, the coarse aggregate in permeable asphalt mixture should be hardness and low needle flake content. Therefore, the coarse aggregate selected in this study is basalt coarse aggregate (BCA) produced in Changchun, the basic mechanical properties of BCA can be referred to in Table 2, and the test methods of bitumen and aggregate are conform to the Standard Test Methods of asphalt and aggregate for Highway Engineering (JTG E42-2005) [25]. Before using BCA, it can be fully exposed to rainwater and air in natural environment for more than 6 months, which can eliminate the volume instability of BCA. [26]

| Properties                                    | Size   | Test Values | Specification |
|-----------------------------------------------|--------|-------------|---------------|
| Crushed stone value (%)                       | 13.2   |             | ≤26           |
| Los Angeles abrasion (%)                      | 17.8   |             | ≤28           |
| Flat and elongated particle in coarse aggregate (%) | 4.2    |             | ≤10           |
| Polished stone value                          | 48     |             | ≥40           |
| Apparent specific gravity (g/cm³)            |        |             |               |
| 13.2mm                                        | 2.90   |             |               |
| 9.5mm                                         | 2.83   |             |               |
| 4.75mm                                        | 2.84   |             | ≥2.6          |
| 2.36mm                                        | 2.69   |             |               |
| Water absorption (%)                          |        |             |               |
| 13.2 mm                                       | 0.40   |             | ≤2.0          |
| 9.5 mm                                        | 0.41   |             |               |
| 4.75 mm                                       | 0.57   |             |               |
| 2.36 mm                                       | 1.01   |             |               |

Diatomite is a kind of siliceous sedimentary rock composed of a skeleton of diatom fossils. Diatomite has low cost and large reserves. Different production areas and production processes will affect the structure and particle size of diatomite. Therefore, the physical and chemical properties of different types of diatomite are different. The diatomite used in this article was produced in Jilin and the product type is filter aid, and the average particle size of diatomite is 10 microns, which is in the form of off-white powder. Figure 1 shows the appearance and volume of 50g of diatomite. Its basic properties are listed in Table 3.

**Figure 1. Appearance and volume of 50g diatomite**

| Properties                      | Test Values | Specification |
|---------------------------------|-------------|---------------|
| pH (100g/L)                     | 9.0         | 8.0-11.0      |
| Apparent density (g/cm³)        | 2.18        | 1.9-2.3       |
The amount of mineral powder in PAM is generally about 5%, which is an indispensable filler for improving the water stability and durability of PAM. The mineral filler used in this article was produced in Jilin Songyuan. Specific technical indicators of mineral filler are given in Table 4.

Table 4. Properties of mineral filler.

| Properties                  | Test Values | Specification |
|-----------------------------|-------------|---------------|
| Hydrophilic coefficient     | 0.5         | <1            |
| Plasticity Index (%)        | 2.3         | <4            |
| Apparent density (g/cm³)    | 2.771       | ≥2.5          |
| Granularity range (%)       | <0.6mm      | 100           |
|                             | <0.15mm     | 92            |
|                             | <0.075mm    | 82            |
|                             | 90-100      | 75-100        |

2.2. Mixing method of Diatomite

According to the research of others, there are two ways to mix diatomite [27]: one method is to mix with aggregate first (Direct mixing method), and in another method the diatomite will be mixed first with asphalt (Indirect mixing method). The first method was selected in this study, which replaces the mineral filler with equal volume. The advantage of this method is that the overall gradation will not be changed and the road performance is practically unaffected. The mixing quality of diatomite was calculated by Equation (1):

\[
m_D = \frac{m_M}{\gamma_M} \times \gamma_D
\]

where \(m_D\) is the mixing mass of diatomite (g); \(m_M\) is the mixing mass of mineral filler (g); \(\gamma_M\) is the unit weight of mineral filler (%); and \(\gamma_D\) is the unit weight of diatomite (%).

2.3. Mixture Design

According to the relevant specifications and the research conclusions of others, in order to obtain a gradation with better comprehensive performance, the void ratio of the mixture is finally determined to be about 20%. The research focuses on the upper layer material of permeable pavement, so the fine-grained permeable asphalt mixture (PAC-13) is selected, and the gradation is adjusted by changing the mass passing rate of 2.36mm mesh [28]. Finally, the obtained gradation is shown in Table 5.

Asphalt and mineral aggregate interact after mixing, and the asphalt forms a structural asphalt film on the surface of the mineral aggregates.

The cohesion of structural asphalt is better than free asphalt, so the higher the content of structural asphalt, the stronger the overall adhesion performance of asphalt film [29]. Diatomite has a unique porous structure and a larger specific surface area, thereby increasing the adsorption capacity of the asphalt mixture [30,31]. Therefore, the relative content of structural asphalt in the mixture is positively correlated with diatomite content.

In order to determine the mixing amount of diatomite, through other people’s research on diatomite modified asphalt, the amount between 5% and 15% has different degrees of improvement on road performance of the mixture. In addition, a control group was set up for comparison. Finally, the amount of diatomite selected in this study was 0%, 5%, 10% and 15%, which were grouped into D0, D5, D10 and D15, respectively. According to Cantabro and Draindown tests, the optimal bitumen-aggregate...
ratios (OBRs) of different modified bitumen groups are 3.25%, 3.35%, 3.40% and 3.5%, respectively [32].

Table 5. Particle size distributions for PAC-13 in this study

| Mesh size (mm) | 0.0750 | 0.150 | 0.6 | 1.182 | 3.647 | 7.5 | 9.5 | 13.2 | 16 |
|---------------|--------|-------|-----|-------|-------|-----|-----|-------|----|
| Passing mass percentage (%) | 5.0 | 6.8 | 7.9 | 10.1 | 12.9 | 16.7 | 23.4 | 66.4 | 94.7 | 100 |

2.4. Specimen Preparation
Refer to specification T0702-2011 [32], the preparation process of specimen is as follows:

- **Step1**: Dehydration. Put the weighed aggregate and fillers into an oven at 180 °C for more than 6 hours, meanwhile, heat the SBS modified asphalt to 180°C to ensure sufficient fluidity.
- **Step2**: Mixing. Firstly, the asphalt mixture mixer was heated to 170°C and put the coarse aggregate into pot and stir for 90s, then add the asphalt and stir for 90s, finally, add the mineral fillers and diatomite into the pot, and then stir for 90s.
- **Step3**: Compaction. Use a standard Marshall hammer to firm the mixture in the mold, 50 times on each side.
- **Step4**: Demolding. The specimens should be cooled to room temperature for more than 12 h before demolding.
- **Step5**: Measure. Use a vernier caliper to measure the diameter and height of the specimen. According to the specification, specimens with a diameter that does not meet 101.6 ± 0.2 mm or a height that does not meet 63.5 ± 1.3 mm should be discarded.

The experimental program is listed in Table 6.

Table 6. Experimental program

| Experiments                             | Number of specimens used in each group | Experimental Condition |
|----------------------------------------|---------------------------------------|------------------------|
| Volume Determination                    | 3                                     | None                   |
| Marshall test                          | 3                                     |                        |
| Immersion Marshall test                | 3                                     |                        |
| F-T 1 cracking resistance              | 6                                     | 3 for F-T 1 test.      |
|                                         |                                       | 3 for F-T test after one F-T cycle. |
| Low-temperature cracking resistance    | 3                                     | AE detection and low-temperature splitting test were carried out simultaneously |

2.5. Test Method

2.5.1. Volume Characteristics. The effective porosity of SPC was determined by the drainage method, using cubic specimens with 100 × 100 × 100 mm. The calculation formula is as follows:

\[
VV = \left(1 - \frac{\gamma_f}{\gamma_t}\right) \times 100\%
\]

\[
VV' = \left(1 - \frac{m_u - m_w}{V \rho_w}\right) \times 100\%
\]

Where \(VV\) is the total porosity (%); \(VV'\) is the connected aid voids (%); \(\gamma_f\) is the bulk specific gravity of bituminous mixtures; \(\gamma_t\) is the theoretical maximum specific gravity of bituminous mixtures; \(m_u\)
is the quality of dry specimens in air (g); $m_w$ is the quality of specimens in water (g); $V$ is the volume of the specimen (mm$^3$); and $\rho_w$ is the water density (g/cm$^3$).

Effective porosity ratio can be used to evaluate the spatial density of connected voidage in asphalt mixture, and can be calculated by Formula 4

$$EPR = \frac{VV'}{VV} \times 100\%$$

(4)

Based on Chinese specification (T0705-2011), the mineral clearance rate (VMA) and the Asphalt saturation (VFA) are calculated by Formulas 5 and 6 [33].

$$VMA = \left(1 - \frac{\gamma_f \times P_s}{\gamma_{sb}}\right) \times 100$$

(5)

$$VFA = \left[(VMA - VA)/VMA\right] \times 100$$

(6)

where $\gamma_f$ is the bulk specific gravity of the mixture; $P_s$ is the aggregate content percent by weight of the mixture (%); $\gamma_{sb}$ is the bulk specific gravity of aggregates; and $VA$ is the air voids of the mixture (%).

2.5.2. Water Stability. Asphalt pavement damage caused by water is a common problem, Water damage will seriously impair the strength, stiffness and durability of the mixture [34,35]. Long-term exposure to water damage will cause the asphalt to peel off the aggregate surface, and the pavement will produce raveled, rutting, and cracking under the influence of traffic load [36,37].

This study uses water immersion Marshall test and the freeze-thaw split test to evaluate the water stability of D-PAM. The immersion Marshall test needs to be divided into immersion group and control group. Immersion group was immersed in a 60° constant temperature water bath for 24 hours, and control group was immersed for 40 minutes under the same conditions. The formula for calculating the stability of the immersion residue used to evaluate the water stability of the Marshall standard specimen is as follows [32]:

$$MS_0 = \frac{MS_1}{MS} \times 100$$

(7)

where $MS_0$ is the stability of immersion residue in immersion group, $MS_1$ is the Marshall stability in immersion group, $MS$ is the Marshall stability in control group.

In the freeze-thaw (F-T) splitting test, the water stability of the asphalt mixture is reacted by measuring the indirect tensile strength (ITS) [38]. The specimens are divided into freeze-thaw group (group 1) and control group (group 2). Put the group 1 into a plastic bag containing 10ml of water after being vacuum-saturated in accordance with the procedure T0717, and then put it in a constant temperature refrigerator (−18 ℃) for 16 hours and then take it out. Group 2 was kept at room temperature for the same time. Before splitting test, the specimens of both groups were immersed in 25 ℃ water sink for 2 hours. The loading rate of the testing machine is 50 mm / min, and the maximum test load is recorded. The Freeze-thaw splitting tensile strength ratio (TSR) is calculated by the Equation 8.

$$TSR = \frac{R_{t2}}{R_{t1}} \times 100$$

(8)
where $R_{T1}$ is the average splitting tensile strength of effective parts in group 1(MPa); $R_{T2}$ is the average splitting tensile strength of effective parts in group 2(MPa).

### 2.5.3. Low-Temperature Cracking Resistance test with using Acoustic emission

The low temperature crack resistance of asphalt mixture can be used to characterize the ability of asphalt pavement to resist temperature stress at low temperature without obvious elastic deformation [39]. In the low temperature season in winter, the surface temperature of the pavement decreases, resulting in internal temperature stress. If the slack capacity of the pavement does not meet the road requirements, low-temperature cracks will easily occur, which will damage the pavement. The average temperature in winter in high latitudes is lower, which puts forward higher requirements on the low-temperature crack resistance of asphalt mixtures.

The test was carried out on a micro-computer-controlled electro-hydraulic servo press. The test temperature is -10 ℃, the specimens were placed at -10 ℃ for 6 hours before the test. the loading mode is strain control, due to the loading rate has a great influence on the flexural strength of asphalt mixture [40], the loading rate used in this test is common rate, 1 mm / min. The calculation of Low Temperature Crack Resistance is as Equation 9 to 12:

\[
R_T = 0.006287P_T / h \quad \text{(9)}
\]

\[
\varepsilon_T = X_T \times (0.0307 + 0.0936\mu) / (1.35 + 5\mu) \quad \text{(10)}
\]

\[
S_T = P_T \times (0.27 + 1.0\mu) / (h \times X_T) \quad \text{(11)}
\]

\[
X_T = Y_T \times (0.135 + 0.5\mu) / (1.794 - 0.0314\mu) \quad \text{(12)}
\]

Where $R_T$ is indirect tensile strength(MPa); $\varepsilon_T$ is failure strain(Dimensionless); $S_T$ is the modulus of fracture stiffness(MPa); $X_T$ is the horizontal deformation(mm); $P_T$ is the peak load (kN); $h$ is specimen height(mm); $\mu$ is the poisson's ratio at -10 ℃(In this experiment, the value is 0.25); $Y_T$ is the modified critical displacement (mm).

The low-temperature split test and the acoustic emission detection are carried out at the same time. A transducer with a frequency acquisition range of 60-400khz was attached to the side wall of specimen, and a special sound transmission coupling agent is used to ensure signal reception well, and an elastic band is used for fixation. Set the threshold of AE signal acquisition to 40dB, and the sampling frequency to 5 MSPS. The specific test environment is shown in Figure 2.

The parameters that can be obtained directly include Total Hits, Energy, Counts, Duration, Rise Time and Amplitude, etc. And the schematic diagram of the characteristic parameters of AE signal is shown in Figure 3. Among them, the energy parameter can more accurately characterize the energy level of the collected signal. The magnitude of the signal energy detected by the device is also related to the amplitude distribution. It is an important indicator for evaluating material damage.
Figure 2. Test environment.  

Figure 3. Parameters of AE signal.

3. Results

The measurement results of Volume indexes are summarized in Table 7. The data of the Marshall test are presented in Tables 8, the data related to water stability test are presented in Table 9 and 10. The test results of low temperature performance test are shown in Table 11, and the energy and strain peaks detected through AE are shown in Table 12.

Table 7. Volume Characteristics test results.

| Diatomite content (%) | VV 1 (%) | VV' 2 (%) | EPR 3 (%) | VMA 4 (%) | VFA 5 (%) |
|-----------------------|----------|----------|-----------|-----------|-----------|
| 0                     | 22.26    | 17.06    | 76.63     | 27.94     | 20.31     |
| 5                     | 19.43    | 15.50    | 79.80     | 25.49     | 23.78     |
| 10                    | 18.47    | 14.34    | 77.65     | 24.69     | 25.20     |
| 15                    | 18.33    | 14.14    | 77.16     | 24.74     | 25.91     |

1 Total porosity. 2 Connected Aid Voids. 3 Effective porosity ratio. 4 Mineral clearance rate. 5 Asphalt saturation.

Table 8. Marshall test results.

| Diatomite content (%) | Test values (kN) | Average MS 1 (kN)St-Dev 2 |
|-----------------------|------------------|--------------------------|
| 0                     | 6.42             | 6.83                     |
|                       | 6.47             | 6.57                     |
|                       | 7.58             | 0.226                    |
| 5                     | 7.99             | 7.9                      |
|                       | 8.13             | 0.287                    |
| 10                    | 9.10             | 8.49                     |
|                       | 9.14             | 8.91                     |
|                       | 0.364            |                          |
| 15                    | 9.72             | 9.32                     |
|                       | 9.42             | 0.281                    |
|                       | 9.17             |                          |

1 Marshall stability. 2 Standard deviation.

Table 9. Immersion Marshall test results.

| Diatomite content (%) | Test values (kN) | Average MS 1 (kN)MS 2 (%) |
|-----------------------|------------------|---------------------------|
| 0                     | 5.83             | 5.58                      |
|                       | 5.97             | 5.79                      |
|                       | 88.2             |                           |
| 5                     | 7.18             | 7.22                      |
|                       | 7.31             | 7.24                      |
|                       | 91.6             |                           |
| 10                    | 8.14             | 8.41                      |
|                       | 8.37             | 8.31                      |
|                       | 93.2             |                           |
| 15                    | 9.07             | 8.31                      |
|                       | 8.74             | 92.8                      |
|                       | 8.84             |                           |

1 Marshall stability. 2 The stability of the Immersion Residue.
Table 10. F-W Cracking Resistance test results.

| Diatomite content(%) | $R_{T1}$ $^1$ (MPa) | $R_{T2}$ $^2$ (MPa) | TSR (%) |
|-----------------------|----------------------|----------------------|---------|
| 0                     | 0.910                | 0.751                | 82.6    |
| 5                     | 0.924                | 0.777                | 84.1    |
| 10                    | 0.951                | 0.858                | 90.2    |
| 15                    | 1.032                | 0.938                | 90.8    |

$^1$average splitting tensile strength in group 1. $^2$average splitting tensile strength in group 2.

Table 11. Low-Temperature Cracking Resistance test results.

| Diatomite content(%) | $R_T$ $^1$ (MPa) | $\varepsilon_T$ $^2$ ($10^{-6}$) | $S_T$ $^3$ (MPa) |
|-----------------------|-------------------|-----------------------------------|------------------|
| 0                     | 2.54              | 6702.1                            | 651.08           |
| 5                     | 2.42              | 8404.8                            | 495.66           |
| 10                    | 2.57              | 9246.81                           | 478.2            |
| 15                    | 2.73              | 10593.3                           | 456.81           |

$^1$indirect tensile strength. $^2$failure strain (Dimensionless). $^3$modulus of fracture stiffness.

Table 12. AE test results

| Diatomite content(%) | $F_L$ $^1$ (MPa) | $E_T$ $^2$ ($10^{-6}$) | Total Hits (Ea) |
|-----------------------|-------------------|------------------------|-----------------|
| 0                     | 25.609            | 77701.70               | 1649            |
| 5                     | 24.449            | 191989.00              | 4671            |
| 10                    | 25.951            | 445855.63              | 8684            |
| 15                    | 26.484            | 740370.23              | 17877           |

$^1$failure load. $^2$total energy.

4. Discussion

4.1. Volume Characteristic

Figure 4a shows the relationship between PT and PE and the content of diatomite. According to the test, there is correlation between the connected porosity and the porosity, and the difference is about 4%. With the increase of diatomite, the VV and VV' decreased too. According to research, a porosity of 15% is a limit of the pavement permeability. When the porosity is above 15%, the water that penetrates into the pavement structure will be discharged in time. When the porosity is less than 15%, the pavement will seep and remain. Water phenomenon, the evaporation rate of water is much lower than the rate of water seepage, which will seriously damage the road surface. The lowest porosity in the test results is still more than 15%, which meets the specification requirements. It is preliminarily speculated that the reason for the decrease in the porosity is due to the increase in the amount of asphalt, except for the coating on the surface of the aggregate, the others distributed between the gaps of the aggregate in the form of free asphalt.

The variation of VMA and VFA with the increase of diatomite content is shown in Figure 4b, which can be seen intuitively from the figure that with the increase of diatomite content, the VMA gradually decreases, while the VFA gradually increases. The increase in asphalt saturation is depending on the larger specific surface area and strong self-adsorption of diatomite, it is easier to absorb free asphalt, thereby improving the adhesion performance of asphalt and mineral aggregates. Figure 4c shows the relationship between EPR and the content of diatomite.
4.2. Water Stability

Figure 5a shows the Marshall stability (MS) and the immersion MS of different diatomite contents. The test results show that as the ratio of diatomite to replace mineral filler increases, the MS gradually increases. Compared with the group D0, the stability of the D5, D10 and D15 groups were increased by 20.24%, 35.62% and 43.38% respectively, and the test results of each group met the specification requirements. It depends on the unique microporous structure and active ingredients of diatomite, which greatly improved the road performance of the D-PAM and ensured adequate adhesion between aggregate and asphalt. Therefore, the MS is maximized when 15% diatomite is added.

Figure 5b shows the water stability of specimens with different diatomite content. After adding diatomite modifier into the mixture, the water stability of mixture with a content of 0-10% gradually increases gradually. Compared with the group D0, the stability of the D-PAM is increased by up to 5%. When the dosage increases from 10% to 15%, the water stability decreases slightly. It may be the diatomite itself is a material with strong water absorption. Long-term soaking will cause excessive residual water in the pores of the specimen, which reduced the adhesion of asphalt, making it easier for aggregates to peel off from the mixture, thus reducing MS.

Figure 4. Volume characteristics test results: (a) the relationship between $P_T$ and $P_E$ and the content of diatomite; (b) the relationship between VMA and VFA with the diatomite content; (c) the relationship between EPR and the content of diatomite.
Figure 5. Water stability test results: (a) Marshall test and Immersion Marshall test Results; (b) the stability of immersion residue in different test groups.

The relationship between F-T splitting strength and diatomite content is shown in Figure 6. It can be seen from figure 6 that the F-T splitting strength increases with the increase of diatomite content. According to the specification requirements, the F-T splitting strength ratio of PAM should not be below 85%. It can be also seen from the figure that the 10% and 15% D-PAM meet the requirements, and the change rate of F-T splitting strength ratio is the largest when the diatomite content increases from 5% to 10%. It indicates that diatomite can greatly enhance the water stability of D-PAM, but excessive amount is just the opposite.

Figure 6. Freeze-Thaw splitting test results.

4.3. Low-Temperature Cracking Resistance with using Acoustic emission

The splitting tensile strength, failure strain and failure stiffness modulus of D-PAM are shown in table 10, and with the increase of diatomite content, the variation trend of splitting tensile strength and failure strain at low temperature (-10 ℃) is shown in Figure 7a. According to the diagram, the higher the content of diatomite, the stronger the cracking resistance of D-PAM at low temperature, but there is no significant change. However, the failure strain increased significant. Compared with the D0 group, the failure strain of D-PAM of other group increased by 25.4%, 38.8% and 58%. The variation trend curve between failure stiffness modulus and diatomite content is shown in Figure 7b. It can be seen from the figure that the failure stiffness modulus of D-PAM decreases with the increase of the diatomite content, the smaller the stiffness modulus is, the higher the low-temperature performance is. Therefore, the PAM with 15% diatomite content has the strongest deformation resistance at low temperature.
The load displacement curves of each group of specimens under low temperature environment are displayed on Fig. 8. It can be found that the PAM with high diatomite content has stronger tensile properties and better ductility at low temperature. This is because diatomite and asphalt are mutually dissolved. Diatomite can evenly spread in asphalt to improve the thickness of asphalt film in the mixture, and diatomite can absorb more structural asphalt, which increases the relative content of structural asphalt and improves the ductility of the mixture. Therefore, PAM with 15% diatomite content has the best crack resistance at low temperature.

In order to more intuitively analyze the corresponding relationship between the relative AE energy value and the load of mixture in the loading process, the parameters of the test process are collected by using AE instrument while the low temperature splitting test is carried out. The analysis results based on the parameters are shown in Figure 9. It can be seen from the figure that the relative AE energy curve is in agreement with the load curve. According to the trend of the Figures, the overall energy curve would be basically divided into three stages: In the first stage, the energy curve rises slowly and the microcracks begin to form. The second stage is the rapid rising area, in which the energy curve rises rapidly in a short time and cracks spread rapidly. And the last stage is destruction stage, as the load reaches its maximum, the energy curve also suddenly changes to its maximum value.

![Figure 7](image_url)

**Figure 7.** Low-Temperature Performance test results: (a) the relationship between the ITS and failure strain with diatomite content; (b) the relationship between the modulus of fracture stiffness and the diatomite content.

For the D0 group, the energy curve rises rapidly at 15s, the load reaches the maximum at 35s, and the AE energy also reaches the maximum; for D5, the energy curve begins to gradually increase at 30s, and the rising rate reaches the maximum at 60s, and it is also the maximum load. The energy curve of D10 group also gradually rises from about 30s, and the ascent rate is much slower than that of the D0 and D5 group. The energy curve of the D15 group is still at a low level at 60s. After that, it rose slowly to the maximum energy until 110s. By comparing the control group and the modified group, it is found that the incorporation of diatomite can reduce the rising rate of energy curve in the second stage and prolong the time required to reach the maximum damage load. In addition, the internal energy of PAM can be uniformly released during the loading process after diatomite modification, which eased up the sudden change in energy give rise to the damage to the PAM at the last stage of the loading, and improves the strength of PAM, and it is particularly evident in the D15 group.
5. Conclusion

In this research, the influence of diatomite on the mechanical properties of porous asphalt mixture was investigated, including volume characteristic test, Marshall test, immersion Marshall test, F-T splitting test and low temperature splitting test. The effects of different diatomite contents on PAM properties were analyzed and the following conclusions can be drawn from the abovementioned experimental dates.

- Compared with the group D0, the porosity and permeability of the modified group decreased slightly. Because of the porous structure of diatomite increased the relative content of structural asphalt...
in the mixture, which significantly improved the strength of the mixture. The MS of D5, D10 and D15 increased by 20.24%, 35.62% and 43.38% compared with D0.

- According to the results of Immersion Marshall test and F-T splitting test, the addition of diatomite improved the immersion residual stability of PAM, and the modified group increased by 3.85%, 5.67% and 5.22% respectively compared with the group D0. The TSR of D10 and D15 are similar. In the all, the water stability of PAM with 10% content of diatomite is the best.

- With the aggrandizing of Diatomite Content, the low-temperature failure strain of PAM increases significantly and the failure stiffness modulus decreases. The failure stiffness modulus of D-PAM decreases with the increase of the diatomite content, the smaller the stiffness modulus is, the higher the low-temperature performance is. Therefore, the low-temperature deformation resistance of PAM with 10% diatomite content increases the most. Moreover, through the analysis of parameters collected by acoustic emission, adding diatomite to PAM can reform its energy release more evenly when it is subjected to damage.

- In conclusion, PAM with Diatomite Content of 10% has the best comprehensive performance, the better porosity, water stability and low temperature crack resistance, which can accelerate the water cycle in urban ecosystem, store groundwater resources and alleviate urban flood. Therefore, D-PAM has advantages in alleviating the shortage of natural resources, reducing the cost of permeable pavement and promoting the sustainable development of pavement materials.

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