DOI: https://doi.org/10.14256/JCE.3373.2021 Građevinar 2/2023

Primljen / Received: 4.10.2021.
Ispravljen / Corrected: 19.7.2022.
Prihvaćen / Accepted: 21.7.2022.
Dostupno online / Available online: 10.3.2023.

Experimental study on freezing resistance of permeable concrete mixed with vinyl acetate-ethylene copolymer emulsion and basalt fiber

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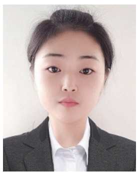

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Research Paper

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Experimental study on freezing resistance of permeable concrete mixed with vinyl acetate-ethylene copolymer emulsion and basalt fiber

In recent years, permeable concrete has been widely used in the construction of urban permeable pavement. However, it has been discovered that during practical use, the cracking of permeable concrete pavement in seasonal freezing areas is more severe due to its poor frost resistance, and the phenomenon of threshing is evident. To obtain permeable concrete that meets the freezing resistance requirements of the seasonal freezing areas, the freezing resistance of permeable concrete mixed with basalt fiber and VAE-707 emulsion was studied in this study. The conclusion drawn from the experiments showed that compared to the basic group show that under the premise of satisfying the water permeability, the compounding of 2 kg/m³ of basalt fiber and 2% VAE-707 emulsion can improve the frost resistance of the permeable concrete.

Key words:

basalt fiber, VAE-707 emulsion, permeable concrete, frost resistance

Prethodno priopćenje

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Eksperimentalno istraživanje otpornosti na smrzavanje poroznog betona s emulzijom kopolimera etilen vinil acetata i bazaltnim vlaknima

Posljednjih godina široka je primjena poroznog betona u urbanim poroznim kolničkim konstrukcijama. Međutim, otkriveno je u praksi da je pucanje poroznog betonskog kolnika u hladnim klimatskim područjima mnogo ozbiljnije zbog njegove slabije otpornosti na djelovanje smrzavanja, a fenomen ljuštenja je očigledan. Osim toga, uočeno je djelovanje vibracija uslijed kretanja vozila na zdravlje vozača osobnih automobila koji prometuju po gradskim cestama. Kako bi se postigao porozni beton koji zadovoljava zahtjeve otpornosti na smrzavanje u hladnim klimatskim područjima, u ovom se istraživanju proučio porozni beton s bazaltnim vlaknima i emulzijom VAE-707. Zaključak koji se izveo na temelju eksperimenata pokazuje da, ako je zadovoljeno svojstvo vodopropusnosti, rezultati pokazuju da uvođenje 2 kg/m³ bazaltnih vlakana i 2 % emulzije VAE-707 može poboljšati svojstvo otpornosti na djelovanje smrzavanja poroznog betona.

Ključne riječi:

bazaltna vlakna, emulzija VAE-707, porozni beton, otpornost na smrzavanje

1. Introduction

Permeable concrete comprises large gaps giving it good permeability. As a green environmental protection material, it is widely used in the construction of urban permeable pavements. However, the stresses exerted on the pavements are concentrated on the contact points between the aggregates, which impart strength to the concrete. The frost resistance of the permeable concrete often does not match the requirements. Especially in the Northeast, during low temperatures in winter, the subgrade and pavement get affected and the cracking of permeable concrete pavement occurs. Therefore, it is important to study the frost resistance of permeable concrete.

In recent years, with the intensive research in the development of permeable concrete, many scholars have studied the effects of water cement ratio, aggregate particle size, slurry aggregate quality ratio, sand ratio, mineral admixtures, and air entraining agents on the frost resistance of permeable concrete. Studies have shown [1] that these factors significantly influence the frost resistance of the permeable concrete, and the degree of influence is from strong to weak. Chen et al. [2] conducted freezing-thawing cycle tests on permeable concrete by using the quick-freezing method. They found that the freezing-thawing failure mode was mainly in the form of fractures, and some permeable concrete specimens could withstand 125 freezing-thawing cycles. Some studies have shown that adding a certain amount of admixtures to permeable concrete can enhance its performance. Vinyl acetate-ethylene copolymer emulsion (a VAE emulsion) has excellent adhesion, flexibility, weather resistance, acid and alkali resistance, film-formation properties and is also widely used in adhesives, external wall insulation, coatings, and other fields [3]. VAE emulsions have also been used in concrete to enhance the mechanical properties of cement mortars [4]. In addition, adding silica fume and fly ash to the permeable concrete also improves its frost resistance [5]. Yang [6] found that adding a certain amount of polypropylene acrylic (PNA) fiber and silica fume to permeable concrete can effectively improve the frost resistance of permeable concrete. However, with the advancing technology, many novel fibers are available. Among them, continuous basalt fibers (CBF), a novel, environmentally friendly, concrete reinforcement material, exhibits better mechanical properties, high-temperature resistance compared to other fibers [7]. The optimal length, diameter, and amount added to the basalt fiber can significantly improve the engineering properties, such as tensile strength, bending strength, impact and fatigue strength, as well as ductility, toughness, and cracking ability of the permeable concrete [8-10]. Huang [11] and Hasan Dilbas [12] et al. used scanning electron microscope images to analyze and evaluate the reinforcement mechanism and bonding status of fibers from a microscopic point of view. They found that the fibers traverse the micro-cracks and form a spatial network in the permeable concrete, playing a certain restrictive role when the micro-cracks expand, thereby improving the mechanical properties.

In summary, there are few studies on the simultaneous addition of basalt fiber and VAE-707 emulsion to permeable concrete. Given this background, this study is devoted to improving the frost resistance of permeable concrete and reducing pavement cracking by adding two admixtures, basalt fiber and VAE-707 emulsion to permeable concrete. It also provides an important theoretical basis for promoting the application of permeable concrete for practical engineering in seasonal frozen soil areas.

2. Experimental materials and methods

2.1. Experimental materials

Ordinary Portland cement P.O42.5 was used in this work. The main chemical components of cement are limestone, clay, and iron ore powder. According to the national industry standards "Determination of Cement Density" (GB/T 208-2014) and "Determination of Cement Specific Surface Area (Bureau method)" (GB/T8074-2008), the density is 3.1 g/cm^3 and the specific surface area is 380 m^3/kg. After experimental tests, the 3-day compressive strength and 3-day flexural strength of the cement were 25.2 MPa and 5.4 MPa, respectively. The initial setting time and the final setting time were 225 min and 275 min, respectively.

Single-graded ordinary crushed stone with a particle size of approximately 5–10 mm was used in the experiment. According to the national standard of The People's Republic of China, "Pebble and Gravel for Construction" (GB/T 14685-2011), the close-packed density of the coarse aggregate is 1630 kg/m^3 and the apparent density is 2720 kg/m^3.

The basalt fiber used in the experiment was produced by Tonghua Basalt Fiber (Group) Co., Ltd. The chopped basalt fiber has a length of 18 mm, a diameter of 14 μm, and a dosage of 2 kg/m^3, as shown in Figure 1. Its properties are listed in Table 1 (the properties are adopted by the manufacturer).

Figure 1. Chopped basalt fiber

Admixtures: The VAE-707 emulsion used in this experiment was a white paste, as shown in Figure 2, and its properties are listed in Table 2. The polycarboxylate acid system, superplasticizer with a water reducing rate of 37 %, was used in the experiment. The main component of silica fume used was 96.74 % SiO_2. The performance indicators of the above admixtures are adopted by the manufacturer.

Figure 2. VAE-707 emulsion

Table 1. Basalt fiber performance index

Diameter [μm]	Length [mm]	Density [g/cm³]	Tensile strength [MPa]	Elastic modulus [GPa]
14	18	2.65	3300-4500	95-115

Table 2. VAE-707 emulsion performance index

pH value	Non-volatile matter [%]	Viscosity [mPa·s]	Particle size [μm]	Ethylene content [%]
4,0-6,0	54.5	500-1000	2	16

2.2. Experimental method

2.2.1. Experiment preparation

For the specimen production, the mixture ratio is calculated by the volume method. The water-binder ratio was 0.3, the design porosity was 15 %, the silica fume content was 5 %, the water reducing agent content was 0.5 %, and the VAE-707 emulsion content was 2 % of the cementitious material. The mixing ratio of the four control groups is listed in table 3. Three specimens were made for each observation index of each mix ratio, and the average value of the three specimens was taken as the result.

Table 3. The mixing ratio of the four control groups

Group	Gravel [kg/m³]	Cement [kg/m³]	Silica fume [kg/m³]	Water reducing agent [kg/m³]	Water [kg/m³]	Fiber [kg/m³]	VAE-707 emulsion [kg/m³]
1	1597.4	392.73	20.78	2,08	124.68	-	-
2	1597.4	392.73	20.78	2,08	124.68	2	-
3	1597.4	377.22	20.39	2,04	122.34	-	8.16
4	1597.4	377.,22	20.39	2,04	122.34	2	8.16
Note: 1 - The basic group, 2 - the basalt fiber group, 3 - the VAE-707 emulsion group, 4 - the basalt fiber + VAE-707 emulsion group							

Table 4. Test program

Group	The properties tested	The standard	The number of samples
1 - No admixtures group	compressive strength-loss rate	≤ 20 % (after 25 freeze-thaw cycles)	24
	mass-loss rate	≤ 5 % (after 25 freeze-thaw cycles)	24
	relative dynamic elastic modulus	< 60 %	24
2 - Only added basalt fiber group	compressive strength-loss rate	≤ 20 % (after 25 freeze-thaw cycles)	24
	mass-loss rate	≤ 5 % (after 25 freeze-thaw cycles)	24
	relative dynamic elastic modulus	< 60 %	24
3 - Only added VAE-707 emulsion group	compressive strength-loss rate	≤ 20 % (after 25 freeze-thaw cycles)	24
	mass-loss rate	≤ 5 % (after 25 freeze-thaw cycles)	24
	relative dynamic elastic modulus	< 60 %	24
4 - Added basalt fiber + VAE-707 emulsion group	compressive strength-loss rate	≤ 20 % (after 25 freeze-thaw cycles)	24
	mass-loss rate	≤ 5 % (after 25 freeze-thaw cycles)	24
	relative dynamic elastic modulus	< 60 %	24

There were 8 freeze-thaw cycles in the experiment, so a total of 24 test pieces were required for each observation index. Details of the test program are listed in Table 4.

According to the research [13-15], the mixing and molding methods of the permeable concrete significantly affect the mechanical properties, water permeability, and frost resistance. The cement-wrapped stone method can completely wrap the aggregates with cement paste, effectively increasing the cohesiveness between the aggregates, thereby improving the early and late strength of the permeable concrete. Therefore, the mixing method used in this study is the cement-coated stone method. The aggregate and fiber were first added to the mixer and stirred for 30 s, then 20 % water was added for 30 s. Following this cement, silica fume, water reducing agent, and the remaining 80 % water were added, and the mixture was stirred for 150 s. The mixture obtained is shown in Figure 3.

Figure 3. Presentation of the obtained mixture

The equipment and process used in the experiment are shown in Figures 4 and 5. Compared with other molding methods, vibration molding is easy to operate and accounts for the mechanical properties and water permeability of the specimens. Therefore, the vibration molding method was selected for this work. During vibration molding, the concrete was placed in the test mold and placed on the vibrating table to vibrate. The specimens were removed after 8 s and then rolled with a Ø40 mm steel bar and smoothened with a spatula.

Figure 4. HJW-60 mixer

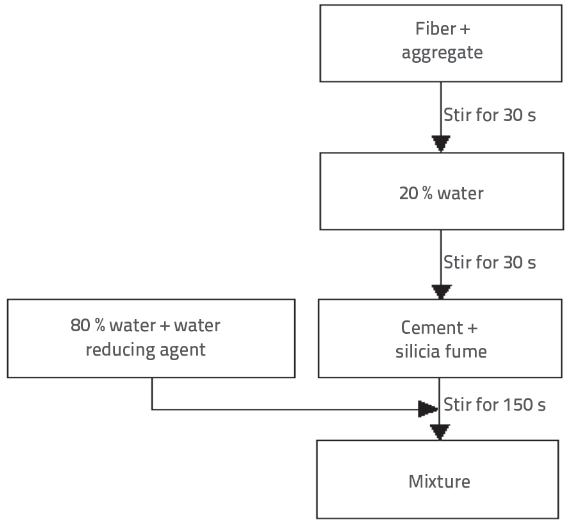

Figure 5. Flow chart of cement-wrapped stone method

As shown in Figure 6, after filling the mixture into a test mold of 100 mm × 100 mm × 100 mm size, the specimens are placed in a room for 48 h and then demolded. The demolded permeable concrete specimen is shown in Figure 7.

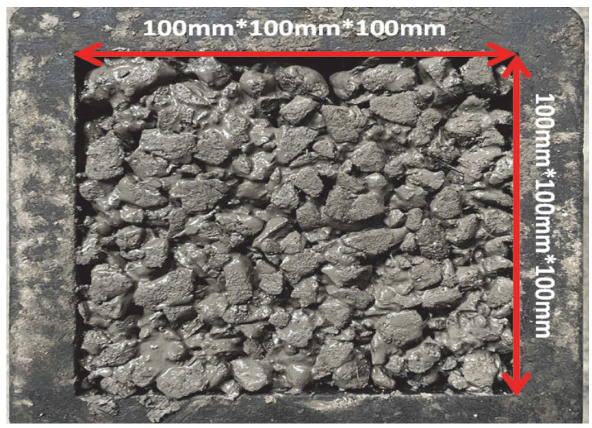

Figure 6. The concrete is placed in the test mold

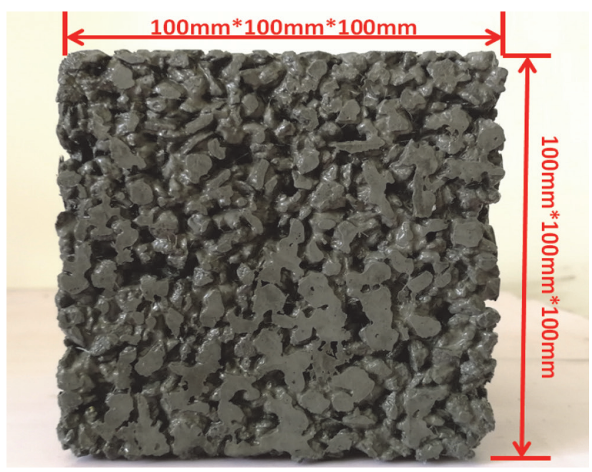

Figure 7. Basalt fiber permeable concrete specimen

The specimens were then placed in a room for 24 days for standard maintenance curing (temperature 20 ± 2 °C, relative humidity greater than or equal to 95 %). The specimens were then placed in 20 to 30 mm of water to cure for 4 days. After that, the specimens were placed in a dark room to dry, and the follow-up experiments were carried out.

2.2.2. Rapid freeze-thaw test

The freeze-thaw cycle experiment was first performed on the prepared specimens in order to compare the mass-loss rate, compressive strength-loss rate, and relative dynamic elastic modulus changes of the permeable concrete specimens after different freeze-thaw cycles. This freeze-thaw cycle test uses the laboratory quick-freezing method and places the specimens in the TDR-16 concrete quick freeze-thaw testing machine, as shown in Figures 8 and 9.

Figure 8. Rapid freeze-thaw testing machine

Before starting the experiment, the temperature mode of the freeze-thaw box was set. According to the "Standard for Long-term Performance and Durability Test Methods of Ordinary Concrete" GB/T50082-2009, it is observed that during the freeze-thaw cycle of the permeable concrete specimens, the central temperature of the specimen is the highest and the lowest, respectively, compared to the other parts, controlled within -18 ± 2 °C and 5 ± 2 °C. At any moment, the highest core temperature should not be higher than 7 °C, and the lowest should not be lower than -20 °C. Each freeze-thaw cycle time should be controlled within 2–4 hours, and the thawing time should not be less than a quarter of the total freeze-thaw cycle time. The samples after 0, 25, 50, 60, 70, 80, 90, and 100 freeze-thaw cycles of the specimens were taken for comparative analysis for changes in the mass loss rate, compressive strength loss rate, and relative elastic modulus.

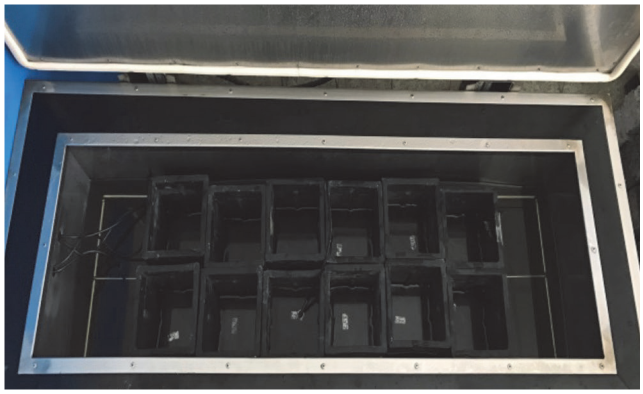

Figure 9. Internal structure of rapid freeze-thaw testing machine

2.2.3. Compressive strength loss rate experiment

The compressive strength was tested using a computer-controlled electro-hydraulic servo hydraulic press, as shown in Figure 10.

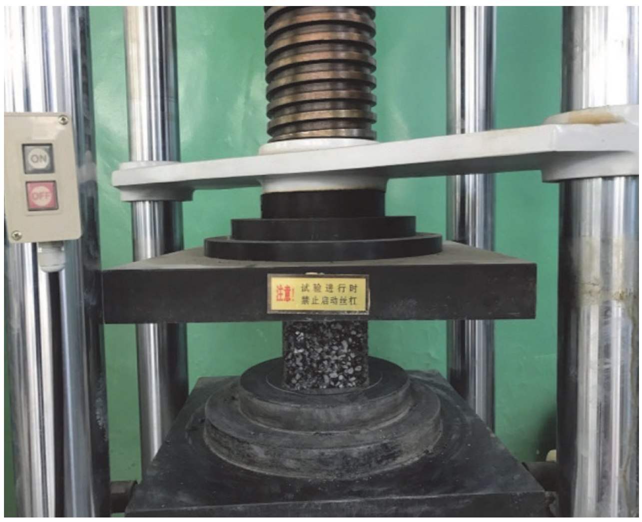

Figure 10. Compressive strength testing machine

The compressive strength tests on permeable concrete specimens with different control groups and freeze-thaw cycles were carried out. After the compressive strength was obtained, the compressive strength loss rate was calculated, and the expression of the compressive strength loss rate is shown in equation (1):

$$\Delta f_c = \frac{f_{c0} - f_{cn}}{f_{c0}} \times 100 \quad [\%] \tag{1}$$

where:
- Δf_c - strength loss rate of permeable concrete after N cycles [%]
- f_{co} - initial compressive strength of permeable concrete [MPa]
- f_{cn} - compressive strength of permeable concrete after N cycles [MPa]

2.2.4. Mass loss rate experiment

The mass-loss rate was calculated by weighing the mass of the permeable concrete specimens before and after the different freeze-thaw cycles, and the mass-loss rate is calculated according to the mass loss rate expression (2):

$$\Delta W_n = \frac{w_0 - w_n}{w_0} \times 100 \quad [\%] \tag{2}$$

where:
- ΔW_n - mass loss rate after N freeze-thaw cycles (accurate to the percentile [%]
- w_0 - the initial mass of the specimen before the freeze-thaw cycle [g]
- w_N - the mass of the specimen after N freeze-thaw cycles [g_0].

2.2.5. Relative dynamic elastic modulus experiment

The concrete ultrasonic detector was used to test the dynamic elastic modulus of the permeable concrete specimens after different freeze-thaw cycles, as shown in Figure 11. The instrument is mainly composed of a host machine and an ultrasonic probe. Its principle is to detect the internal continuity, integrity, uniformity, and other conditions of concrete through the comprehensive method of ultrasonic rebound and then evaluate the integrity of the specimen. Before the experiment, the coupling agent was coated on the probe part to ensure that there was no gap between the probe and the specimen, to improve the conduction effect, and reduce the noise. During the experiment, the probe was attached to the concrete specimen to be measured, and the conduction velocity of ultrasonic waves in the concrete could be seen through the host part. The ultrasonic transmission speed would decrease with an increasing degree of damage to the internal structure of the specimen. The degree of damage to the internal structure of the specimen can be evaluated by the conduction velocity of ultrasonic waves. The relative dynamic elastic modulus expression is shown in equation (3):

$$E_r = \frac{V_n^2}{V_0^2} \tag{3}$$

where:
- E_r - relative dynamic modulus of elasticity
- V_n - ultrasonic wave velocity after N freeze-thaw cycles [m/s]
- V_0 - initial wave velocity [m/s_0].

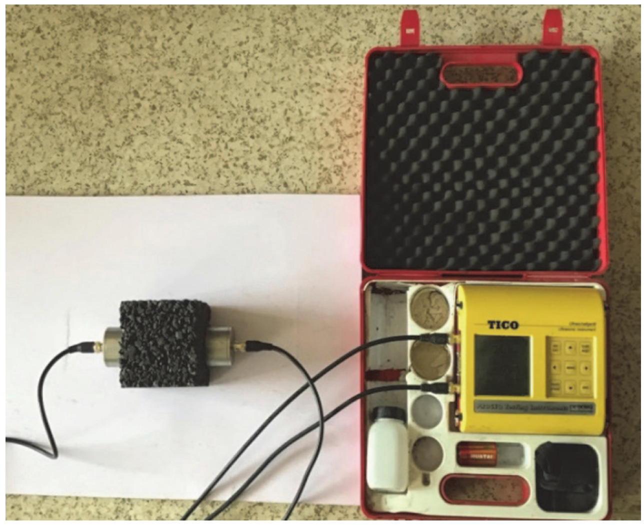

Figure 11. Concrete ultrasonic detector

3. Experimental results and analysis

3.1. Experimental results and analysis of compressive strength loss rate

The experimental results of the compressive strength of permeable concrete in the basic group, basalt fiber group, VAE-707 emulsion group, and basalt fiber + VAE-707 emulsion group are shown in Table 5. From the experimental data, it can be concluded that when 2 kg/m^3 of basalt fiber is mixed alone, the compressive strength loss rate of the permeable concrete compared with the basic group is reduced by 6 %. When 2 % of the VAE-707 emulsion is mixed alone, the compressive strength of the permeable concrete decreases by 8 % compared with the basic group. When 2 kg/m^3 of basalt

Table 5. Compressive strengths of the specimens after different freeze-thaw cycles in different control groups

Compressive strength of samples after different cycles of freezing and thawing [MPa]								
Group	**0 cycles**	**25 cycles**	**50 cycles**	**60 cycles**	**70 cycles**	**80 cycles**	**90 cycles**	**100 cycles**
1	23.78	22.77	21.31	20.2	18.99	17.72	16.7	15.91
2	25.84	24.95	23.74	22.67	20.92	19.97	19.35	18.96
3	20.7	20.09	19.41	18.46	17.43	16.6	15.85	15.51
4	21.49	20.97	20.32	19.6	18.6	17.61	16.97	16.67

Note: 1 - The basic group, 2 - the basalt fiber group, 3 - the VAE-707 emulsion group, 4 - the basalt fiber + VAE-707 emulsion group fiber and 2 % of VAE-707 emulsion were mixed, the compressive strength loss rate of the permeable concrete compared with the basic group was reduced by 11 %.

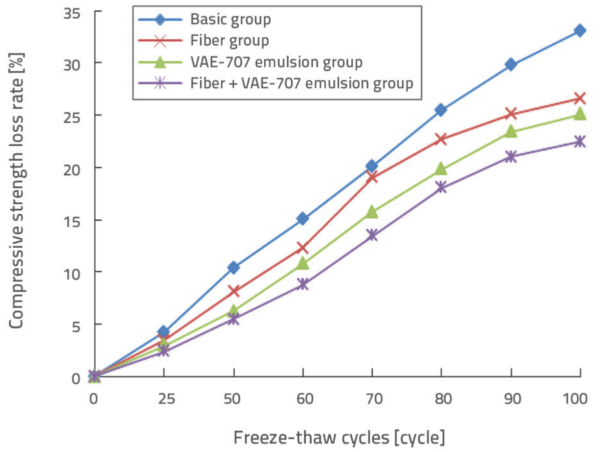

Figure 12. Comparison of compressive strength loss rate of different control groups

According to the "Technical Specification for Permeable Cement Concrete Pavement "(CJJ/T 135-2009), the frost resistance of the permeable cement concrete should meet the compressive strength loss rate of less than or equal to 20 % after 25 freeze-thaw cycles. It can be seen from Figure 12 that the compressive strength loss rates of the four different control groups all meet the requirements of the specification, but with the continuous increase in the number of freeze-thaw cycles, the compressive strength loss rate of permeable concrete is also increasing. The loss rate of compressive strength in the basic group reached 20 % after 70 freeze-thaw cycles. The loss rate of compressive strength in the fiber group reached 20 % between 70 and 80 freeze-thaw cycles. And the loss rate of compressive strength in the VAE-707 emulsion group reached 20 % after 80 freeze-thaw cycles. Compared to the other three groups, the compressive strength loss rate of the fiber + VAE-707 emulsion group is significantly reduced, and the loss rate reaches 20 % when the freeze-thaw cycle is about 90 cycles, which is about 20 cycles higher than the number of antifreeze in the basic group and about 10 cycles higher than the number of antifreeze in the fiber and VAE-707 emulsion group. Wang [16] and Bai et al. [17] concluded that after adding VAE polymer emulsion into permeable concrete, the gelation time of the cementing material could be significantly prolonged, the gelation effect can be significantly improved, and the internal microstructure of concrete can be influenced to a certain extent. A certain amount of VAE polymer emulsion can significantly improve the compressive strength of concrete.

At the same time, compared with the basic group, the rate of increase in the compressive strength-loss rate of the other three groups after 80 freeze-thaw cycles significantly slowed down. This is due to the addition of VAE-707 emulsion, which affects the hydration reaction in the concrete as well as the hardening process. It can not only prevent the rapid loss of moisture in the cement mortar, resulting in stronger aggregate adhesion, but also in the hydration reaction of cement, and when combined with $Ca(OH)_2$ generated by the hydration reaction, it forms a gel which can fully encapsulate the aggregate, resulting in significantly improved aggregate bondability. In addition, Akand et al. [18] studied the influence of fiber on the microstructure strength and stiffness of the permeable concrete by establishing a model and concluded that fiber delayed the generation of cracks and improved the strength of the permeable concrete matrix. It is observed that with the increase of compressive strength, the permeable concrete begins to produce micro-cracks. At this time, the fiber acts as a "bridge," effectively preventing the rapid expansion of micro-cracks. From the above analysis, it can be concluded that the compounding of basalt fiber and VAE-707 emulsion can effectively improve the frost resistance of the permeable concrete.

3.2. Experimental results and analysis of mass-loss rate

Table 6 lists the masses of permeable concrete in the basic group, the basalt fiber group, the VAE-707 emulsion group, and the basalt fiber + VAE-707 emulsion group. It can be seen from the table that when 2 kg/m^3 of basalt fiber is mixed alone, the mass-loss rate of the permeable concrete is reduced by 0.5 % compared to the basic group. When the 2 % VAE-707 emulsion is mixed, the mass-loss rate of the permeable concrete is reduced by 1.2 % compared with the basic group. When compounded with 2 kg/m^3 of basalt fiber and 2 % of VAE-707 emulsion, the mass-loss rate of the permeable concrete compared with the basic group is reduced by 1 %.

According to the "Technical Specification for Permeable Cement Concrete Pavement" (CJJ/T 135-2009) regulations, the frost

Table 6. The measured mass after different freeze-thaw cycles in different control groups

Group	Measured mass after a certain number of freezing and thawing cycles [g]							
	0 cycles	25 cycles	50 cycles	60 cycles	70 cycles	80 cycles	90 cycles	100 cycles
1	2159.7	2155.2	2149.5	2142.9	2134	2126.9	2117.2	2106.4
2	2177	2173.1	2170.2	2165.5	2157.2	2150.2	2140.6	2133.9
3	1971.9	1968.4	1966.2	1964.2	1957.7	1952.9	1949.4	1946.7
4	2133.3	2130.8	2129.7	2127.1	2123.3	2117.9	2113	2109.4

resistance of permeable cement concrete should satisfy the mass-loss rate of less than or equal to 5 % after 25 freeze-thaw cycles. The results show that as the number of freeze-thaw cycles increases, the mass-loss rate of the four control groups also increases to varying degrees, which shows that after the freezing and thawing cycle for a certain number of cycles, the surface material of the permeable concrete begins to get damaged, and an apparent flaking phenomenon will occur. As the number of freeze-thaw cycles increases, the interior of the concrete will also be destroyed, and freeze-thaw damage will occur when the freeze-thaw reaches a certain level. It can be seen from Figure 13 that the mass loss rate of the four groups does not reach 5 % even after 100 freeze-thaw cycles, meeting the requirements of the antifreeze performance. However, the rate of change in mass loss gradually slowed down after 80 freeze-thaw cycles for the VAE-707 emulsion and the fiber + VAE-707 emulsion group compared to the basic and the fiber group, indicating that the addition of VAE emulsion improved the bonding performance between the cement paste and aggregate, thereby slowing down the peeling and damage of the permeable concrete.

Studies have shown [19-21] that the VAE emulsion is an environmentally-friendly material with good adhesion, weather resistance, acid and alkali resistance, and other properties. It is widely used in adhesives, coatings, and other fields. As an admixture, VAE emulsion can be used in permeable concrete to compensate for the microstructure defects in the cement stone and prevent the occurrence and development of microcracks. It can also be seen from Figure 4.2 that after 100 freeze-thaw cycles, the mass-loss rate of the basic group reaches 2.5 %, for the fiber group reaches 2 %, and for the VAE-707 emulsion group is lower than 2 % and higher than 1 %. The fiber + VAE-707 emulsion group has the least mass loss rate, only 1 %. Overall, the fiber + VAE-707 emulsion group exhibits a slower increase in mass-loss rate than the other three groups. It is observed that the compounding of basalt fiber and VAE-707 emulsion, significantly reduces the mass loss rate, thereby effectively improving the frost resistance of permeable concrete.

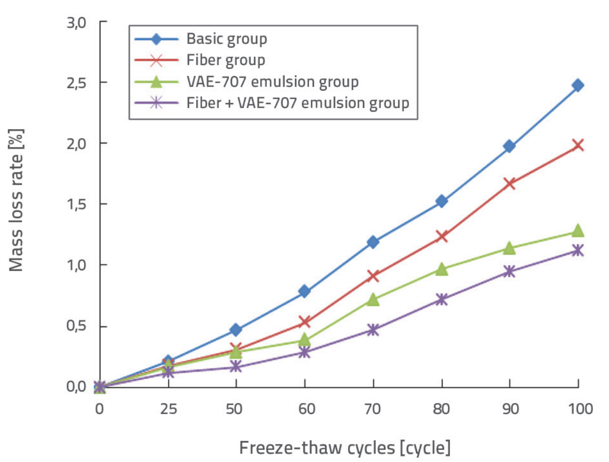

Figure 13. Comparison of mass-loss rate of different control groups

3.3. Experimental results and analysis of relative dynamic elastic modulus

Studies have shown that the relative dynamic elastic modulus as an indicator of concrete durability has high reliability [22]. At present, the methods of measuring the dynamic elastic modulus of concrete mainly include the resonance method, the ultrasonic method, and the shock elastic wave method. Among them, the resonance method cannot measure the dynamic elastic modulus of concrete on site, while the principle of the shock elastic wave method is the same as that of the ultrasonic method, and the dynamic elastic modulus of concrete is calculated by measuring the elastic wave velocity inside the concrete [23]. It is generally believed that when the relative dynamic elastic modulus of concrete is less than 60 %, it is deemed to have reached a freeze-thaw failure state.

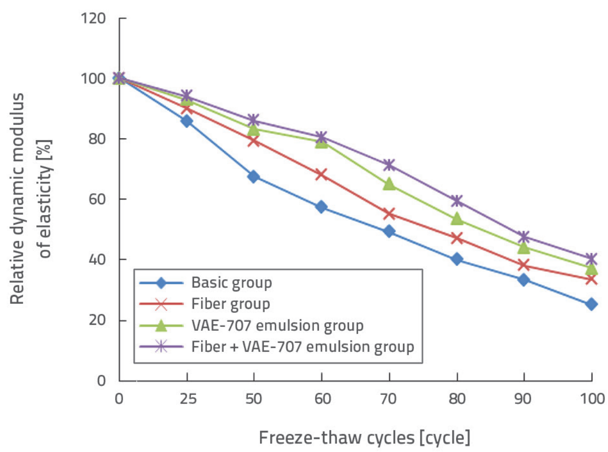

Figure 14. Comparison of relative dynamic elastic modulus of different control groups

Figure 14 is a comparison chart of four sets of relative dynamic elastic modulus. According to the relative dynamic elastic modulus analysis, when 2 kg/m^3 basalt fiber is mixed alone, the relative dynamic elastic modulus of permeable concrete increases by 8 % compared to the basic group. When 2 % VAE-707 emulsion is mixed, the relative dynamic elastic modulus increases by 12 % compared with the basic group of permeable concrete. When 2 kg/m^3 of basalt fiber and 2 % VAE-707 emulsion are mixed, the compressive strength loss rate compared with the basic group of permeable concrete is reduced by 11 %. In addition, when the freeze-thaw cycles are 50–60 cycles, the relative dynamic elastic modulus of the basic group first reaches 60 %, and freeze-thaw failure occurs. During the freeze-thaw cycle of 60-70 cycles, the relative dynamic elastic modulus of the fiber group reaches 60 %, reaching the state of freeze-thaw failure. The relative dynamic elastic modulus of the emulsion group increases compared with the former two groups, reaching 60 % between 70-80 freeze-thaw cycles, reaching the state of freeze-thaw destruction. While basalt fiber and VAE-707 emulsion groups have the strongest resistance to freeze-thaw damage, the relative dynamic elastic modulus reaches 60 % when the freeze-thaw cycle is about 80 cycles, and freeze-thaw damage occurs.

The relative dynamic elastic modulus of the different control groups all show a decreasing trend as the number of freeze-thaw cycles increases. This is because the internal structure of the permeable concrete has been damaged as the number of freeze-thaw cycles increases and the micro-cracks appear on the interface, causing the phenomenon of shedding between the cement and the aggregate, thereby reducing the integrity of the permeable concrete. However, basalt fiber added to permeable concrete can play the role of a "bridge" and improve the strength of the permeable concrete. The intricate distribution of fibers can resist the frost-heave force generated by the freezing and expansion of water in the permeable concrete and delay the migration of moisture in the internal pores of the concrete, inhibiting the generation of cracks, so as to slow down the internal destruction speed of permeable concrete. In addition, the blending of emulsion also has a more noticeable impact. Lou [24] found that the relative dynamic elastic modulus of the permeable concrete specimens blended with VAE-707 emulsion was higher than that of the basic control group. It shows that VAE-707 emulsion played a stabilizing role in the internal structure of the permeable concrete under freezing and thawing conditions. In summary, the frost resistance of permeable concrete significantly improved due to the combined action of basalt fiber and VAE-707 emulsion.

4. Conclusion

Conclusions are drawn from the comparative analysis of the compressive strength-loss rate, mass-loss rate, and relative elastic modulus after different freezing and thawing cycles for the permeable concrete in four different control groups, namely the basic group, basalt fiber group, VAE-707 emulsion group, and basalt fiber + VAE-707 emulsion group:

- Compared with the basic group of permeable concrete, the single mixed basalt fiber has a certain degree of influence on the frost resistance of permeable concrete. After 80 freeze-thaw cycles, the increase in compressive strength-loss rate was less. After 100 freeze-thaw cycles, compared with the basic group, the compressive strength-loss rate and mass-loss rate were reduced by 6.5 % and 0.5 %, respectively. The relative dynamic modulus of elasticity increased by 8.4 %. Thus indicating that the incorporation of basalt fiber could significantly increase the strength of permeable concrete and enhance the toughness and ductility of permeable concrete.
- Compared with the basic group and the fiber group, the antifreeze performance of permeable concrete was further improved by the addition of the VAE-707 emulsion. After 100 freeze-thaw cycles, the compressive strength-loss rate and mass-loss were reduced by 8.0 % and 1.19 % compared with the basic group, and the relative dynamic modulus of elasticity was increased by 12.07 %. Compared with the fiber group, the compressive strength-loss rate and mass-loss rate were reduced by 1.54 % and 0.7 %, respectively, and the relative dynamic modulus of elasticity was increased by 3.63 %. It was found that VAE emulsion used in permeable concrete compensated for the microstructure defects in the cement stone and prevented the occurrence and development of microcracks.
- The composite fiber + VAE-707 emulsion further enhanced the frost resistance of the permeable concrete. Compared with the basic group, the compressive strength-loss rate and mass-loss rate decreased by 10.6 % and 1.35 %, respectively, after 100 freeze-thaw cycles, and the relative dynamic modulus of elasticity increased by 15.1. The combined effect of basalt fiber and VAE-707 emulsion on permeable concrete improves the anti-freezing performance of permeable concrete through the inhibition of the expansion of internal micro-cracks by the fiber and the bonding effect of the emulsion on internal aggregate.
- Among the four different control groups set up in the experiment, the basic group reached freeze-thaw failure after 50–60 freeze-thaw cycles. The fiber group reached freeze-thaw failure after 60 to 70 cycles. The VAE-707 emulsion group reached the freeze-thaw failure after 70–80 cycles. The fiber + VAE-707 emulsion group reached the freeze-thaw failure after 70–80 cycles. The first indication to reach the freeze-thaw failure condition was the relative dynamic elastic modulus for all the groups. The compounding of 2 kg/m^3 of basalt fiber and 2 % of VAE-707 emulsion effectively improved the frost resistance of permeable concrete, and the compressive strength-loss rate and mass-loss rate met the requirements of the specification.

Research on the frost resistance of permeable concrete mixed with different materials shows that under the combined action of basalt fiber and VAE-707 emulsion, the anti-freezing performance of permeable concrete can be improved through the inhibition of the expansion of internal micro-cracks by the fiber and the bonding effect of the emulsion on internal aggregate. Therefore, the addition of 2 kg/m^3 basalt fiber and 2 % VAE-707 emulsion successfully improved the frost resistance of permeable concrete.

Acknowledgements

This study is financially supported by the Science and Technology Development Project of Jilin Province: Research on key technology of application of basalt fiber permeable concrete in permeable pavement of sponge city in the seasonal frozen area [grant numbers 20210203143SF]. We would like to express our sincere thanks to the anonymous reviewers for their valuable suggestions and constructive comments, which greatly improved the presentation of this study.

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