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Research paper

Research on the compressive strength properties of expanded perlite concrete under alternating temperatures

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Abstract: In order to study the compressive strength performance of expanded perlite concrete under low-temperature alternating action, different mixing ratios, mesh sizes, and temperatures were selected as research parameters in this paper using 90–120 mesh, in vitro incorporation at 0%, 10%, 20%, 30%, and 40%. The external mixing ratio of 30% was used, with mesh sizes of 30–50, 50–70, 70–90, and 90–120 mesh. The low-temperature alternating temperature was –20°C and 20°C, and 16 groups of 48 test blocks were designed and manufactured. Concrete compressive strength tests and SEM interface scanning tests were conducted. The results showed that the compressive strength of expanded perlite concrete with 90–120 mesh external addition was higher than that of ordinary concrete, and showed a trend of first increasing and then decreasing with the increase of external rate. When the external ratio was 30%, the compressive strength value was the highest, the compressive strength value increases with the increase of expanded perlite mesh size. Under low-temperature alternating action, the compressive strength values of expanded perlite concrete decrease. When using 90–120 mesh, the compressive strength loss rate gradually decreases with the increase of external mixing rate. When the external mixing ratio was 30%, the compressive strength loss rate was 9.16%, but still higher than that of ordinary concrete. Combining SEM to scan the concrete interface, the failure mechanism of the internal structure of expanded perlite concrete was explained from a microscopic perspective, confirming the rationality of the experimental data. According to the actual test results, it is proposed that using expanded perlite concrete with a 90–120 mesh addition ratio of 30% can effectively improve its compressive and frost resistance properties.

Keywords: expanded perlite, concrete, high low temperature change, compressive strength, SEM analysis

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1. Introduction

According to the January isotherm distribution map released by the China Meteorological Administration, the meteorological temperatures in northern cities such as Harbin, Changchun, Hohhot, and Urumqi are around –20°C, while in July, they rise to around 20°C. The low-temperature environment imposes high requirements on energy-saving and thermal insulation materials for buildings, and it significantly affects the microstructure and mechanical properties of concrete [1–3].

Currently, Expanded Perlite (EP) is widely promoted and applied due to its advantages,such as low cost, the energy conservation, environmental protection, lightweight thermal insulation [4–6], good durability, and seismic performance [7]. Gao et al. selected 20–30 mesh EP to replace a certain amount of sand, finding that when the replacement rate is 20%, the basic mechanical properties of EP concrete are optimal [8]. Sun et al. demonstrated that the incorporation of EP can compensate for the shrinkage of cement mortar in the early stages. As the EP content increases, the shrinkage rate decreases, and the mechanical properties gradually decline. Excessive incorporation, however, can reverse this trend and increase the shrinkage rate [9]. Liu et al. used EP as an internal curing material and studied the effects of EP volume mixing ratio, pre-wetting rate, and particle size on the growth of concrete compressive strength. Internal curing can enhance the compressive strength of concrete and its growth rate, with the growth rate first decreasing and then increasing. Larger EP particle sizes result in faster initial growth ratio, stabilizing later, while smaller particle sizes show the opposite trend [10]. Cheng et al. selected temperature, steel fiber volume fraction, and EP replacement rate as research parameters. Their study revealed that temperature had the most significant impact on the mechanical properties of steel fiber-reinforced EP concrete, followed by steel fiber volume fraction, in contrast,the EP replacement rate had a relatively minor effect on both the tensile and compressive strength of the concrete [11]. Song et al. investigated the degradation and deterioration laws of concrete materials under “artificial climate” freeze-thaw cycles. With an increase in the number of freeze-thaw cycles, the compressive strength of concrete gradually decreases at a roughly constant rate. The study indicated that increasing the strength grade of concrete is beneficial to its frost resistance [12]. Zhao et al. used residue as a mineral admixture to investigate the effects of different proportions of residue content (0%, 2.5%, 5.0%, 7.5%, and 10.0%) on the workability and mechanical properties of C50 concrete [13].

Currently, there is limited research on the effects of EP external mixing ratio and EP mesh size on the mechanical properties of EP concrete under alternating temperature conditions. In consideration of the application of EP concrete in northern construction engineering, this paper first examines the impact of EP external mixing ratio and mesh size on the mechanical properties of concrete. Secondly, it investigates the influence of temperature alternation on the mechanical properties of EP concrete. Three variables – different temperatures, EP external mixing ratios, and mesh sizes – are selected. The concrete is subjected to alternating temperature curing at –20°C and 20°C to simulate the impact of low-temperature environmental alternations on the compressive performance of EP concrete in practical construction. SEM scanning electron microscopy is used to analyze changes in the internal structure of concrete after temperature alternation. Based on the measured data, it is proposed that using a 30% mixing ratio and 90–120 mesh EP can effectively improve the compressive performance of concrete. This provides a reference basis for the preparation and application of EP concrete insulation materials in cold regions.

2. Experimental scheme

2.1. Test materials

The cement used in the test is ordinary Portland cement produced by xinyang huaxin cement plant. The coarse aggregate is crushed stone from mines, and the fine aggregate is natural river sand. The mixing water is tap water. The expanded perlite has particle sizes ranging from 30–50, 50–70, 70–90, and 90–120 mesh, sourced from Xinyang Baichuan Mining Co., Ltd. To further investigate the chemical composition of the expanded perlite, an XRD diffraction pattern analysis was conducted. The diffraction results indicate that the main components of the perlite are SiO_2, Al_2O_3, Fe_2O_3, CaO, K_2O, Na_2O, MgO, H_2O (to be filled in based on the actual XRD results). Through XRF testing, it was found that the chemical composition of the expanded perlite contains some active substances. The chemical composition of the perlite (by mass fraction) is presented in Table 1.

Table 1. Chemical composition of expanded perlite

Ingredient	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**K_2O**	**Na_2O**	**MgO**	**H_2O**
content (%)	73%	11%	3.2%	0.8%	3%	4.5%	0.3%	4.2%

2.2. Experimental design

Literature [10] shows that concrete with a 30% external admixture ratio of Expanded Perlite (EP) achieves the same compressive strength as ordinary concrete in 56 days, this experiment employs a 30% external admixture ratio of EP. Using different particle sizes of EP (30–50, 50–70, 70–90, 90–120 mesh) as the research parameter, ten groups, totaling 30 cubic specimens with dimensions of 150 × 150 × 150 mm, were prepared. These specimens are used to investigate the effect of different EP particle sizes and low-temperature alternating conditions on the compressive strength of EP concrete.

Given that XRF analysis detected active substances in the chemical composition of the expanded perlite, this experiment utilizes EP with a particle size of 90–120 mesh. With the external admixture ratio of EP (0%, 10%, 20%, 30%, 40%) as the research parameter, ten groups, totaling 30 cubic specimens with dimensions of 150 × 150 × 150 mm, were prepared. These specimens are used to study the impact of different external admixture ratios and low-temperature alternating conditions on the compressive strength of EP concrete.

Since concrete maintains a relatively consistent level of damage after being frozen for three days, this experiment involves alternating curing cycles in environments of –20°C and 20°C, with 12-hour intervals (12 hours of freezing followed by 12 hours of thawing), for a total of three cycles over three days. This setup is used to explore the influence of varying EP external admixture ratios and particle sizes on the compressive strength of concrete under alternating temperature conditions. The experimental mix design is presented in Table 2.

Table 2. Test mix ratio

Test number	**Pebble (kg)**	**Sand (kg)**	**Cement (kg)**	**Water (kg)**	**Water cement ratio**	**EP mesh number (90–120) amount of admixture (%)**	**EP mesh number (30%) amount of admixture**
1	1211.38	519.16	520.06	272.46	0.52	0	–
2	1211.38	519.16	520.06	272.46	0.52	10	30–50
3	1211.38	519.16	520.06	272.46	0.52	20	50–70
4	1211.38	519.16	520.06	272.46	0.52	30	70–90
5	1211.38	519.16	520.06	272.46	0.52	40	90–120

2.3. Test casting and loading

The process of casting the experimental cubic concrete specimens is illustrated in Fig. 1. Concrete samples with different particle sizes and external admixture ratios of expanded perlite were prepared and subjected to natural curing for 28 days. To ensure that the interior of the specimens reached the target temperature under low-temperature conditions, they were soaked in water for four hours on the 24th day, satisfying the requirements for a single water-freezing environment. After the low-temperature alternating treatment, the specimens were loaded for testing.

The test employed a YAW-2000 kN compression testing machine manufactured by Jinan Zhonglu Chang Test Machine Manufacturing Co., Ltd. for loading. Scanning was conducted using a Zeiss Sigma 500 scanning electron microscope. Low-temperature curing was achieved using a DWX-40-170 low-temperature test chamber produced by Zhong Sitrong Measurement and Control Technology Co., Ltd. The test methods followed the standards outlined in GB/T 50081-2019 “Standard for test methods of mechanical properties of ordinary concrete”.

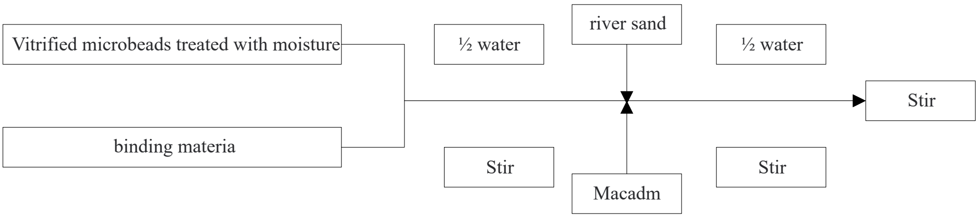


Fig. 1. Concrete specimen making process

3. Test phenomena and results

3.1. Compressive strength results of specimens

The measured values of the compressive strength of the specimens are presented in Tab. 3. Here, $f_{\mathrm{cu},t}$ represents the compressive strength value of the EP concrete cubes, R_{cu} denotes the ratio of the compressive strength of the EP concrete cubes to that of ordinary concrete cubes, and P_{cu} indicates the rate of change in the compressive strength of the EP concrete cubes relative to ordinary concrete cubes, where positive values represent an increase and negative values represent a loss.

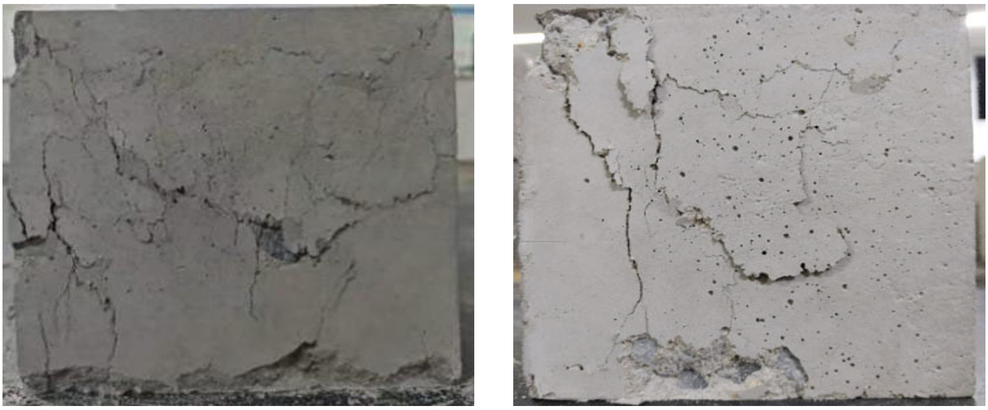
Table 3. Compressive strength results of specimens

Specimen number	$f_{\mathrm{cu},t}$ **(MPa)**	R_{cu}	P_{cu} **(%)**
C-EP-M0C0	32.90	1.000	0.00
C-T20-EP-M0C0	34.20	1.040	3.95
C-EP-M90–120C0.1	35.00	1.064	6.38
C-T20-EP-M90–120C0.1	30.95	0.905	–5.93
C-EP-M90–120C0.2	35.30	1.073	7.29
C-T20EP-M90–120C0.2	31.47	0.920	–4.35
C-EP-M90–120C0.3	36.60	1.112	11.25
C-T20-EP-M90–120C0.3	33.62	0.983	2.19
C-EP-M90–120C0.4	35.70	1.085	8.51
C-T20-EP-M90–120C0.4	36.39	1.064	10.61
C -EP-M30–50C0.3	24.47	0.744	–25.62
C-T20-EP-M30–50C0.3	22.20	0.649	—32.52
C-EP-M50–70C0.3	25.63	0.779	–22.10
C-T20-EP-M50–70C0.3	24.54	0.718	–25.41
C-EP-M70–90C0.3	27.37	0.832	–16.81
C-T20-EP-M70–90C0.3	26.63	0.779	–19.06

Note: The specimen codes in the table have the following meanings: The first letter "C" represents a concrete cube compressive specimen; the second letter "T" indicates temperature alternating curing; the third letter "EP" stands for Expanded Perlite; the fourth letter "M" signifies Mesh (particle size), and the fifth letter "C" denotes the external admixture content of the concrete block. Therefore, "C-T20EP-M90-120C0.1" represents an EP concrete specimen with a particle size of 90–120 mesh, an external admixture ratio of 10%, and subjected to low-temperature alternating curing.

3.2. Compressive strength and appearance phenomena of specimens

From Table 3, the concrete with an external admixture ratio of 30% and EP (30–50 mesh) exhibited the highest compressive strength loss rate of 32.52%, while the concrete with an external admixture ratio of 30% and EP (90–120 mesh) showed the highest compressive strength increase rate of 11.25%. Representative images of the failure modes of the specimens under loading are shown in Fig. 2. The loading process is divided into three stages: early, middle, and late, with the boundaries set at 30% and 70% of the ultimate load value.



(a) (b)

Fig. 2. Failure pattern of cube test block: (a) C-EP-M0C0, (b) C-EP-M30-50C0.3

Figure 2(a) illustrates a control group consisting of standard concrete specimens that was subjected to curing at room temperature for a duration of 28 days. During the initial phase of loading, it was observed that there were no considerable alterations or changes visible on the surface of the concrete. However, as the load was incrementally increased and the loading process entered the intermediate and subsequent stages, a gradual increase in the number of micro-cracks on the surface of the concrete became evident. Despite this, no pronounced vertical through-cracks were formed that would indicate significant structural failure. In contrast, Figure 2(b) depicts the experimental polymer (EP) concrete specimens, which is characterized by their surfaces that are peppered with numerous tiny pores. During the early stages of loading, these specimens exhibited micro-cracks that emerged around the aforementioned pores. As the loading process advanced into the middle and later stages, a substantial proliferation of micro-cracks was observed. These micro-cracks continued to expand and eventually interconnected, forming a network of intersecting through-cracks that extended in both vertical and horizontal directions. This extensive cracking penetrated deep into the internal structure of the specimens, ultimately resulting in the detachment and peeling off of the surface mortar layer.

Figures 3 refer to the results of failure pattern of cubic specimens after low-temperature exposure, The microscopic analysis was shown in Figure 9.

(a) (b)

Fig. 3. Damage pattern of cube test block after low temperature action: (a) C-EP- M90-120C0.3, (b) C-T20-EP- M90-120C0.3

Figure 3(a) illustrates an EP concrete specimen that has been cured at room temperature for a duration of 28 days. Throughout the initial and intermediate phases of the loading process, it was observed that there were a limited number of micro-cracks and through-cracks that began to form on the surface of the concrete. As the loading process entered its later stages, it became evident that cracks started to emerge at the corners of the specimen and progressively extended towards the center of the specimen. Conversely, Figure 3(b) portrays an EP concrete specimen subsequent to experiencing a low-temperature alternating treatment. During the early stages of loading, a substantial quantity of micro-cracks became apparent on the surface of the specimen. Progressing into the middle stages of loading, these micro-cracks experienced rapid development and subsequently evolved into vertical through-cracks, which led to the detachment of the surface mortar. As the loading process reached its final stages, the cracks on the surface extended further into the interior of the specimen, ultimately resulting in the disintegration of the specimen due to the separation of coarse and fine aggregates.

4. Analysis of test results

4.1. Effect of EP particle size and the admixture ratio on compressive strength

Based on the measured compressive strength values of the specimens in Table 3, the influence curves of different EP particle sizes and admixture ratios on compressive strength were shown (Fig. 4, Fig. 5).

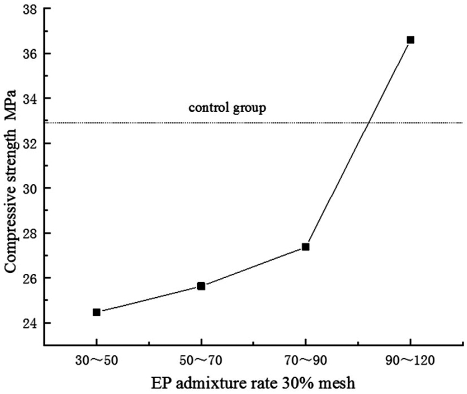


Fig. 4. Measured compressive strength of EP with 30% admixture rate

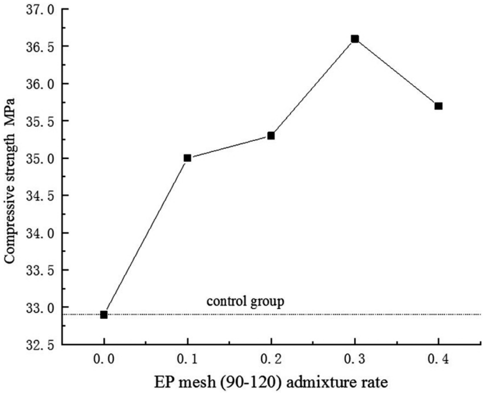


Fig. 5. Measured compressive strength of EP mesh (90–120)

From Fig. 4, it can be observed that when the external admixture ratio of EP is 30%, the measured compressive strength values show an increasing trend with the increase in the mesh size of the concrete. This is because smaller mesh sizes of Expanded Perlite (EP) have larger particle sizes, which impede effective cohesion between the concrete aggregates. Coupled with the low compressive strength of EP itself, this results in a reduction in the compressive strength of the specimens. The ring growth rates of compressive strength from 30–50 mesh to 70–90 mesh is 4.74% and 6.79%, respectively, which are basically consistent. From 70–90 mesh to 90–120 mesh, the ring growth rate of compressive strength is 33.72%, exceeding the compressive strength value of the control group. This is attributed to the fact that 90–120 mesh EP contains certain active substances, which enhances the cementitious effect between the aggregates. Moreover, the smaller particles fill the internal pores of the specimens caused by the process and materials, thereby increasing the compressive strength of the concrete. This also corroborates the observation that the specimens with 90–120 mesh have fewer visible cracks under compression than the control group.

From Fig. 5, it is evident that when using EP with a mesh size of 90–120, the measured compressive strength values all exceed those of the control group, and they show a trend of first increasing and then decreasing with the increase in the external admixture ratio of the concrete. When the external admixture ratios are 0%, 10%, 20%, and 30%, the ring growth rates are 6.4%, 0.9%, and 3.7%, respectively, indicating a significant enhancement effect at an external admixture ratio of 10%. At an external admixture ratio of 30%, the compressive strength reaches a maximum of 36.6 MPa. When the external admixture ratio is 40%, the compressive strength decreases to 35.7 MPa. The reason for this is that 90–120 mesh EP contains certain active substances, which can partially act like cement. An appropriate amount of EP provides internal curing conditions due to its water absorption, reducing the drying shrinkage and cracking of the concrete, thereby improving its strength. However, when the external admixture ratio of 90–120 mesh EP exceeds 30%, as it is an external admixture, excessive amounts will occupy the volume of cement and fine aggregates in the specimens, leading to a reduction in their content. The internal curing effect cannot offset the adverse impact of EP on compressive strength, resulting in a decrease in the compressive strength of the specimens. The results indicate that the optimal external admixture ratio of EP concrete should be controlled at around 30%, which can balance the internal curing effect and the volumetric contribution of increased cementitious materials.

4.2. Influence of low temperature alternations on the compressive strength of EP mesh

Figure 6 shows the compressive strength values of EP concrete after low- temperature alternating curing are all lower than those under standard curing conditions. When EP (90–120) mesh admixture the external admixture ratios are 0, 0.1, 0.2, 0.3, and 0.4, the loss rates are 8.57%, 12.34%, 11.29%, 8.87%, and 3.10%, respectively. The reasons for this are as follows.

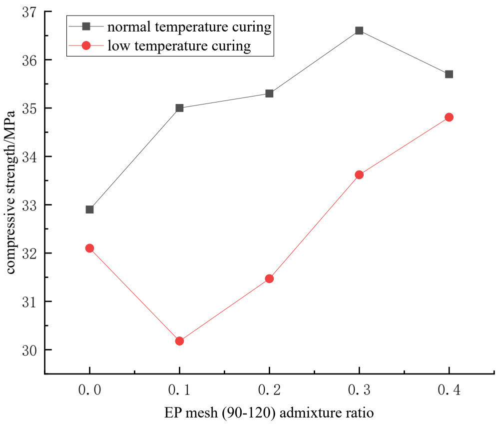


Fig. 6. Strength of concrete test block after 28 d of low temperature alternations with different dosage of 90–120 mesh

Firstly, due to material properties and unfavorable manufacturing processes during specimen preparation, air bubbles and pores form within the specimens, creating initial defects. Secondly, after low-temperature curing, the free water in the bubbles and pores freezes, causing volumetric expansion and further enlarging the pores. When subjected to alternating temperatures, the ice in the pores melts and forms connecting cracks. When the specimens are loaded, stress concentration occurs at the ends of the pores within the concrete, causing the connecting cracks to develop further into through-cracks, thereby reducing the compressive strength of the concrete. However, as the externally added amount of EP increases, the compressive strength values of the specimens exceed those under standard curing conditions. This is because soaking before low-temperature curing further promotes the hydration of cement and EP active substances. Additionally, the increase in external admixture fills the pores within the concrete, reducing the porosity and thus enhancing the compressive strength of the concrete.

4.3. Effect of low-temperature alternating curing on compressive strength of EP external admixture ratio

From Fig. 7, when comparing the compressive strength values of EP concrete under low-temperature alternating curing and standard curing, the loss rates are 6.90%, 3.32%, 2.25%, and 9.16%, respectively. The loss rate is highest for EP with a particle size of 90–120 mesh, but it still exceeds the compressive strength value of ordinary concrete; the loss rate is lowest for EP with a particle size of 70–90 mesh. The reasons for this, apart from initial defects, are that expanded perlite is lightweight and floats within the aggregate, possessing the ability to absorb water and mud. The smaller the particle size, the greater the surface area and more robust the adsorption capacity, thereby reducing the bond strength between the aggregates. During low-temperature curing, as the EP within the specimens absorbs water, a network of channels forms, which undergoes frost heave and expands in volume, causing the initial defect pores to connect with the additional pores created by the EP. This results in the separation of expanded perlite from the cementitious material and coarse aggregate, significantly reducing the compressive strength of the concrete.

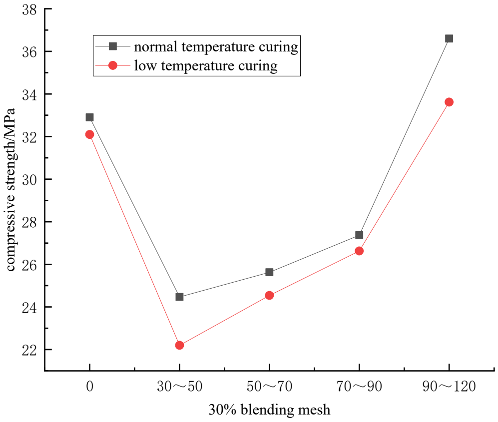
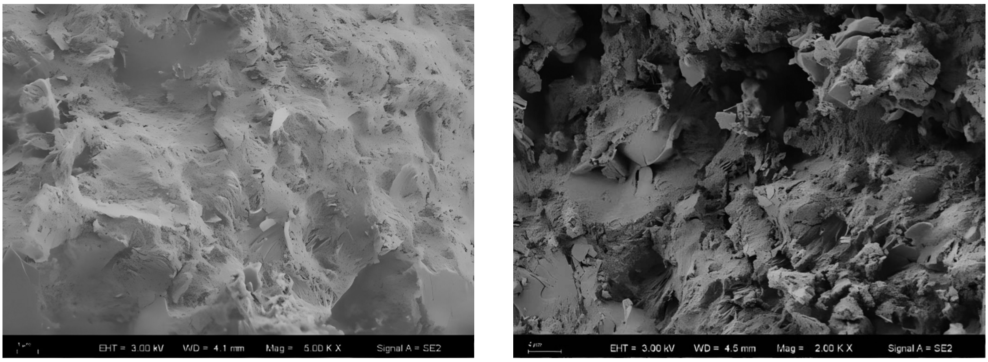


Fig. 7. Strength of concrete test block after 28 d of 30% content with different mesh number at low temperature

4.4. Micro-structural analysis

Figure 8 shows concrete specimens of C-EP-M0C0 and C-EP-M90-120C0.3 under standard curing, while Figure 9 presents concrete specimens of C-T20-EP-M90-120C0.3 after low-temperature alternating curing.

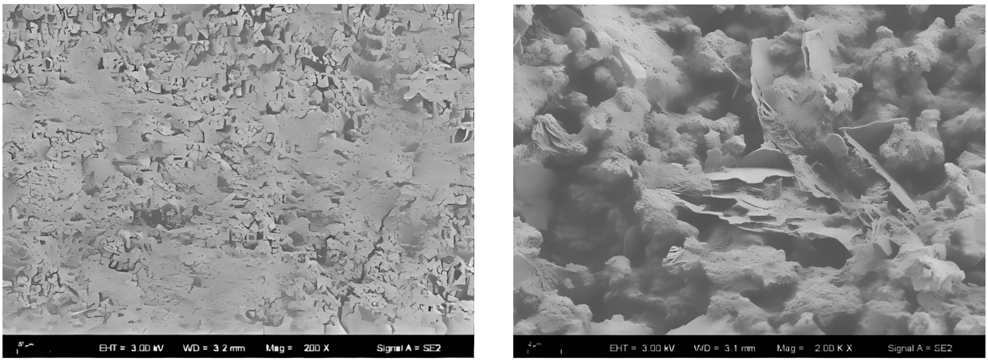
Figure 8(a) shows that its microstructure is mainly composed of cement hydration products. Due to manufacturing processes and material defects, there are minimal pores and scattered cracks, exhibiting high density. From Figure 8(b), the active substances in the expanded perlite particles act as a portion of the cement. The water adsorbed around these particles promotes the hydration reaction, filling the pores in the cement matrix and further optimizing



(a) (b)

Fig. 8. Microstructure of EP concrete cured at room temperature: (a) C-EP-M0C0, (b) C-EP-M90-120C0.3

the pore structure. Moreover, an excellent interfacial transition zone is formed between the expanded perlite and the cement matrix, effectively eliminating the voids and cracks present in Figure 8(a). This results in higher strength for the EP concrete, corroborating the analysis of the compressive strength of C-EP-M90-120C0.3 concrete presented in Section 3.1.



(a) (b)

Fig. 9. Micro-structure of EP concrete under low temperature alternating curing: (a) C-T20-EP-M90-120C0.3 (200 times), (b) C-T20-EP-M90-120C0.3 (2000 times)

From Figure 9(a), the concrete surface exhibits numerous pores and increased micro-cracks, forming connected cracks. This is attributed to the strong water absorption capacity of EP particles, where the water adsorbed around them and the internal capillary water freeze and expand in volume. After melting, this causes loosening of the micro-structure, an increase in porosity, and a tendency for cracks to gradually connect. Comparing the surface morphologies of the concrete in Figure 8(b) and Figure 9(b), the EP concrete subjected to low-temperature alternating curing shows higher porosity, a loosened micro-structure, and lack of density.

There is also debonding between the concrete and the coarse aggregate interface, significantly reducing the compressive strength of the concrete. This microscopic analysis corroborates the analysis of the compressive strength of C-T20-EP-M90-120C0.3 concrete presented in Sections 3.1 and 3.2.

5. Conclusions

The results of studies when using EP with a particle size of 90–120 mesh as an external admixture, the compressive strength exceeds that of ordinary concrete as the external admixture ratio increases, showing a trend of first increasing and then decreasing. The compressive strength reaches its maximum when the external admixture ratio of EP is 30%. With an external admixture ratio of EP set at 30%, as the particle size of the externally admixed EP in concrete specimens decreases, the compressive strength also decreases. Research has shown that EP with a particle size of 90–120 mesh can improve the compressive strength of concrete. After exposure to low-temperature alternating conditions, the compressive strength of expanded perlite with different external admixture amounts and particle sizes decreases. When using 90–120 mesh EP as an external admixture, as the admixture ratio increases, the rate of change in compressive strength gradually decreases. When using an external admixture ratio of 30%, the measured compressive strength value is highest for the 90–120 mesh size. This paper proposes that using a 30% admixture ratio of 90–120 mesh EP concrete can effectively resist the effects of low temperatures, improving the compressive strength and frost resistance of the concrete.

Acknowledgements

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