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*Research Article*

# Temperature Effect on the Thermal Conductivity of Expanded Polystyrene Foamed Concrete: Experimental Investigation and Model Correction

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In this research, ultralightweight expanded polystyrene foamed concrete (EFC) was made by the chemical foaming method, and its thermal insulation property was measured by the transient method at different environment temperatures (from −10 to 40°C). Then, the effect of temperature and EPS volume fraction on the thermal conductivity and dry density of EFC were observed. Ultimately, the Cheng–Vachon equation was modified by introducing the temperature parameter. The results indicated that EFC thermal conductivity decreases with increasing temperature. It was also demonstrated that the suitable volume of EPS particles can not only decrease the EFC thermal conductivity but also reduce the impact of temperature on the thermal conductivity. The thermal conductivity of EFC at different temperatures was accurately predicted in this study using the proposed model.

## 1. Introduction

Foamed concrete (FC) is a type of cement-based lightweight porous material with a density between 400 kg/m$^3$ and 1900 kg/m$^3$ that is widely used in the construction field, especially for reducing the dead load of structures and for heat preservation, damping, sound insulation, and pore filling [1]. Compared with organic insulating materials, FC has higher strength, better resistance to fire, and durability [1–3]. However, in order to meet the higher requirements of thermal insulation performance, density of FC should be further decreased to less than around 400 kg/m$^3$. In the relevant researches, it has been found that the chemical foaming method is more suitable for ultralightweight FC than mechanical foaming [4–9].

Expanded polystyrene (EPS) was firstly introduced as lightweight aggregate for concrete by Cook in 1973 [10]. Due to its excellent insulation and close cellular properties, EPS particles have significant effect on the thermal performance of FC. For instance, Sayadi et al. [11] added regenerated EPS particles into FC and found that the thermal conductivity of the FC sample with an EPS volume fraction of 82% was reduced by 45% and the density was reduced by 62.5%. It can be seen that EPS has broad application prospects and great potential value in FC [12–14].

Thermal conductivity is an important parameter in representing the ability of concrete to transfer heat. Many researches have studied thermal conductivity of composite materials and revealed the influence of various factors on thermal conductivity [15]. Temperature as an external condition has an important effect on thermal conductivity of concrete [16–20]. Rahim et al. [21] tested the thermal conductivities of three bio-based concrete materials under various temperature conditions (10 to 40°C) in steady state by using the guarded hot plate method. They found that the thermal conductivity of concrete materials becomes larger with an increase in temperature. Tandiroglu [22] studied the thermal conductivity of lightweight raw perlite aggregate concrete and established relationship functions for the thermal conductivity, the water-cement ratio, perlite amount by mass, and temperature. The proposed empirical correlations of thermal conductivity can be applicable within the range of temperatures −70 to 30°C. Li et al. [23] discussed common thermal conductivity models based on the experimental data and proposed a prediction model for the thermal conductivity of FC, but they failed to consider the influence of external environmental factors on the thermal conductivity of the model, such as temperature. In summary, the thermal conductivities of various types of concrete are significantly different when the temperature changes. Presently, theoretical models of FC thermal conductivity ignore the temperature effects.

In this study, ultralightweight expanded polystyrene foamed concrete (EFC) with different EPS contents is prepared by the chemical foaming method, and its thermal conductivity is measured at different environment temperatures (from −10 to 40°C). Based on test results and existing models of thermal conductivity, a thermal conductivity model of EFC is derived by temperature correction.

## 2. Experimental Programs

*2.1. Raw Materials and Mixture Ratio.* The gelled material used in this study was made from Chinese 42.5 ordinary Portland cement and class I fly ash. The relevant technical indicators for these two materials are shown in Tables 1 and 2. The addition of fly ash can optimize the pore structure of FC and enhance its thermal insulation performance. In addition, The EPS has particle sizes between 2 and 4 mm with apparent density of 18.8 kg/m$^3$ and thermal conductivity of 0.0313 W/(m·K). The foaming agent used in this test was a hydrogen peroxide solution with a concentration of 30%. The stabilizer was calcium stearate. The early strength agent was sodium nitrite, and the thickening agent was an acrylate copolymer emulsion. The water used was tap water. The water-binder ratio, foaming agent content, and fly ash dosage were adjusted to determine the benchmark mixture ratio, which is shown in Table 3. A total of 12 test blocks of chemical foaming EPS foamed concrete were prepared by changing the volume fraction of EPS (0%~60%).

*2.2. Testing Instrument*

*2.2.1. Thermal Conductivity Tester.* The ISOMET 2114 thermal characterization analyzer produced in Slovakia was used for the thermal conductivity test (Figure 1). The instrument can be used to determine the thermal conductivity, volumetric heat flux, and thermal diffusivity of cement-based composites [24]. It is based on the transient test principle, and the measuring temperature range is 15~+50°C with an accuracy of $1 \times 10^{-4}$ W/(m·K). The instrument can be tested with a probe or a flat plate. This test uses a surface probe with a test range of 0.04~0.3 W/(m·K).

*2.2.2. High-Low Temperature Test Box.* This test used the high-low temperature simulation test box developed by Northeast Agricultural University. Its main performance indicators are shown in Table 4.

*2.3. Preparation Technology and Experimental Method of Chemical Foaming EPS Foamed Concrete*

*2.3.1. Preparation Technology.* According to the EPS performance and the molding technology of chemical foaming foamed concrete, chemical foaming EPS foamed concrete samples were prepared according to the following process:

(a) The EPS particles were wet for one minute with one-third of the total water.
(b) The mixing cement, fly ash, other solid materials, remaining water, and the thickening agent were mixed and stirred until the mixture was evenly blended. Then the wetted EPS particles were put into the mixture and stirred for one minute. The temperature of the slurry was maintained at 25°C.
(c) Sodium nitrite solution was added. The mixture was stirred at a low speed for 30 seconds and then stirred at high speed for 10 seconds.
(d) Hydrogen peroxide was poured into the mixture, and it was stirred for 10 seconds.
(e) The mixture was quickly poured into the mold and left to stand for 24 hours at 20°C. Then, the specimens were removed from the mold when they had certain strength, and standard curing was then implemented. The concrete sample is shown in Figures 2(a) and 2(b).

*2.3.2. Experimental Methods.* A dry density test of the specimens was carried out according to the Chinese standard GB/T11969-2008. Measurements were taken after the specimens were dried to a constant weight. A constant temperature environment was provided by the high-low temperature test box. The thermal conductivities of the specimens were tested after standing at a constant temperature for two hours. When the temperature was constant, the thermal conductivity of the polished samples on both sides was measured using a thermal characteristic analyzer. The thermal conductivities of some of the EFC samples at 20°C are shown in Table 5. Due to the heterogeneity of FC, three molding face positions were tested, and the average of the results was calculated.

## 3. Results and Discussion

*3.1. Relationship between the Dry Volume Density and Thermal Conductivity of EFC Samples at Different Temperatures.* Thermal conductivity is a basic physical parameter used to characterize the heat transfer performance of materials. The heat conduction mechanism is different for different substances. According to the heat transfer theory [25, 26], free electron mobility and lattice vibration are the two main independent heat transfer mechanisms of solid. It is mainly the elastic wave (or lattice wave) that, produced from the lattice vibration at the place of higher temperature, drives the adjacent lattice vibration to transfer heat in inorganic nonmetal solid materials. Because concrete is composed of primarily solid components, the

Table 1: Physical and mechanical properties of ordinary Portland cement.

| Cement type | Specific surface area ($m^2$/kg) | Setting time (min) | | Flexural strength (MPa) | | Compressive strength (MPa) | |
|---|---|---|---|---|---|---|---|
| | | Initial set | Final set | 3d | 28d | 3d | 28d |
| P.O 42.5 | 345.00 | 150 | 210 | 5.0 | 8.0 | 16.5 | 46.2 |

Table 2: Technical parameters of the fly ash.

| Chemical composition (%) | | | | | | Apparent density ($kg/m^3$) | Bulk density ($kg/m^3$) |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | Cao | MgO | $NaO_2$ | | |
| 58 | 30 | 4.3 | 1.5 | 2.8 | 3.2 | 2100 | 1086 |

Table 3: Experimental ratio.

| Specimens | Cement (g) | Fly ash (g) | w/b | Foam volume (%) |
|---|---|---|---|---|
| $A_1$ | 193 | 157 | 0.48 | 6.3 |

w/b: water-binder ratio.

Figure 1: ISOMET 2114 thermal characteristics analyzer.

Table 4: Performance parameters of the high-low temperature simulation test box.

| | |
|---|---|
| Effective volume | 5 m × 4 m × 2.5 m |
| Temperature range | −45~+60°C |
| Temperature fluctuation | ±(0.05~0.1)°C |
| Heating power | 1500 W |
| Refrigerating capacity | 1500 W |

heat transfer mechanism of the skeleton is similar to that of a solid. Therefore, the thermal conductivity of concrete primarily depends on the density of the materials. Usually, a low density corresponds to low thermal conductivity [27].

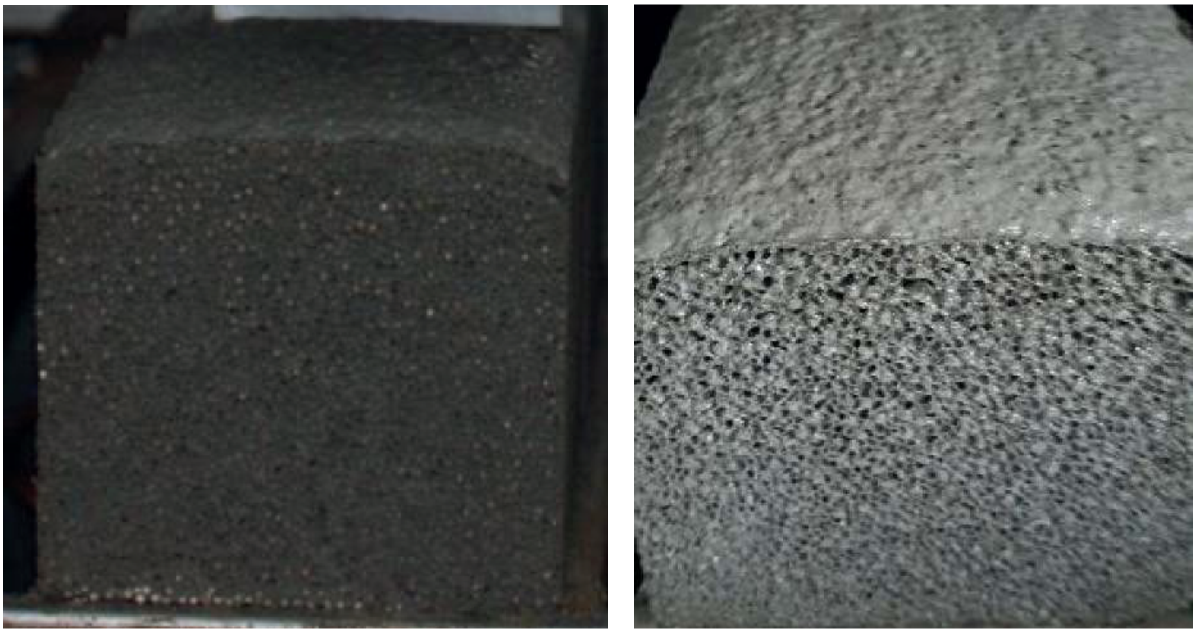
The variation law was obtained by fitting the test results of the dry volume density and thermal conductivity at different temperatures, as shown in Figure 3. The dry volume density of chemical foaming EPS foamed concrete is positively correlated with the thermal conductivity.

The test data were fitted to obtain the relational expression between the dry volume density and thermal conductivity of EFC when the temperature was 0°C. The relational expression may be written as

$$\lambda = 0.0028\rho^{0.5629}, \quad R^2 = 0.8826. \tag{1}$$

The foam content and EPS content determine its dry volume density in EFC and affect the thermal conductivity of EFC. Under the same conditions, the pore number in the porous material determines its thermal conductivity. When the pore number is the same, the thermal conductivity increases with the increase of pore size. However, connected pores will increase the thermal conductivity of concrete. Additionally, the EPS volume fraction is a key factor that changes the dry volume density of FC. Figure 4 presents the influence curve of the EPS volume fraction on the dry volume density of FC. According to Figure 4, the micropores did not change with the addition of a small amount of EPS particles until 10% of EPS particles were added. At this point, the ratio of large pores in the specimens showed an increasing trend, resulting in a decrease in the dry volume density. However, when the pore percentage with diameters reaching 200~400 $\mu$m was too big, the internal pore structure would be unstable, and some large pores may be destroyed. This would result in an increase in the dry volume density of the specimen and thus affect the thermal conductivity of the EFC [28].

*3.2. Effect of Temperature on the Thermal Conductivity of EPS Foamed Concrete.* This experiment used five temperatures, namely, −10°C, 0°C, 20°C, 30°C, and 40°C. These temperatures were used to study the thermal insulation performance of EFC. The thermal conductivities of FC mixed with different contents of EPS particles were tested to obtain a variation law for the thermal conductivity of FC with different EPS volume fractions with temperature, as shown in Figure 5. As seen from Figure 5, the thermal conductivity of chemical foaming concrete is positively correlated with the external temperature. With a change in temperature, the largest variation amplitude of the FC without EPS particles reached 52%, which shows the significant effect of temperature on the thermal conductivity of FC [29]. This is because the thermal conductivity of FC is related to not only the intensity of particle movement in the solid, liquid, and gas phases but also the



(a) (b)

Figure 2: EPS foamed concrete (EFC) specimens: (a) After standing for 24 hours at 20°C and (b) after 28 days under standard curing.

Table 5: Dry volume density, porosity, and thermal conductivity of the EFC.

| Dry volume density (kg/m$^3$) | Porosity (%) | Average thermal conductivity (W/(m·K)) | Dry volume density (kg/m$^3$) | Porosity (%) | Average thermal conductivity (W/(m·K)) |
|---|---|---|---|---|---|
| 304 | 73.47 | 0.0838 | 291 | 73.04 | 0.0704 |
| 366 | 68.06 | 0.0926 | 230 | 79.93 | 0.0761 |
| 357 | 68.85 | 0.0890 | 315 | 72.51 | 0.0921 |
| 362 | 70.07 | 0.1000 | 237 | 79.32 | 0.0750 |
| 336 | 71.99 | 0.0810 | 267 | 76.70 | 0.1037 |

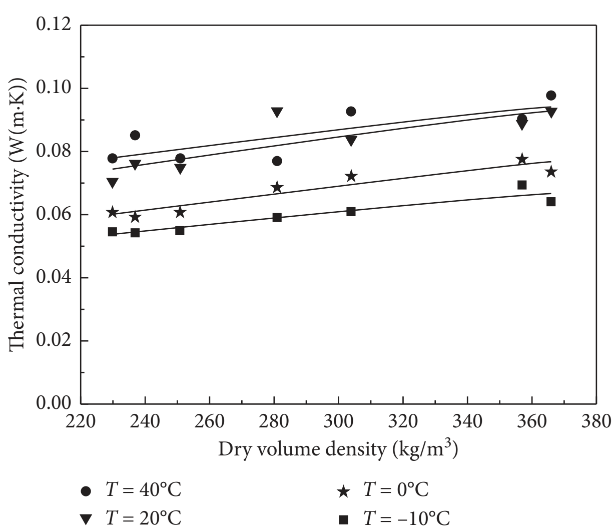



Figure 3: The thermal conductivities of FC composed of different dry densities at various temperatures.

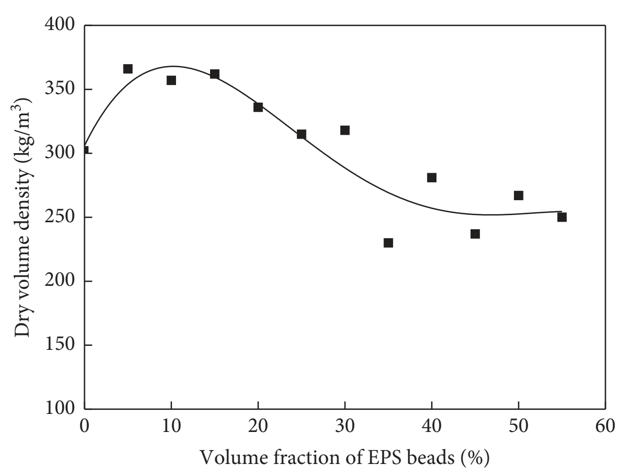



Figure 4: The dry volume densities of FC with various EPS volume fractions.

interaction forces between the different phases of the particles and their spatial distributions. Due to the large porosity of FC, a high temperature would intensify irregular movement and the collision of gas molecules in the pores. This would enhance the interactions between different phases of the particles, thus enhancing the thermal conductivity.

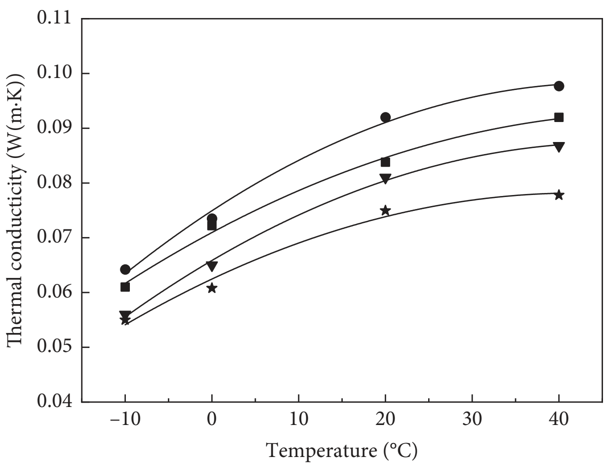



Figure 5: Thermal conductivity of different EPS volume fraction FC with temperature.

Figure 5 shows compared with the thermal conductivity curve of FC without EPS beads, the other curves with EPS beads are obviously smoother and with smaller slopes in the same temperature gradient range. When the EPS volume content was 55%, the thermal conductivity was the least affected by temperature change. This result demonstrates that the proper amount of EPS particles can not only reduce the thermal conductivity of EFC but also buffer changes in the thermal conductivity caused by temperature changes. This effect is a primary benefit from EPS's structure and its improvement of FC pore structure. The empirical correlations between the FC thermal conductivity and the temperature under different volume fractions of EPS are shown in Table 6.

Table 6: Empirical correlations of thermal conductivity and temperature ($T$).

| EPS volume fraction (%) | $\lambda = a(T^2) + bT + c$ | $R^2$ |
|---|---|---|
| 0 | $\lambda_0 = -0.000008T^2 + 0.0008T + 0.071$ | $R^2 = 0.995$ |
| 5 | $\lambda_5 = -0.00001T^2 + 0.001T + 0.0749$ | $R^2 = 0.995$ |
| 20 | $\lambda_{20} = -0.000001T^2 + 0.0009T + 0.0659$ | $R^2 = 0.998$ |
| 55 | $\lambda_{55} = -0.000009T^2 + 0.0007T + 0.0625$ | $R^2 = 0.987$ |

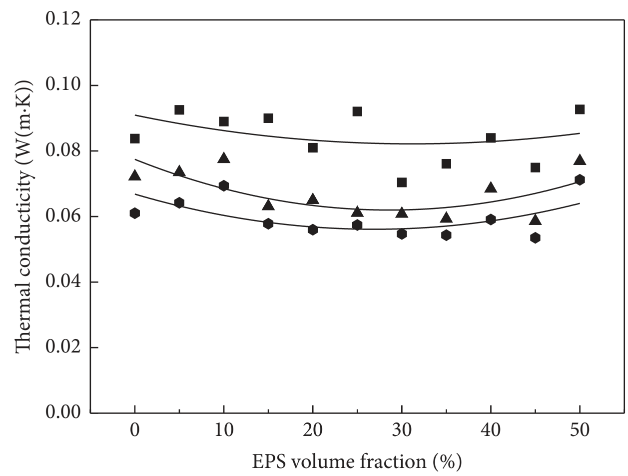



Figure 6: Thermal conductivity of different temperature FC with various EPS volume fractions.

*3.3. Effect of EPS Content on the Thermal Conductivity of FC at Different Temperatures.* The excessive content of bubbles introduced into the cementitious matrix will cause some difficulty in concrete formation. Therefore, it is difficult to reduce the density and thermal conductivity of ultralight FC by increasing the amount of the foaming agent. In this study, a certain volume fraction of EPS particles was added to chemical foaming foamed concrete to modify the self-weight and thermal insulation performance of the concrete.

EPS particles have good thermal performance. The effect of the EPS volume fraction on the thermal conductivity of FC at different temperatures is shown in Figure 6. The addition of EPS particles greatly changed the thermal conductivity of the FC. Compared with that of FC without EPS, the maximum change amplitude of the thermal conductivity of the FC decreased by 46% after a certain volume fraction of EPS particles were added. According to Figure 6, the thermal conductivity of the EFC decreased at first and then increased with an increase in EPS content. This was primarily because EPS particles (98% air and 2% polystyrene) have many closed pores inside them, and these have a large thermal resistance. With an increase in the EPS content, the thermal resistance of the EFC increased correspondingly. Therefore, its thermal conductivity decreased. Recent research demonstrates that when adding foam to EPS concrete, the foaming agent creates a micropore gap structure among EPS granules [30]. However, when the EPS volume fraction is too large, the distance between EPS particles will decrease. This causes the surrounding foam to gather together and connect to form larger pores. As a result, the internal connected porosity increased, and the thermal conductivity increased significantly, which even affected the normal foaming molding of the FC.

As can be seen from Figures 4 and 6, the results show that a chemical foaming EPS ultralightweight foamed concrete with a dry density of less than 300 kg/m$^3$ and a normal thermal conductivity between 0.0704 and 0.0767 W/(m·K) could be prepared when the volume fraction of EPS was 25%~35%. In addition, compared with ordinary FC, it displayed an effective thermal insulation property with changes in temperature.

## 4. Temperature Modified Thermal Conductivity Model for EFC

### *4.1. Basic Thermal Conductivity Model for Foamed Concrete*

*4.1.1. Series and Parallel Models.* The main form of heat transfer inside concrete materials is thermal conduction. Hashin and Shtrikman have proposed effective thermal conductivity models of the two-phase system [31]. The series and parallel models are based on the upper and lower limits of thermal conductivity of the materials, respectively. In these models, foam and EPS particles are used as the dispersed phase and the cement, fly ash, and slurry are used as the continuous phase to calculate the thermal conductivity of concrete. The expressions can generally be written as shown in the following equations:

Series models:

$$\lambda = \frac{1}{(1-\nu)/\lambda_1 + \nu/\lambda_2}. \tag{2}$$

Parallel models:

$$\lambda = (1-\nu)\lambda_1 + \nu. \tag{3}$$

*4.1.2. Maxwell–Eucken Model.* The Maxwell–Eucken model assumes that the foam consists of homogeneous spheres that are irregularly dispersed and without interaction forces. More succinctly, the model asserts that heat transfer cannot be carried out between dispersed phases. On this basis, the minimum boundaries of the thermal conductivities of isotropic and macroscopic homogeneous two-phase materials were able to be successfully deduced [32].

When foam is mixed into concrete, its shape and distribution will be changed due to squeeze from the slurry, but the model only considers an index of porosity. Its expression is as follows [32]:

$$\lambda = \frac{2\lambda_1 + \lambda_2 + 2\nu\left(\lambda_2 - \lambda_1\right)}{2\lambda_1 + \lambda_2 - \nu\left(\lambda_2 - \lambda_1\right)}\lambda_1. \tag{4}$$

*4.1.3. Modified Volume Model for Foamed Concrete.* Li considered the volume content of foam and proposed a modified model that could be applied to the calculation of FC thermal conductivity by combining FC test data based on the Cheng–Vachon thermal conductivity model [23]. The model assumes that there are no pores in the concrete slurry, and the thermal convection, radiation, and contact resistance are not considered. It primarily corrects the volume content of the dispersed phase and considers the influence of complex factors such as the heat transfer path and tortuosity during the heat transfer process. This model can accurately predict the thermal conductivity of FC.

The following are the equations for the thermal conductivity volume correction model of FC [23]:

The difference in the thermal conductivity between the foam and the cement-fly ash mortar is represented by using a simple equation:

$$M = \frac{k_c}{k_d}. \tag{5}$$

The modified volume content of the foam can be expressed as follows:

$$\varphi' = \varphi^{1/t}\frac{M^{1/t} - \varphi^{1/t}}{M^{1/t} - 1}. \tag{6}$$

From equations (5) and (6), the effective thermal resistance of FC is represented as follows:

$$R_e = \frac{\sqrt{\varphi'}}{k_c + \left(k_d - k_c\right)\sqrt{\varphi'}} + \frac{1 - \sqrt{\varphi'}}{k_c}. \tag{7}$$

Then, the thermal conductivity equation for FC is

$$k_e' = \frac{1}{R_e}. \tag{8}$$

It should be noted that $t$ is the foam volume content correction coefficient obtained by fitting the test data.

*4.2. Model Evaluation and Parameter Determination.* The volume correction model proposed by Li was used to verify and study the experimental results of FC in the study. Because 98% of the EPS particles were air and the difference in the thermal conductivity between them was small, the porosity and EPS were simplified to be the dispersed phase and the cement-fly ash mortar was the continuous phase. Comparisons between the predicted value and the experimental value of the series and parallel models, the Maxwell–Eucken model, and the volume correction model are shown in Figure 7.

According to Figure 7, the thermal conductivity data predicted by the parallel and series models were in the upper and lower limits, respectively, and they were significantly different from the experimental results. The thermal conductivity predicted by the Maxwell–Eucken model was much larger than that of the experimental data. This was because the Maxwell–Eucken model assumed that the stomata in the test blocks were homogeneous and independent spheres. In reality, these pore shapes vary greatly, and some of them are connected pores, leading to a large deviation between the predicted value and the experimental value.

A least squares fitting of the modified volume model proposed by Li was performed by using partial test data. When $t = 2.15$, the best fitting effect was obtained, and the predicted result was closest to the test value. Therefore, the modified volume model proposed by Li was used to predict and evaluate the thermal conductivity of EFC in this study.

The model evaluated the effect of temperature on the thermal conductivities of different phases based on the modified volume model proposed by Li and corrected the volume correction coefficient using the temperature function.

In the present study, we propose a new correlation for the dispersed phase:

$$k_d'' = -0.000002T^2 + 0.0078T + 2.4363. \tag{9}$$

The difference between two phases in the thermal conductivity with correction was given by

$$M_x = \frac{k_c}{k_d''}. \tag{10}$$

The influence of temperature was introduced into the thermal conductivity to correct the volume content correction coefficient of foam:

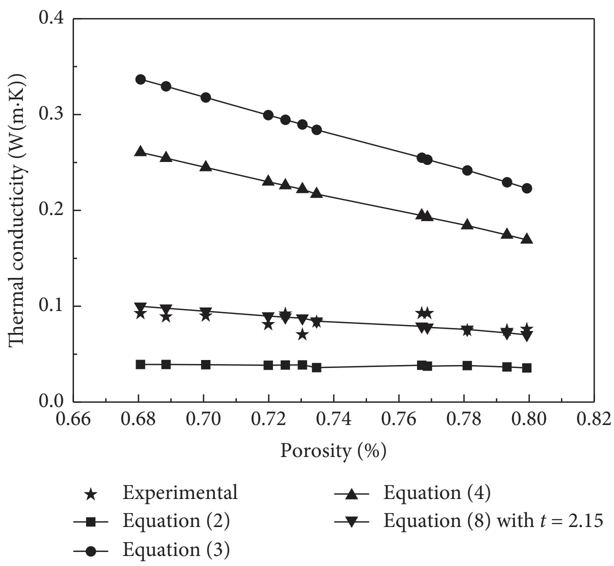



Figure 7: Comparison between the theoretical and experimental results.

$$t' = 0.0003T^2 - 0.0229T + 2.4783. \tag{11}$$

The porosities at different temperatures were then corrected can be written as shown in the following equations:

$$n = \frac{\varphi}{0.7347}, \tag{12}$$

$$\eta = -10.24n^2 + 19.519n - 8.2249. \tag{13}$$

The volume correction coefficient of the foam after two times of correction can be written as follows:

$$t_x = \eta t'. \tag{14}$$

The correction equation of the volume content of the foam at different temperatures was as follows:

$$\varphi_x = \varphi^{1/t_x} \frac{M_x^{1/t_x} - \varphi^{1/t_x}}{M_x^{1/t_x} - 1}. \tag{15}$$

By combining equations (9) and (15), the modified thermal resistance of FC was obtained

$$R_e'' = \frac{\sqrt{\varphi_x}}{k_c + \left(k_d'' - k_c\right)\sqrt{\varphi_x}} + \frac{1 - \sqrt{\varphi_x}}{k_c}. \tag{16}$$

Then the modified thermal conductivity equation of FC can be expressed by the simplified form

$$k_e'' = \frac{1}{R_e''}. \tag{17}$$

The experimental data of EFC thermal conductivities at different temperatures were input into the corrected EFC thermal conductivity model to obtain Figure 8. In the figure, the predicted values of the temperature-modified model at different temperatures are compared with the experimental values. Results show that the predicted values coincided with the experimental values at different temperatures, indicating a good prediction effect of the model. Compared with other prediction models, the model in this study not only represented the influence of temperature parameters but also calculated the EFC thermal conductivities at different temperatures.

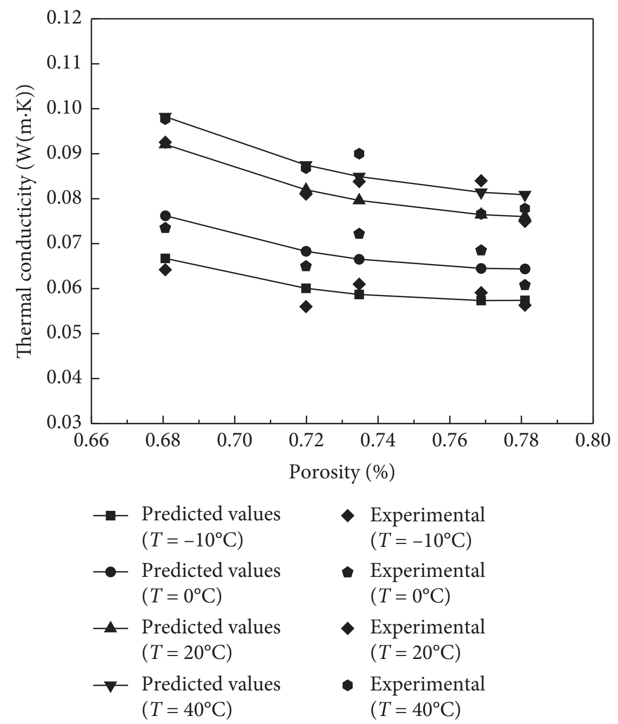



Figure 8: Comparison between the theoretical and experimental results at different temperatures.

## 5. Conclusions

(1) Temperature had a significant effect on the thermal conductivity of EFC. The thermal conductivity of EFC increased with an increase in temperature. With a change in temperature, the amplitude changes in the thermal conductivity of the same EFC reached 28%–52%.

(2) With an increase in the EPS content, the influence of temperature on the thermal conductivity of FC was reduced, which indicated that an appropriate amount of EPS particles could not only reduce its thermal conductivity but also buffer the change of thermal conductivity caused by temperature changes.

(3) EPS particles had good thermal performance. With an increase in the EPS volume fraction, the thermal conductivity of EFC decreased. However, when the EPS volume fraction was too large, the thermal conductivity increased obviously. The results showed that the chemical foaming EPS ultralight foamed concrete with a dry density of less than 300 kg/m$^3$ and a normal thermal conductivity between 0.0704 and 0.0767 W/(m·K) could be prepared when the

volume fraction of EPS was 25%~35% with the change of temperature. In addition, compared with ordinary FC, it had good temperature stability.

(4) An EFC thermal conductivity prediction model that considered the influence of temperature was established based on a modified thermal conductivity model of the dispersed phase volume. Also, the predicted results were verified using experimental data to prove its accuracy. It is important to note that the model is only applicable for the prediction of EFC thermal conductivity under the condition of an outdoor ambient temperature, and the determination of the temperature correction coefficient was not unique.

## List of Symbols

$k_{\mathrm{c}}$: Thermal conductivity of cement-fly ash slurry (W/(m·K))
$k_{\mathrm{d}}$: Air thermal conductivity (W/(m·K))
$k_{\mathrm{d}}''$: Modified thermal conductivity of dispersed phase (W/(m·K))
$k_{\mathrm{e}}'$: Thermal conductivity of foamed concrete (W/(m·K))
$k_{\mathrm{e}}''$: Modified thermal conductivity of foamed concrete (W/(m·K))
$M$: Magnification coefficient between two phases
$R_x$: Temperature correction magnification coefficient between two phases
$n$: Proportional coefficient
$R_e$: Modified thermal resistance ((m·K)/W)
$R_{\mathrm{e}}''$: Temperature correction thermal resistance ((m·K)/W)
$T$: Test temperature (°C)
$t'$: Volume correction coefficient prediction
$t_x$: Temperature correction coefficient of foam volume content
$v$: Porosity (%)
$\eta$: Temperature correction constant
$\lambda$: Effective thermal conductivity (W/(m·K))
$\rho$: Dry volume density (kg/m$^3$)
$\lambda_1$: Thermal conductivity of continuous phase (W/(m·K))
$\lambda_2$: Thermal conductivity of dispersed phase (W/(m·K))
$\varphi$: Volume fraction of dispersed phase (%)
$\varphi'$: Modified volume fraction of dispersed phase (%)
$\varphi_x$: Temperature correction volume content of dispersed phase (%).

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

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