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Preparation and mechanical properties of phase change energy storage concrete

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Butyl stearate was used as phase change material, expanded perlite was used to absorb butyl stearate, and the phase change energy storage aggregate was prepared by surface modification of limestone powder. Phase change energy storage concrete is prepared by partially replacing fine aggregate with phase change material and partially replacing cementitious materials with silica powder. The compressive and splitting tensile properties of concrete mixed with phase change energy storage aggregate and silica powder were studied. The test results show that the admixture of phase change energy storage aggregate will lead to the reduction of compressive strength and splitting tensile strength of concrete, when the content of phase change energy storage aggregate is constant and the content of silica powder increases from 0% to 10%, the compressive strength and splitting tensile strength of concrete increase with the increase of the content of silicon powder. But when the content of silica powder increased from 10% to 15%, the compressive strength and splitting tensile strength of concrete decreased. When the phase change energy storage aggregate content is 5%, the silica powder content is 10-15%, the compressive strength and splitting tensile strength of the phase change energy storage concrete were basically the same as that of plain concrete.

Keywords: phase change energy storage aggregate, silica powder, concrete, compressive strength, splitting tensile strength.

Отримання та механічні властивості бетону для зберігання енергії. *H.Cao, C.Zhou*

Вивчено міцнісні властивості при розтягуванні і стисненні теплоізоляційного бетону, отриманого за допомогою додавання фазового заповнювача і кремнеземного порошку у різних концентраціях. Результати випробувань показують, що така добавка і додавання кремнезему у концентрації до 10 % призводить до зниження міцностей на стиск і на розрив бетону. Міцності на стиск і на розрив при розтягуванні бетону збільшуються зі збільшенням вмісту порошку кремнію. Коли вміст заповнювача становить 5 %, порошку кремнезему — 10–15 %, міцність на стиск і межа міцності при розтягуванні у бетону, який досліджується, в основному залишаються такими ж, як у звичайного бетону.

Изучены прочностные свойства при растяжении и сжатии теплоизоляционного бетона, полученного при помощи добавления фазового заполнителя и кремнеземного порошка в разных концентрациях. Результаты испытаний показывают, что такая добавка и добавление кремнезема в концентрации до 10 % приводит к снижению прочности на сжатие и прочности на разрыв бетона. Прочности на сжатие и на разрыв при растяжении бетона увеличиваются с увеличением содержания порошка кремния. Когда содержание заполнителя составляет 5 %, порошка кремнезема — 10–15 %, прочность на сжатие и предел прочности при растяжении у исследованного бетона, в основном такие же, как у обычного бетона.

1. Introduction

The popularity of green buildings is the best solution for building comfort and energy conservation, the development trend of the building industry, and an important way to solve energy problems. Concrete is the main material of modern engineering structures. Concrete is the most widely used building material in the world. The energy storage performance of ordinary silicate concrete buildings is poor and the energy saving effect of buildings is not obvious. Therefore, the development of concrete with both energy storage performance and mechanical properties is an inevitable trend of the development of green building materials [1, 2].

Phase change materials (PCM) mainly use latent heat to store energy. PCM has the advantages of high energy storage density, small volume expansion rate, and the material itself can remain approximately isothermal during the process of heat absorption or release. Therefore, in order to improve the living comfort and energy saving effect, researchers and workers began to add PCM into concrete to prepare phase change energy storage concrete [3–5].

In [6], microcapsules were used to encapsulate phase change materials in the experiment, and then the encapsulated phase change materials were mixed into concrete to prepare phase change concrete. According to the experimental study, under the same temperature difference between day and night, the changes of indoor temperature of the ordinary concrete room model are greater than that of the phase-change concrete room model under the same conditions. Authors of [7] used various methods to package over 200 kinds of phase change materials, and then applied the packaged phase change materials to the building structure. The test indicate that the phase change materials have a good effect of phase change energy storage, which achieve good application effect in building structure. In [8], a paraffin/diatomite composite phase change material was directly mixed into concrete to prepare phase change energy storage concrete. The test indicate that the basic mechanical properties of PCM concrete decrease with an increase of the incorporation amount of paraffin/alga composite PCM. Authors of [9] found that the addition of PCM reduced the basic mechanical strength of PCM concrete, but the reduced compressive strength and splitting tensile strength of phase change concrete could meet the requirements of anti-compression degree and splitting tensile strength of some structures. In [10] it was found in the experimental study that phase change materials can reduce the thermal conductivity of concrete, but phase change materials can improve the heat storage capacity of concrete, so concrete has the effect of phase change energy storage. Authors of [11] mixed phase change materials with phase change temperature of about 5°C into concrete in the test to prepare phase change energy storage concrete. According to the experimental study, phase change energy storage concrete can delay the freezing-thawing cycle failure of the bridge deck or concrete pavement when applied to the bridge deck or pavement. In [12] it was shown that the phase-change aggregate prepared with expanded perlite as the matrix material has good thermal and chemical stability.

In [13] limestone powder was used to modify the surface of phase-change energy storage aggregate, and it was found that limestone powder can make phase-change energy storage aggregate hydrophilic, thus reducing the strength loss of concrete.

Due to its inherent characteristics of low strength and porosity, phase change aggregate has a negative effect on the strength performance of concrete [14]. To improve the mechanical performance of phase change concrete, admixtures can be added to enhance the strength. As an additive, silica powder can not only save energy and protect environment, but also increase the compactness and compressive strength of concrete [15].

In this paper, butyl stearate was used as a phase change material, expanded perlite was used to absorb butyl stearate, and a phase change energy storage aggregate was prepared by surface modification of limestone powder. Phase change energy storage concrete is prepared by partially replacing fine aggregate with phase change material and partially replacing cementitious materials with silica powder. The basic mechanical strength of the concrete are studied in order to develop a kind of phase change energy storage concrete with good mechanical properties.

2. Experimental

2.1. Test materials

The phase change energy storage material used in the experiment is butyl stearate of industrial grade with purity of over 99 % and a melting point of 18 ~ 20°C. The main physical properties of silica powder and expanded perlite are shown in Tables 1 and 2, respectively. The limestone powder

Table 1. The main physical properties of silica powder

SiO_2	$K_2O + Na_2O$	CaO + MgO	Fe_2O_3	Al_2O_3	45 μm sieve residue ratio	pH value	Specific surface
95 %	1.5 %	1.5 %	1 %	1 %	1.7 %	7.1	15 m^2/g

Table 2. The main physical properties of expanded perlite

Bulk density, $kg \cdot m^{-3}$	Granularity, mm	Closed-cell ratio, %	Volume loss rate of 1 MPa pressure, %	Water absorption rate, %
130	0.1 ~ 1.5	≥95	38	85

was chemically pure and the $CaCO_3$ content was 99 %. The ordinary Portland cement grade is P·042.5, and the fineness modulus of middle sand is 2.7. Gravel with particle size of 5 ~ 10 mm was selected. The test water is ordinary tap water.

2.2. Specimen preparation

Expanded perlite was dried to a constant weight in a blast oven at a temperature of (105±5)°C. To ensure uniform adsorption of butyl stearate, a certain amount of liquid butyl stearate is sprayed at room temperature 30°C, onto a suspension of well-dried expanded perlite, stirred well for 3 h so that butyl stearate is completely immersed in the internal porosity of expanded perlite; the adsorption of butyl stearate by expanded perlite is defined as 150 %. The surface modification was carried out on expanded perlite so that it sufficiently absorbed butyl stearate; for this, the double-mass limestone powder was evenly scattered over it. The limestone powder was stirred and mixed for 1 h, and then the excess limestone powder was screened out to prepare phase change energy storage aggregate.

The concrete strength grade is designed as C30. According to specification for mix proportion design of ordinary concrete (JGJ 55-2011), the mix proportion of concrete is cement: water: sand: gravel = 1:0.52:1.42:2.86, sand rate 34.3%. Phase change energy storage aggregate, gravel, sand, silica powder, cement and water are measured in a certain proportion to prepare phase change energy storage concrete samples. Add stones, sand (phase change energy storage aggregate) > cement, silicon powder > water into the mixer, mix evenly and then pour into the mold with oil on the surface for mechanical vibration. Remove the mold after 24 h and maintain it in the curing room for 28 days.

Silica powder adopts internal mixing method to replace 0%, 5%, 10% and 15% of cement content with equal mass, and phase change energy storage aggregate with equal volume to replace 0%, 5%, 10% and 15% of sand. According to orthogonal test, 16 groups of mixing ratios are designed. Each type consists of three compression specimens with a diameter of 150×150×150 mm^3 and three splitting tensile specimens with a diameter of 150×150×150 mm^3.

2.3 Test method and results

After the cube specimens reaches the age of 28 days, they are put into the concrete mechanical properties laboratory with the ambient temperature of 25°C. When the surface of the specimen is dried, the cube compression and splitting tensile tests are carried out. According to standard test methods for mechanical properties of ordinary concrete (GB/T 50081-2002), the basic mechanical properties (the compressive strength and splitting tensile strength) of concrete were tested. In the splitting tensile test, a T-type auxiliary loading device with greater rigidity is installed in the middle of the upper and lower pressure surfaces of the specimen.

The formula for calculating the compressive strength is:

$$f_c = F/A, \quad (1)$$

where f_c is the compressive strength of the specimen (MPa); F is the specimen ultimate load (N); A is the specimen compression area (mm^2).

The formula for calculating the splitting tensile strength is:

$$f_s = 2F/\pi A = 0.637F/A, \quad (2)$$

where f_s is the splitting tensile strength of specimen (MPa); F is the ultimate load of splitting tensile test of specimen (N); A is the area of splitting surface of specimen (mm^2).

Each group of concrete has three specimens of 150×150×150 mm^3 and the strength of each specimen is calculated according to

Table 3. Test results of compressive strength, MPa

Phase change energy storage aggregate content, %	Silica powder content, %			
	0	5	10	15
0	39.29	45.76	48.97	43.67
5	37.16	44.52	48.16	42.69
10	35.28	42.85	46.78	41.21
15	33.58	38.98	43.21	37.95

Table 4. Test results of splitting tensile strength, MPa

Phase change energy storage aggregate content, %	Silica powder content, %			
	0	5	10	15
0	3.02	3.22	3.42	3.16
5	2.77	3.14	3.34	3.05
10	2.54	3.05	3.24	2.99
15	2.39	2.79	2.89	2.76

the ultimate load measured in the test and the formula. According to the data processing principle in GB/T 50081-2002, the cubic compressive strength and splitting tensile strength of this group of concrete are determined. The compressive strength and splitting tensile strength of concrete with different contents of phase change energy storage aggregate and silica powder measured by the test are shown in Table 3 and Table 4, respectively.

3. Results and discussion

3.1. Influence of phase change energy storage aggregate

According to Table 3, the dependence of the compressive strength on the phase change energy storage aggregate content is shown in Figure 1.

As can be seen from Fig. 1, when the content of silica powder is constant, the compressive strength of concrete gradually reduced with the increase of the content of phase change energy storage aggregate.

When the content of silica powder is 0%, and the content of phase change energy storage aggregate increases to 15%, the compressive strength of concrete decreases by 14.53%. The slope of the whole curve is almost the same, which can be regarded as a linear decrease. When the content of silica powder is 5%, 10% and 15%, respectively, when the content of phase change energy storage aggregate is less than 10%, the rate

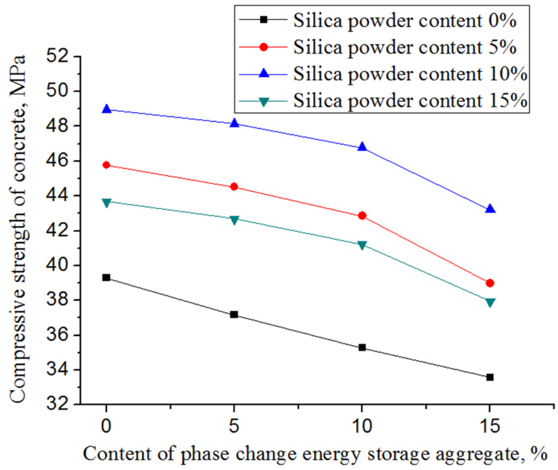

Fig. 1. Dependences of the compressive strength of the concrete on the phase change energy storage aggregate content.

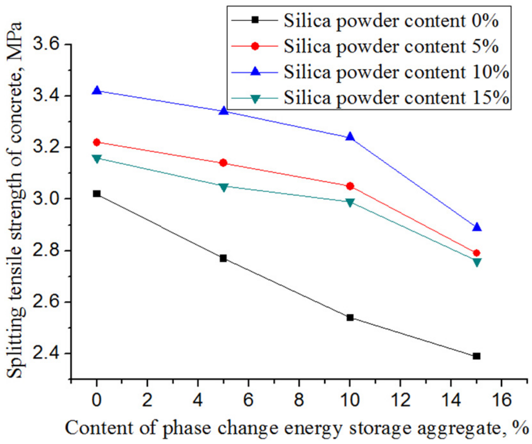

Fig. 2. Dependences of the splitting tensile strength of concrete on the content of the phase change energy storage aggregate.

of decrease of compressive strength is relatively slow. When the content of phase change energy storage aggregate exceeds 10%, the rate of decrease of compressive strength is increased. Taking concrete with silica powder content of 10% as an example, the content of phase change energy storage aggregate increased from 0% to 10%, and the compressive strength decreased by 4.47%. The content of phase change energy storage aggregate increased from 10% to 15%, and the compressive strength decreased by 7.63%. In conclusion, the appropriate content of phase change energy storage aggregate is 10%, and the reduction of compressive strength can be controlled within 10%.

The dependences of the splitting tensile strength on phase change energy storage ag-

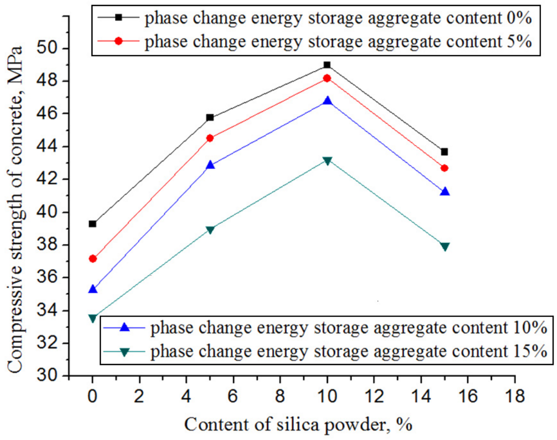

Fig. 3. Dependences of the compressive strength on content of silica powder.

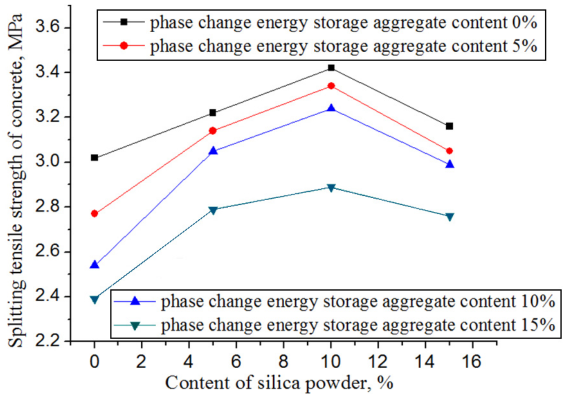

Fig. 4. Dependences of the splitting tensile strength on content of silica powder.

gregate content is shown in Figure 2. When the content of silica powder is fixed, with the increase of phase change energy storage aggregate in the concrete, its splitting tensile strength reduced. When silica powder was not added and phase change energy storage aggregate content was 5%, 10% and 15%, respectively, the splitting tensile strength of concrete decreased by 9.03%, 15.89% and 20.86%, respectively. When the content of silica powder is 5%, the splitting tensile strength of concrete with phase change energy storage aggregate content of 10% is almost the same as that of concrete without phase change energy storage aggregate. Later, with the increase of phase change energy storage aggregate content, the splitting tensile strength of concrete reduced. When the content of phase change energy storage aggregate increases to 15%, the splitting tensile strength of concrete is 2.79MPa, which is 7.62% lower than that of concrete unmixed with phase change energy storage aggregate. When the content of silica powder was 10% and 15% and that of phase change energy storage aggregate was 15%, the splitting tensile strength of concrete was 2.89 MPa and 2.76 MPa, respectively, which decreased by 4.31% and 8.61% compared with the concrete without phase change energy storage aggregate.

The strength of expanded perlite is lower than that of sand [6]. After partial replacement of sand, the splitting tensile and compressive strength of concrete will be directly reduced. In addition, when the specimen is subjected to an external load, expanded perlite in concrete first fails, and the damaged expanded perlite is equivalent to the existence of pores. Under the action of an external load, the stress concentration resulting in pores in the expanded perlite tends to accelerate the failure of concrete. Although the surface modification of the phase change energy storage aggregate by limestone powder can improve its adhesion to concrete, compared with sand, its adhesion to concrete is still weak, leading to the reduction of compressive and splitting tensile strength.

3.2. Influence of silica powder

According to the data in Table 3, the dependence of the compressive strength on content of silica powder is drawn, as shown in Fig. 3.

Figure 3 shows that when the content of phase change energy storage aggregate is constant and the content of silicon powder increases from 0% to 10%, the compressive strength of phase change energy storage concrete increases gradually. However, when the content of silica powder exceeds 10% to 15%, the trend of increase changes and the compressive strength of concrete decreases somewhat. The compressive strength of phase change energy storage concrete with 15% silica powder content is lower than that with 10% content. Taking concrete with a phase change aggregate content of 5% as an example, when the content of silica powder is 5%, 10% and 15% respectively, the compressive strength of concrete increases by 19.81%, 29.60% and 14.88%, respectively. Therefore, the reasonable content of silica powder is 10%. However, if the content of silica powder is between 5% and 10%, the curve may also change and there is an extreme point. Therefore, the reasonable dosage of silicon powder is between 5% and 10%.

Figure 4 shows the dependence of the splitting tensile strength on content of silica powder. The mixing of silica powder increases the

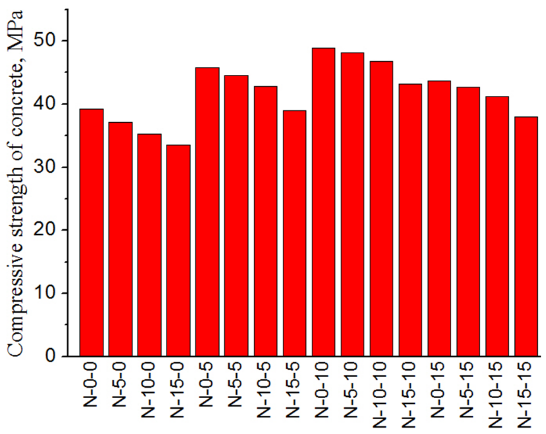

Fig. 5. Column charts of compressive strength of concrete.

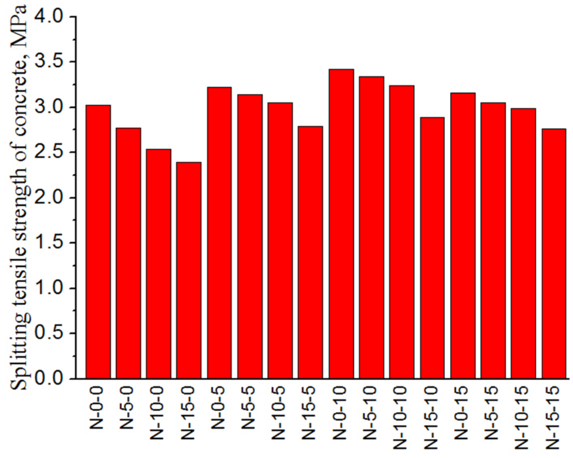

Fig. 6. Column charts of splitting tensile strength of concrete.

splitting tensile strength of concrete as shown in Figure 4. When 10% silica powder is added, the splitting tensile strength increases the most obviously. When the silica powder content increases to 15%, the splitting tensile strength decreases, but it increases compared with the concrete without silica powder. When the content of phase change energy storage aggregate was 0%, 5%, 10% and 15%, and the content of silica powder increased from 0% to 10%, the splitting tensile strength of phase change energy storage concrete increased by 11.70%, 20.58%, 27.56% and 20.92%, respectively. When the phase change energy storage aggregate content was 0%, 5%, 10% and 15%, and the silica powder content increased from 10% to 15%, the splitting tensile strength of phase change energy storage concrete decreased by 7.60%, 8.68%, 7.72% and 4.50%, respectively, but increased by 4.64%, 10.11%, 17.72% and 15.48%, respectively, compared with the concrete without silica powder.

The silica powder has a large specific surface area and can be dispersed in the pores of cement paste, which improves the compacting degree of concrete and hence the compressive and splitting tensile strength [17]. In addition, the pozzolanic effect and the pore solution chemical effect are also the key factors that can improve the compressive and splitting tensile strength by adding silica powder.

3.3. Influence of double mixing silica powder and phase change energy storage aggregate

Adding phase change energy storage aggregate to concrete will lead to the reduction of basic mechanical strength (splitting tensile strength and compressive strength) of concrete, and adding silica powder will make up for the reduction of basic mechanical strength. Therefore, it is possible to increase the content of phase change energy storage aggregate to improve its heat storage performance without reducing the strength of concrete.

The column diagram of compressive strength of concrete is shown in Figure 5. N-5-10 indicates that there is 5% phase change energy storage aggregate and 10% silicon powder in the concrete, and so on. The compressive strength of N-15-5 is 38.98 MPa and that of N-10-15 is 41.21 MPa, which are comparable to the compressive strength of plain concrete (39.29 MPa). Therefore, N-15-5 and N-10-15 are the optimal groups. However, the content of N-10-15 silica powder increased by 10% compared with N-15-5, the phase change energy storage aggregate decreased by 5%, and the compressive strength only increased by 5.7%. Therefore, considering economic factors, the optimal group was N-15-5.

The column diagram of splitting tensile strength of concrete is shown in Figure 6. The splitting tensile strength of N-10-5 is 3.05 MPa and that of N-5-15 is 3.05 MPa, which are comparable to the splitting tensile strength of plain concrete (3.02 MPa). Therefore, N-10-5 and N-5-15 are the optimal groups. However, the content of N-5-15 silica powder increased by 10% compared with N-10-5, and the phase change energy storage aggregate decreased by 5%. Therefore, considering economic factors, the optimal group was N-10-5.

To sum up, the mix ratio of concrete with silica powder content of 5 % and the phase change energy storage energy aggregate content of 10 %–15 % is suitable and achieves the expected effect. Therefore, appropriate amounts of silica powder and phase change energy storage energy aggregate compound should be used to prepare phase change energy storage concrete with good mechanical properties.

4. Conclusions

The admixture of phase change energy storage aggregate will lead to the reduction of basic mechanical strength of concrete, and the admixture of phase change storage energy aggregate should be in the range of 10%-15%.

When the phase change energy aggregate content is constant and the silica powder content is less than 10%, the splitting tensile strength and compressive strength of concrete increase. But when the content of silica fume increases from 10% to 15%, the splitting tensile strength and compressive strength of concrete decrease.

It was determined that the reasonable content of double doped phase change energy storage aggregate and silica powder are 5% of mass substitute cement like silica powder and 10-15% of volume substitute sand like phase change energy storage aggregate. The splitting tensile strength and compressive strength of the phase change energy storage concrete basically reach the strength of plain concrete.

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References

1. D.L.Zhao, C.Y.Hu, D.S.Bai et al., *Build. Ener. Conserv.*, 43 (2015).
2. S T, S W., *J. Chin. Ceram. Soc.*, **7**, 36 (2008).
3. T.C.Ling, C.S.Poon, *Constr. Build. Mater.*, 46 (2013).
4. F.Kuznik, D.David, S.K.Johannes et al., *Renewable Sustain. Energy Rev., 15 (2011).*
5. Y.Konuklu, M.Ostry, H.O.Paksoy et al., *Ener. Build.*, 106 (2015).
6. L.Derradji et al., *J. Ener. Engin.*, **4**, 141 (2014).
7. G.A.Lane, Solar Heat Storageaatent Heat Material, Floridar, CRC Press (2006).
8. B.W.Xu, Z.J.Li, *Appl. Energy*, 105 (2013).
9. L.F.Cabeza, C.Castellon, M.Nogues et al., *Ener.Build.*, **2**, 39 (2007).
10. K.D.Pejman, R.H.Matthew, R.D.Anderw et al., *Intern. J. Pavement Engin.*, **5**, 14 (2013).
11. D.P.Bentz, R.Turpin, *Cem.Concr.Compos.*, **7**, 29 (2007).
12. Y,He, X.Zhang, Y.Zhang, *J. Tongji University (Natural Science)*, **3**, 43 (2015).
13. J.Wang, Study on the Basic Theories and Preparation of Phase and Temperature Self-control Concrete, Wuhan University of Technology, Wuhan (2011).
14. X.S.Zhang, Y.Xia, X.Jin, *J. Southeast Univ. (Natural Science Edition)*, **3**, 45 (2015).
15. C.L.Ni, H.L.Tan, X.J.Zhou et al., *Bull. Chin. Ceram. Soc.*, **11**, 33 (2014).
16. Z.D.Hu, S.X.Zhao, H.T.Wang, *Bull. Chin. Ceram. Soc.*, **9**, 37 (2018).
17. J.G.Sun, Y.L.Gu, *Concrete*, **9**, 287 (2013).