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Feasibility Research of Using Phase Change Materials to Reduce the Inner Temperature Rise of Mass Concrete

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Abstract: In order to evaluate the feasibility of using phase change materials to reduce the inner temperature rise of mass concrete, the interior temperature of normal concrete specimen under semi-adiabatic curing condition was measured. The effect of embedding phase change material (PCM) and replacing water with suspension of phase change material (SPCM) as cooling fluid were compared in the experiment. The cooling effect and the affecting factors were analyzed and calculated. The research results showed that the peak of inner temperature could be decreased obviously by the method of pre-embeding PCM in concrete, however, this method is only effective in the initial stage of cement hydration process. Besides, the volume of PCM is rather big and the PCM can not be used circularly, which means that this method can only be used under special condition and the feasibility is low. When SPCM was used as cooling fluid, the interior temperature rise of mass concrete was reduced more effectively, and the temperature grads peak around the cooling pipe was also reduced. Besides, both the SPCM consumption amount and the circulation time were decreased, and most important is that the SPCM is recyclable. The technical and economical feasibility of using SPCM to reduce the inner temperature rise of mass concrete is high.

Key words: phase change material; suspension of phase change material; mass concrete; interior temperature rise; feasibility

1 Introduction

During the casting process of mass concrete, the temperature crack induced by cement hydration heat affects the security of structures heavily, which must be avoided by some cooling methods. In this research, three cooling methods were adopted to reduce the inner temperature rise and the temperature deformation of concrete.

Generally speaking, the adiabatic temperature rise was reduced by the choice of suitable materials and the optimization of the proportion of concrete based on the characteristics of raw materials. Within the construction processes, suitable cooling methods and heat preservation on the concrete surface were adopted to reduce the temperature grads.

The cooling water was circulated in the pre-embedded pipe to reduce the inner temperature rise when the above methods can't meet the cooling requirement of mass concrete[1]. However, the cooling effect is limited because of the characteristics of concrete materials and construction methods, and the temperature stress around the cooling pipe is too big to induce serious impenetrating crack potentially even through the above cooling methods were all adopted[2,3]. So, it is necessary to find new cooling methods to reduce the inner temperature rise effectively.

Phase change materials (PCM) is defined as a substance with a high heat of fusion, which melts and solidifies at a certain temperature, and is capable of storing and releasing large amounts of energy. It has been successfully used in solar energy storage, the recycling utilization of industrial waste heat, the thermal treatment of electronic devices, the heating and air-conditioning system, building construction and so on[4]. The PCM has important practical significance

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Table 1 The hydration heat of cement at different age

Time/h	5	10	12	18	24	28	36	42	48	60	72	96	120
$Q(t)$/ (kJ/Kg)	37	125	165	213	224	233	239	241	245	246	255	261	269

and broad application prospect. It is hopeful that the PCM can be used to reduce the interior temperature rise of mass concrete successfully. Many researchers began to study this problem in the 1990s. The absorption characteristic and mechanism of organic PCM in different kind of cement were summarized by Feldman[5], and the influence of temperature, humidity, glutinosity, absorption acreage and press to the absorption characteristic were also analyzed. The preparation methods of energy storage concrete, the characteristic and influencing factors of energy storage concrete were studied by Zhang[6]. The heat characteristic of self-compacting concrete mixed with PCM microcapsule was studied by Hunger M[7]. Xing Juanjuan and Deng Anzhong indicated that after PCM was blended with cement, the temperature peak could be reduced and the appearance time of temperature peak was delayed[8,9], but it is not useful to reduce the inner temperature rise after the PCM melts down. The choice standard, the mixture method and proportion of PCM were studied by Chen Meizhu based on the production mechanism of temperature crack and the characteristic of PCM[10]. The results of Yang Yongkang indicated that the speed of temperature rise could be reduced after PCM was mixed, but the strength of concrete was also decreased[11].

In the research field of SPCM, the results of Thaicham showed that, the heat transfer ability could be increased by 52% when the SPCM consistence is 20%, and the consumption of pump energy could be reduced by 16%[12]. Inaba's experimental results showed that the coefficient of heat transfer of SPCM was 2-2.8 times larger than that of water[13]. The results of Goel indicated that the temperature rise of pipe wall could be reduced by 50%[14]. Zhao Zhennan indicated that the heat transfer ability of SPCM was increased obviously comparing to that of water, but the sliminess of SPCM and the resistance coefficient of cycling system were increased[15]. The results of Zhang Yinping showed that the average specific heat of tetradecane latex was 6.6 J/g·℃, and the maximum specific heat was 13.8 J/g·℃[16]. The application method of using phase change materials to reduce the inner temperature rise of dam concrete was studied by Gao[17]. All the aforementioned researches have established the foundation of using SPCM to reduce the interior temperature rise of mass concrete.

In order to study the feasibility of using phase change materials to reduce the inner temperature rise of mass concrete, the characteristics and the temperature history of mass concrete, the phase change characteristics of PCM were considered in this paper. Two kinds of methods of using PCM to reduce the interior temperature rise of mass concrete were compared.

2 Experimental

2.1 Materials

P.O 42.5 Portland cement was used in the experiments and its hydration heat at different age is shown in Table 1.

The phase change enthalpy of PCM is 241J/g, the phase change temperature of PCM was 32.4 ℃, and the density of PCM was 1.48 g/cm^3. The SPCM used was a kind of milk white liquid, the density was 0.985 g/cm^3, and the average specific heat was 5.33 J/g·℃ in the temperature range of 16-24 ℃, and the max specific heat was 8.716 J/g·℃,

Siliceous-river sand with fineness modulus of 2.8 was used as fine aggregate, and crushed limestone with continuous grading range of 5-25 mm was used as coarse aggregate. Fly ash of Grade II according to Chinese standard was used, and its sieve residue was 14.2% and loss on ignition was 1.6%. Naphthalin water reducer with concentration of 30% was used, and its water reducing rate was 18.6%.

2.2 Method and procedure

The mixture proportions of concrete are shown in Table 2.

Table 2 The proportion of concrete/ (kg/m^3)

Cement	Fly ash	Sand	Aggregate	Water-reducer	Water
350	50	727	1 091	4.8	165

Specimens of 500 mm×500 mm×500 mm were prepared, and the weight of each specimen was 300 kg. The precision of thermometer was 0.1℃, and the measure range was 0-55 ℃.

In the pre-embedded PCM research device, 5 iron pipes with each filled with 0.8 kg solid PCM were embedded in the specimen in the concrete casting process. The interior temperature at different points was measured at different ages.

In the SPCM research device, the cooling system began to work 10-48 h later after concrete was prepared. Water and SPCM was adopted as cooling fluid in different specimens respectively. The entrance and exit temperatures of cooling fluid were 15 and 25 ℃, respectively. The cycling flow velocity of water and SPCM was 16 L/m^3·h. The interior temperature at different points was measured 10 h after the specimen was cast.

2.3 Experimental setup

The experiment was carried out in home-built semi-adiabatic insulated box. The boxes were prepared with bamboo plywood 10 mm thick, and each size was 500 mm×500 mm×500 mm. Expandable polystyrene (EPS) board 50 mm thick was used in the inner wall to prevent the heat diffusion. The inner wall of insulated box was covered with single-layer plastic film to prevent the diffusion of water. In order to reduce the heat diffusion, all the specimens were blocked up 10 cm.

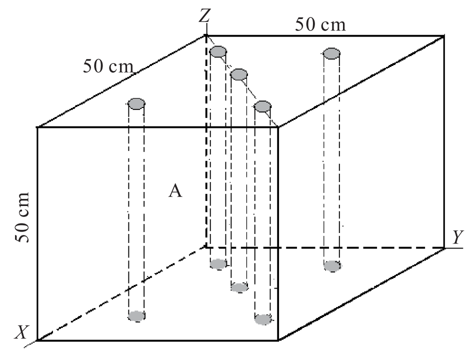

Fig. 1 The embedded position of iron pipe filled with PCM

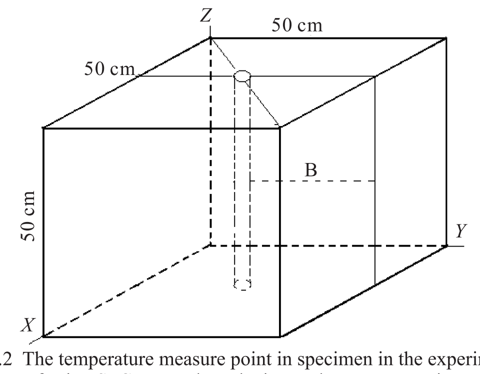

Fig.2 The temperature measure point in specimen in the experiment of using SPCM to reduce the internal temperature rise

In the experiment of pre-embedding PCM in concrete, the embedded position of iron pipe filled with PCM is shown in Fig.1. The temperature test point was A which lied in the middle position between two iron pipes. In the experiment of SPCM researches, the cooling pipe was set in the center place of the concrete specimen, and the temperature test point was B which lied in the middle position between the iron pipe and side surface of specimen, as shown in Fig.2.

3 Results and discussion

3.1 Influence of embedded PCM on inner temperature rise of concrete

The inner temperature of specimen was measured after the concrete was cast. The temperature was recorded under semi-adiabatic condition because of the inevitable heat emission from the insulated box during cement hydration. The influence of embedded PCM on semi-adiabatic temperature rise of concrete is shown in Fig.3.

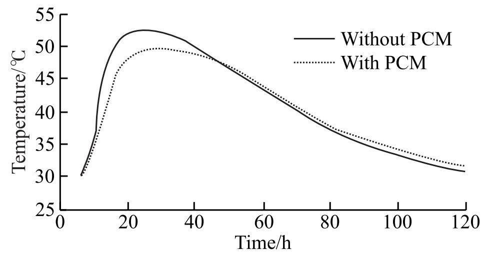

Fig.3 Influence of embedded PCM on semi-adiabatic temperature rise of concrete

Fig.3 shows that in the specimens embedded without PCM, the inner temperature reached peak value of 52.7 ℃ 24 hours after the concrete was prepared, while in the specimens embedded with 4 kg PCM, the time and peak temperature were 27 hours and 49.9 ℃, respectively. That means, the inner temperature peak could be reduced and the appearance time could be prolonged in a certain extent because a certain amount of PCM was embedded. Because the PCM changed from solid to liquid at 32 ℃ and the absorption speed of hydration heat researched the maximum value at this time, the inner temperature curves of different specimens were separated at 32 ℃. In order to study the effect and the influencing factors of embedded PCM to reduce the inner temperature rise of concrete deeply, theoretical analysis and calculation were carried out in the next section.

3.2 Influence of SPCM on inner temperature rise of concrete

In this section, the interior temperature of normal concrete cooled by water and SPCM was compared. The temperature was tested 6 hours after concrete was prepared. The inner temperature of different specimen is shown in Fig.4.

Fig.4 shows that the interior temperature peak of specimens with no cooling method, cooled by water and SPCM was 52.7, 48.6 and 46.2 ℃, respectively. It can be indicated that the cooling effect of SPCM is better than that of water. Compared to water, SPCM could be more effective to carry hydration heat outside concrete under the same cycling volume and temperature increasing, because the average specific heat of SPCM is higher than that of water within its phase change temperature range

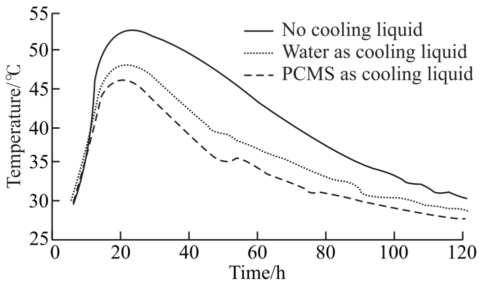

Fig.4 The change of inner temperature of different specimen

In the experiment, it was also found that the interior temperature of the specimens cooled by SPCM was lower than that of the specimens cooled by water, and the grads around the cooling pipe was also reduced, and this is beneficial to avoid the formation of the temperature cracks. From Fig.4, it can also be found that the appearance time of interior temperature peak was 24, 22 and 21 h, respectively. So, the better the cooling effect, the earlier the interior temperature peak appearance.

When the evaporation speed of hydration heat is higher than the heat release speed from specimen surface, the interior temperature of concrete specimen will increase, and *vice versa*. Because only part of hydration heat could be carried out by water and SPCM, the balance time of hydration heat and the evaporation speed from specimen surface was shortened, however, the appearance time of interior temperature peak was advanced. In order to study the influence of SPCM to the reduction of inner temperature rise of concrete, theoretical analysis and calculation would be carried out in the next section.

4 Theoretical analysis

4.1 Theoretical analysis of embedded PCM to reduce the inner temperature rise of concrete

The heat absorption process of PCM can be divided into three steps[18]. In the first step, the interior temperature is lower than the phase transition temperature and PCM exists in solid phase, and the heat absorbed by PCM in this step can be described as $Q_1 = C_1 M_P (T - t_0)$. In the second step, the interior temperature is equal to the phase transition temperature, so the PCM changes from solid to liquid, and the heat absorbed by PCM can be described by $Q_2 = M_P q$. In the third step, the interior temperature is higher than the phase transition temperature and PCM exists in liquid phase, and the heat absorbed by PCM in this period is $Q_3 = C_1' M_P (T'_{\max} - T)$. So, the total heat absorbed by PCM during heating process can be described as:

$$\begin{aligned} Q' &= Q_1 + Q_2 + Q_3 \\ &= C_1 M_{\mathrm{P}} (T - t_0) + M_{\mathrm{P}} q + C_1' M_{\mathrm{P}} (T'_{\max} - T) \end{aligned} \quad (1)$$

Because the absorbed amount of hydration heat in the first and third step is very limited, the energy of these two parts could be ignored. The whole hydration heat was translated into temperature rise of concrete under adiabatic condition, so the adiabatic temperature rise of concrete can be calculated by[19]:

$$T(t) = \frac{(M_{\mathrm{C}} + K M_{\mathrm{F}}) Q(t)}{C\rho} \quad (2)$$

The hydration heat was partly absorbed by PCM, so the interior temperature rise of concrete was reduced. And the maximum adiabatic temperature rise of concrete with pre-embedded PCM could be described by:

$$T'(t) = \frac{(M_{\mathrm{C}} + K M_{\mathrm{F}}) Q(t) - Q'}{C\rho} \quad (3)$$

The weight of pre-embedded PCM was assumed to be 60 kg/m^3, the phase change enthalpy of PCM was 241 J/g, the density and specific heat of concrete were assumed to be 2 400 kg/m^3 and 0.96 J/g℃. Based on Eq.(3) and Table 2, the adiabatic temperature rise of concrete can be calculated in different hydration ages. The adiabatic temperature rise of concrete embedded without PCM was 35.24 ℃ (24 hours later after the concrete was prepared), and the adiabatic temperature rise of concrete embedded with 60 kg/m^3 PCM was 28.97 ℃, meanwhile the pre-embedded volume of PCM was 0.04 m^3.

Generally speaking, the inner diameter of cooling pipe in mass concrete was 32 mm. It means that the length of the pipe should be at least 50.4 m to accommodate 60 kg PCM in 1 m^3 concrete, which is disadvantageous to the structure and the cost control. When the inner diameter of cooling pipe is increased to 227 mm, only 1m pipe is needed to accommodate 60 kg PCM, however, it is obviously too wide to keep the strength and integrity of the concrete structure.

Obviously, it is really a contradiction between the volume of embedded PCM and the cooling effect, so this method can only be used in the initial stage of cement hydration, and the PCM pre-embedded in concrete can't be used circularly. Based on these limitations, this method could be used under special condition to reduce the inner temperature rise of mass concrete.

4.2 Theoretical analysis of SPCM to reduce the inner temperature rise of concrete

The heat absorbed by the cooling water can be described by

$$Q_{\mathrm{w}} = C_{\mathrm{w}} v_{\mathrm{w}} \rho_{\mathrm{w}} (T_2 - T_1) t_{\mathrm{w}} \tag{4}$$

The heat absorbed by SPCM can be described by

$$Q_1 = \overline{C_1} v_1 \rho_1 (T_2 - T_1) t_1 \tag{5}$$

Part of hydration heat was absorbed by cooling fluid, and hence the interior temperature of concrete was decreased. When water was adopted as the cooling fluid, the average adiabatic temperature rise can be calculated by

$$\overline{T'_{\mathrm{w}}}(t) = \frac{(M_{\mathrm{c}} + KM_{\mathrm{F}})Q_{\mathrm{c}}(t) - C_{\mathrm{w}} v_{\mathrm{w}} \rho_{\mathrm{w}} (T_2 - T_1) t_{\mathrm{w}}}{C_{\mathrm{c}} \rho_{\mathrm{c}}} \tag{6}$$

When SPCM was adopted as the cooling fluid, the average adiabatic temperature rise of concrete can be calculated by

$$\overline{T'_1}(t) = \frac{(M_{\mathrm{C}} + KM_{\mathrm{F}})Q_{\mathrm{c}}(t) - C_1 v_1 \rho_1 (T_2 - T_1) t_1}{C_{\mathrm{c}} \rho_{\mathrm{c}}} \tag{7}$$

Here, we use Ertan Dam and Sutong Bridge concrete as examples, the mixture proportions of concrete are shown in Table 3[20, 21].

Table 3 The concrete proportion of mass concrete/(kg/m^3)

Sample	Cement	FA	Gravel	Sand	Superplasticizer	Water
Pile cap concrete	242	148	1 180	710	3.7	151
Dam concrete	133	57	1 726	574	1.332	85

The entrance and exit temperatures of cooling fluid are 15 and 25 ℃, and the circulating liquid velocities in dam concrete and bridge concrete are 3 and 5 L/h·m^3, respectively. Based on those conditions and the cement hydration heat at different time, the adiabatic temperature rise of concrete could be obtained by Formulae (5), (6) and (7), the results are shown in Fig.5.

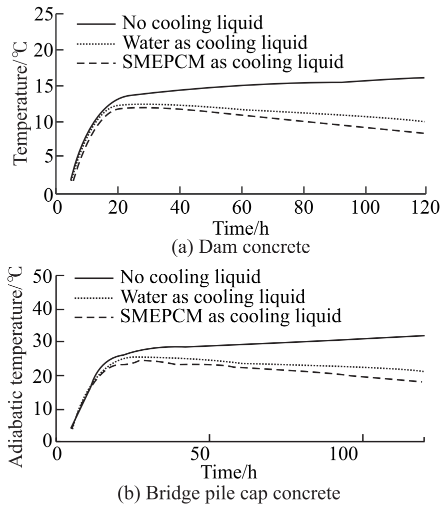

Fig.5 The change of adiabatic temperature of concrete with different cooling liquid

From Fig.5(a) it can be found that the adiabatic temperature of Dam concrete can be reduced by 8.13 ℃ when water is used as the cooling fluid, while this value will increase to 10.85 ℃ when SPCM is used as the cooling fluid. Besides, the circulation time of water is 96 h, while that of SPCM is only 72 h. From Fig.5(b) it can also be found that the corresponding adiabatic temperature reduction of Bridge Pile Cap concrete is 21.50 and 27.36 ℃, respectively, and the cycling time of water and SPCM is 96 and 75 h, respectively.

So, when water is replaced by SPCM as the cooling fluid, the extent of temperature reduction can be increased by 27%-28%, and the cooling circulation time can be correspondingly shortened by 20%-25%. The most important is that the SPCM can be used circularly, and thus the technical and economical feasibility of using SPCM to reduce the inner temperature rise of mass concrete is high. However, there are still many questions that should be solved, such as using SPCM to reduce the inner temperature rise of mass concrete at initial step, the preparation of SPCM with high stability, high average specific heat, and suitable phase change temperature. Besides, in the application process, practicable technologies to control the circulation flow velocity, the temperature between the entrance and exit, the pipe layout method design and so on should also be developed to get good cooling effect.

5 Conclusions

a)The inner temperature peak could be reduced and the appearance time could be prolonged in a certain extent because a certain amount of PCM was embedded. However, it is really a contradiction between the volume of embedded PCM and the cooling effect, so this method can only be used in the initial stage of cement hydration, and the PCM pre-embedded in concrete can't be used circularly. Based on these limitations, this method could be used under special condition to reduce the inner temperature rise of mass concrete.

b)When water was replaced by SPCM as the cooling fluid, the interior temperature rise of mass concrete was reduced more effectively. Besides, the consumption amount, the circulation time and the temperature grads peak around the cooling pipe were decreased. The most important is that the SPCM can be used circularly, and thus the technical and economical feasibility of using SPCM to reduce the inner temperature rise of mass concrete is high.

c)The research of using SPCM to reduce the inner temperature rise of mass concrete is still not intensive, there are still many works that should be conducted to study the mechanism and the application of SPCM to get good cooling effect.

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Notation:

C_1 Specific heat of solid PCM

T Phase transition temperature of PCM

M_n Weight of PCM

t_0 Initial temperature of concrete

q Phase transition heat of PCM

C'_1 Specific heat of liquid PCM

T_{max} Maximum adiabatic temperature rise of concrete embedded with PCM

$T(t)$ Adiabatic temperature rise of concrete at the age of hour

M_c Cement dosage of concrete per unit volume

K Discount coefficient, for fly ash, k=0.25, for slag powder, k=0.3

M_F Fly ash dosage of concrete per unit volume

$Q(t)$ Hydration heat of cement per unit at the age of hour, kJ/kg

C Specific heat of concrete

ρ Density of concrete

$T'(t)$ Adiabatic temperature rise of concrete at the age of hour after pre-embedded PCM

Q_1, Q_w The absorption heat of SPCM and water, kJ

C_c Specific heat of concrete, kJ/kg·℃

ρ_c Density of concrete, kg/m^3

$T'_w(t)$, $T'_1(t)$ Adiabatic temperature rise of concrete at time with water and SPCM as cooling fluid, respectively, ℃

C_w, C_1 Specific heat of water and SPCM, kJ/kg·℃

ν_w, ν_1 Cycle flow velocity of water and SPCM, L/h

ρ_w, ρ_1 Density of water and SPCM, kg/m^3

T_1, T_2 The entrance and exit temperature of cooling fluid, ℃

t_1, t_w Cooling time of water and SPCM, s