A Study on Specific Heat of Paste, Mortar, and No-Fine Concrete Containing Fly Ash

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Abstract

This study is aimed to investigate the specific heat of fly ash concrete. The experiments were conducted to obtain the specific heat of fly ash-cement pastes, mortars, and no-fine concrete. The model for predicting specific heat regarding time dependent properties of fly ash concrete was proposed. The specific heat of concrete was computed based on the weight fractions and respective specific heat values of each ingredient including the hydrated and pozzolanic products. The specific heat of hydrated and pozzolanic products was derived by back analysis using the results of measured specific heat of paste. From the experimental results it was found that the specific heat depends largely on the amount of free water content in the specimens. The specific heat reduces with a decrease in the amount of free water content. The replacement of cement by fly ash yields high specific heat at young age but tends to reduce in long term due to pozzolanic reaction. The specific heat of mortars, and no-fine concrete are lower than that of cement pastes. The comparisons between the experimental results and the specific heat model show that the proposed model is almost satisfactory for predicting the specific heat of the tested pastes, mortars and no-fine concrete.

1. Introduction

Fly ash has been used as a cement-replacing material for producing many types of concrete such as low heat concrete, self-compacting concrete, and roller compacted concrete, etc. Fly ash improves many physical and mechanical properties of concrete. In mass concrete, fly ash is effective for controlling temperature from hydration reaction to prevent thermal cracking.

Specific heat is little affected by the mineralogical character of the aggregate, but is considerable increased by an increase in the moisture content of the concrete [1]. In 1970, Brown and Javaid [2] reported that the specific heat for normal strength concrete varies from 1.15 to 0.89 kJ/kg /°C at ages varying from 6 hours to 7 days, respectively. A test method for the specific heat during hardening, taking account of the hydration heat production, was described by Hansen et al. in 1982 [3]. They reported a decrease in specific heat of about 15 percent from a few hours after casting to an age of 5 days. In 1995, Schutter and Taerwe [4] measured the specific heat of hardening cement paste samples made with blast furnace slag cement and found that the specific heat decreases linearly with the degree of hydration. In 2000, Xu and Chung [5] reported that sand addition decreases the specific heat of mortars with and without silica fume by 11% and 13%, respectively when compared to those of cement pastes with and without silica fume. Although almost all researchers reported a decrease of the specific heat during hardening but few efforts had been made to quantitatively predict the specific heat especially for fly ash concrete as well as considering time dependent properties.

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Specific heat of concrete is an important parameter for computing the temperature distribution in mass concrete. Nowadays, the constant specific heat values of matured concrete have been traditionally used in analysis of thermal cracking problems, however, this is not realistic especially during very early age where the thermal cracking problems is the most serious. As a result, the model for predicting the specific heat regarding time dependent properties of fly ash concrete was proposed in this study. The objective is to adopt the proposed model for simulating thermal cracking normally occurs at early age of mass concrete.

During the reaction process specific heat changes with respect to time. The amount of free water in concrete decreases with an increase in the degree of reaction. As the specific heat of water is the highest among those of all ingredients of concrete, specific heat of concrete is considered to decrease rapidly at the early stage of reaction with a decrease in the amount of free water.

2. Experimental Program

2.1 Mix proportion and materials

A total number of nine mixtures were produced and tested. They were cement-fly ash pastes, mortars and no-fine concrete. In each set, ratio of water to binder (w/b) and replacement ratio of cement by fly ash (f/(c+f)) were varied. The mix proportions of the tested mixtures are shown in Table 1.

Table 1 Mix proportion of the tested samples

Mixture Type	w/b	f/(c+f)	s/(c+f)	g/(c+f)
w25r0	0.25	0	0	0
w40r0	0.40	0	0	0
w25r3	0.25	0.3	0	0
w25r5	0.25	0.5	0	0
w40r3	0.40	0.3	0	0
w40r5	0.40	0.5	0	0
w40s1	0.40	0	1	0
w40s3	0.40	0	3	0
w40g3	0.40	0	0	3

Remarks: w: water, f: fly ash, c: cement, s: sand, and g: limestone coarse aggregate

Cement-fly ash pastes were cast and tested for specific heat at various ages (1, 3, 7, and 28 days). Mortars and no-fine concrete were tested to observe the effect of aggregates. The chemical compositions and physical properties of cement and fly ash are shown in Table 2.

Table 2 Chemical composition and physical properties of Portland cement type I and fly ash

Chemical Compositions (% by weight)	Cement Type I	Fly Ash
SiO_2	20.99	45.88
Al_2O_3	5.18	26.20
Fe_2O_3	3.20	10.94
CaO	64.63	8.28
MgO	1.30	2.83
SO_3	2.61	1.04
Na_2O	0.04	0.90
K_2O	0.40	2.78
TiO_2	0.25	0.51
P_2O_5	0.05	0.10
LOI	1.17	0.17
Free Lime	0.75	0.18
Specific Gravity	3.15	1.85
Blaine Fineness (cm^2/g)	3190	3460

All samples were cast in PVC pipes which have 1-inch diameter and 2- inch length. After one day, the pipes were removed and all specimens were sealed by aluminum foil. Because the thickness of aluminum foil is very thin and possesses very high heat conductivity and low specific heat so the effect of aluminum foil on the specific heat of specimen can be neglected. The specimens were kept in the room temperature (28 + 2 °C) and in seal-curing condition.

2.2 Specimen preparation and test procedure

Two specimens were cast for each type of mixture. For the first one, the thermocouple was placed at the center of the specimen while for the second specimen, thermocouple was placed near the surface (0.5 cm. from the surface of the specimens). The positions of the thermocouple are shown in Figure 1. This effort was firstly for taking into account the non-uniform temperature that might occur within the specimen. However, it was found later from the test that the differences were negligible. The specific heat, obtained from the tests, was then the average value of these two specimens.

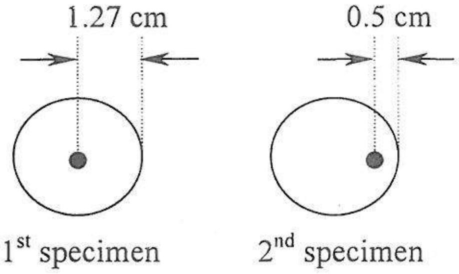


Figure 1 The positions of the thermocouples

The apparatus and its setting for testing specific heat are shown in Figure 2 and Figure 3.

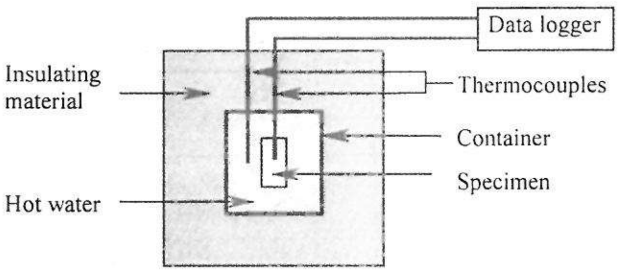
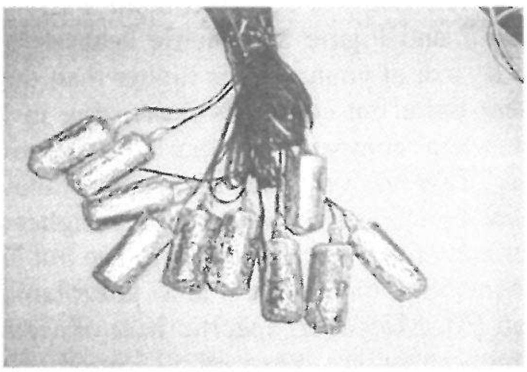
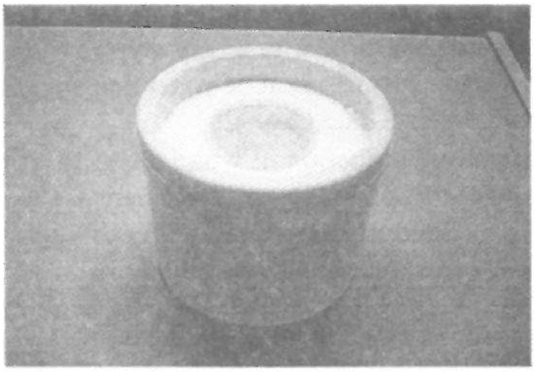


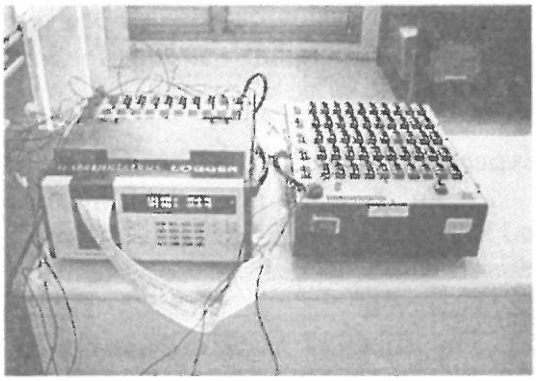
Figure 2 Schematic of apparatus for testing the specific heat values



(a) Sealed specimens



(b) Insulated container



(c) Data logger

Figure 3 Apparatus for testing the specific heat

In the tests, the specimens were submerged in hot water in an insulated container. The heat supplied to the specimens was obtained from the hot water. Temperature of the hot water and the specimens were recorded by using data logger at every 30 seconds. The calculations of specific heat are shown in Eq. (1) to Eq. (3).

$$Q_w - Q_{loss} = Q_{sp} \quad (1)$$

$$m_w c_w \Delta T_w - m_w c_w \Delta T_{loss} = m_{sp} c_{sp} \Delta T_{sp} \quad (2)$$

$$c_{sp} = \frac{m_w c_w (\Delta T_w - \Delta T_{loss})}{m_{sp} \Delta T_{sp}} \quad (3)$$

where Q_w is the heat reduced in water (kcal), Q_{loss} is the heat loss from water to the environment (kcal), Q_{sp} is the heat intake in specimens (kcal). m_w and m_{sp} are the mass of water and specimen, respectively (kg). c_w and c_{sp} are the specific heat of water and specimen, respectively (kcal/kg/°C). ΔT_w is the temperature reduction of water (°C), ΔT_{sp} is the temperature increase of specimen (°C), and ΔT_{loss} is the temperature reduction of water due to loss of heat to the environment.

In order to measure temperature loss (ΔT_{loss}), the system with water only was used to record the temperature change of the water due to loss into the environment. The temperature was recorded by using data logger at every 30 seconds. This calibration was done for 3 cycles then the average value was used.

3. Experimental Results

From the experimental results, it was found that the specific heat of concrete decreased with a decrease in the amount of free water in concrete.

The effect of water to binder ratio are shown in Figure 4 to Figure 6. Pastes with lower free water content (w/b = 0.25) have lower specific heat than those with higher free water content (w/b = 0.40). The specific heat of water is much higher than that of cement, so lower w/b gives lower specific heat.

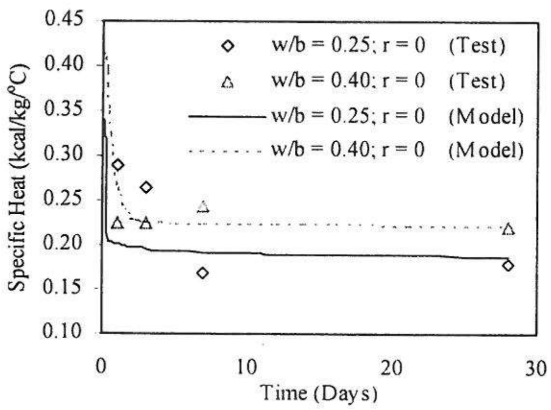


Figure 4 Comparisons between test results and the specific heat model of cement paste with w/b = 0.25 and 0.40

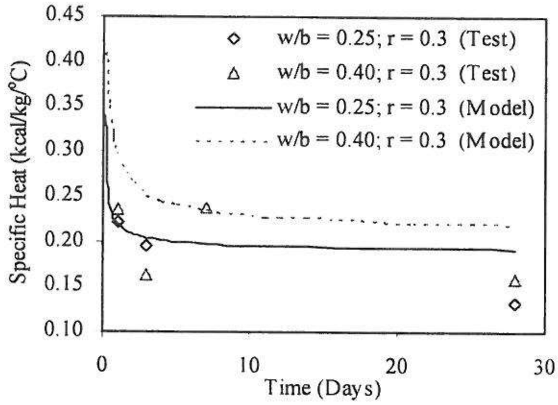


Figure 5 Comparisons between test results and the specific heat model of cement paste with fly ash replacement ratio of 0.3, and w/b = 0.25 and 0.40

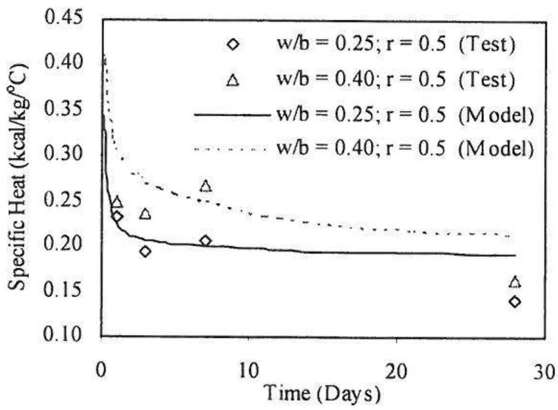


Figure 6 Comparisons between test results and the specific heat model of cement paste with fly ash replacement ratio of 0.5, and w/b = 0.25 and 0.40

The effect of fly ash content is shown in Figure 7 and Figure 8. Specific heat of pastes with fly ash at young age is higher than that of cement paste but continues decreasing in long term when compared to that of the cement paste. This is because the replacement of cement by fly ash causes relatively higher free water content of mixtures at early age but tends to decrease in longer age due to pozzolanic reaction [6]. Moreover, specific heat of water is the highest among those of all ingredients of concrete. As the results, the specific heat of fly ash-cement paste has similar time-dependent tendency as the amount of free water content.

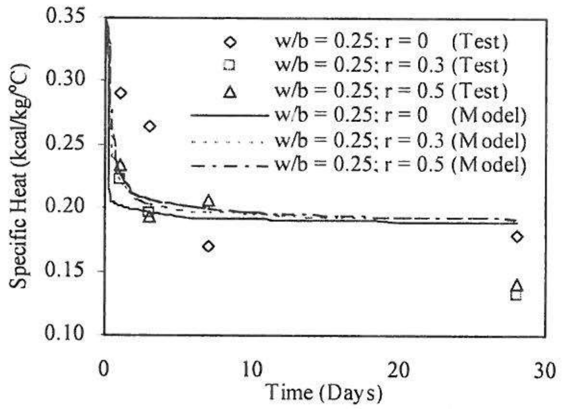


Figure 7 Comparisons between test results and the specific heat model of cement paste with fly ash replacement ratio of 0, 0.3 and 0.5, and w/b = 0.25

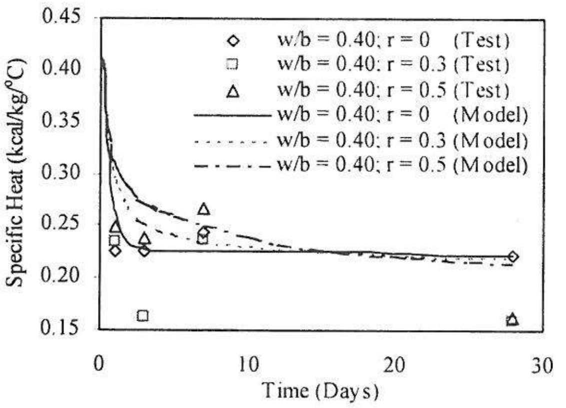


Figure 8 Comparisons between test results and the specific heat model of cement paste with fly ash replacement ratio of 0, 0.3 and 0.5, and w/b = 0.40

The higher specific heat of paste with fly ash at young age indicates that fly ash is beneficial as cement replacing material to reduce temperature of mass concrete in addition to the lower heat generation.

The effects of fine aggregate content and limestone coarse aggregate content are shown in Figure 9 and Figure 10, respectively. The specific heat of cement paste is higher than that of mortars and no fine concrete because of its higher amount of free water content. Moreover, both sand and limestone coarse aggregate have lower specific heat than water, so the specific heat of mortars and no-fine concrete are lower than that of the cement paste and the mixtures with more aggregate content yields smaller specific heat.

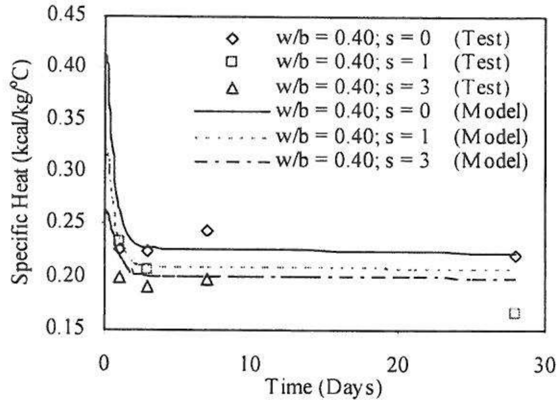


Figure 9 Comparisons between test results and the specific heat model of mortars with sand to binder ratio of 0, 1 and 3, and w/b = 0.40

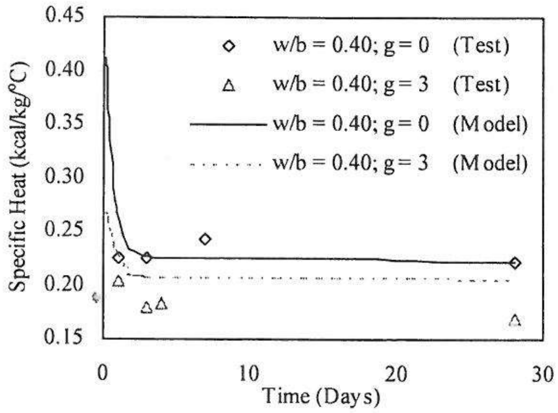


Figure 10 Comparisons between test results and the specific heat model of no-fine concrete with limestone coarse aggregate to binder ratio of 0 and 3, and w/b = 0.40

4. Specific Heat Model

In this study, Eq. (4) was proposed for estimating the value of specific heat of pastes, mortars and no-fine concrete. The specific heat of concrete was assumed to be computed based on the weight fraction of the ingredients including the hydrated and pozzolanic products and their individual specific heat. The assumptions of the model are as follows:

1. The changes of total volume and unit weight of concrete during hydration are

assumed to have negligible effect on specific heat of concrete.

2. As the weight of air is negligibly small compared to those of the other components of concrete, it is ignored to compute the specific heat.
3. All hydrated and pozzolanic products have the same specific heat

As the reaction proceeds, the amount of free water in concrete reduces with an increase in the amount of reacted product and concrete converts from a fresh state to plastic and hardened states. So the specific heat of concrete decreases with time. As coarse aggregate, and fine aggregate are inert, their weight fractions and specific heat remain constant throughout the reaction. At the same time the volume of non-reacted cementitious material (e.g. cement and fly ash) and free water reduces and the amount of reacted product increases with time. Considering these factors, the following equations were proposed to determine the specific heat of concrete during the reaction process.

$$c(t) = w_g c_g + w_s c_s + w_{fw}(t)c_w + w_{uc}(t)c_c + w_{ufa}(t)c_{fa} + w_{hp}(t)c_{hp} \quad (4)$$

$$w_{uc}(t) = (1 - \frac{\alpha_{hy}(t)}{100})w_{c0} \quad (5)$$

$$w_{ufa}(t) = (1 - \frac{\alpha_{poz}(t)}{100})w_{fa0} \quad (6)$$

at anytime, t,

$$w_g + w_s + w_{w0} + w_{c0} + w_{fa0} = 1.0 \quad (7)$$

$$w_{hp}(t) = 1.0 - (w_g + w_s + w_{fw}(t) + w_{uc}(t) + w_{ufa}(t)) \quad (8)$$

where c(t) is the specific heat of concrete at the time considered (kcal/kg/°C). w_g, and w_s are the weight ratio of gravel, and sand per unit weight of concrete, respectively. $w_{fw}(t)$, $w_{uc}(t)$, $w_{ufa}(t)$, and $w_{hp}(t)$ are the weight ratio of free water, unhydrated cement, non-reacted fly ash, and the hydrated and pozzolanic products, respectively, at the time considered. c_g, c_s, c_w, c_c, c_{fa}, and c_{hp} are the values of specific heat of coarse aggregate, sand, water, cement, fly ash, and the hydrated and pozzolanic products, respectively (kcal/kg/°C). w_{c0}, w_{fa0}, and w_{w0} are the weight of cement, fly ash, and water per unit weight of concrete at the time of mixing (at t = 0). $\alpha_{hy}(t)$, and $\alpha_{poz}(t)$ are the average degree of hydration, and the degree of pozzolanic reaction of paste at the considered age, respectively (%).

The weight fraction of free water content at a certain age used in this study was proposed by Tangtermsirikul and Saengsoy [6] as in Eq. (9).

$$w_{fw}(t) = w_{w0} - w_{whp}(t) - w_{wgel}(t) \quad (9)$$

$$w_{whp}(t) = \theta_f \cdot (w_{c0} + w_{fa0}) \cdot \frac{\alpha_{avg}(t)}{100} \quad (10)$$

$$\theta_f = 0.21 - 0.13 \cdot r^{2.15} \quad (11)$$

$$w_{wgel}(t) = \theta_{gel} \cdot (w_{c0} + w_{fa0}) \cdot \frac{\alpha_{avg}(t)}{100} \quad (12)$$

$$\theta_{gel} = (0.19 + 0.13 \cdot r^{2.15}) \cdot \phi_{w/b} \cdot \phi_r \quad (13)$$

$$\alpha_{avg}(t) = (1-r) \cdot \alpha_{hy}(t) + 0.4 \cdot r \cdot \tan^{-1}[13 \cdot \alpha_{poz}(t)] \quad (14)$$

where $w_{fw}(t)$ and $w_{wgel}(t)$ are the weight fraction of free water and gel water in paste at time t, respectively. $w_{whp}(t)$ is the weight fraction of water consumed by hydration and pozzolanic reactions. θ_f is the minimum ratio of water to binders for completing reactions. θ_{gel} is the ratio of gel water to binders in paste at the state of complete reactions (kg/m^3). r is the replacement ratio of fly ash in total binder content by weight, w/b is the water to binder ratio, and t is the age of paste (days). $\alpha_{avg}(t)$ is the average degree of reaction of paste from Eq. (14) (%). $\phi_{w/b}$ is the effect of water to binders ratio on gel water content at state of complete reactions, and ϕ_r is the effect of replacement ratio of cement by fly ash on gel water content at the state of complete reactions.

5. Verification of Specific Heat Model

The values of specific heat of other ingredients of concrete except that of hydrated and pozzolanic products were obtained from the American Society of Heat and Refrigerating Engineers Fundamentals Handbook [7]. The specific heat of hydrated and pozzolanic products was derived from back analysis using the test results of specific heat of the tested paste samples and Eq. (4). Table 3 shows the values of the specific heat of all ingredients in the cement pastes, mortars and no-fine concrete.

Table 3 Specific heat of the ingredients of concrete

Concrete Ingredients	Specific Heat (kcal/kg/°C)
Water	1.00
Cement	0.18
Fly Ash	0.17
Fine Aggregate (Sand)	0.19
Coarse Aggregate (Limestone)	0.20
Hydrated and Pozzolanic Products*	0.13

* from back analysis

The specific heat of hydrated and pozzolanic products obtained from back analysis was found to be about 0.13. By using Eq. (4), and the specific heat of the ingredients in the concrete in Table 3, the specific heat of the tested pastes, mortars and no-fine concrete were computed. The comparison between the analytical results and the experimental results are shown in Figure 4 to Figure 10. Figure 4 and Figure 5 show the effect of replacement ratio of fly ash. The effect of water to binder ratio is shown in Figure 6 to Figure 8. Figure 9 and Figure 10 show the effect of fine aggregate content and limestone coarse aggregate content, respectively. It is shown in the figures that the specific heat model is qualitatively satisfactory to predict the specific heat of the tested pastes, mortars and no-fine concrete. The model shows, in Figure 4 and Figure 5, that the specific heat of pastes with fly ash tend to continue decreasing in long term when compared to that of the cement paste. The model also shows, in Figure 6 to Figure 8, that the pastes with higher free water content (w/b = 0.4) have higher specific heat than those with lower free water content (w/b = 0.25). Figure 9 and Figure 10 show that the model is able to predict the lower values of specific heat of mortars and no-fine concrete than that of the cement paste.

6. Conclusions

It can be concluded from the experimental results that the specific heat depends largely on the amount of free water content in the specimens. The replacement of cement by fly ash yields high specific heat at young age but will prolong to decrease in long term due to pozzolanic reaction. The specific heat of hydrated product obtained from back analysis was equal to 0.13.

The proposed equations can be nearly quantitatively used to predict the specific heat of the tested pastes, mortars and no-fine concrete.

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