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Predicting early-age temperatures of blended-cement concrete

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The advisability of controlling the temperature rise and fall in concrete at early age is well recognised, and the choice of an appropriate low-heat cement with suitable heat of hydration characteristics can assist in this control. This is particularly pertinent with respect to water-retaining and massive concrete structures, where the need to prevent early-age thermal cracking is paramount. Portland cement/ground granulated blast-furnace slag (PC/ggbs) or PC/fly ash cements are often used in these structures because of their low heat of hydration properties. This paper describes a study carried out to predict the early temperature rises for concrete containing different PC/ggbs and PC/fly ash cements. Current UK guidance normally requires knowledge of the proportion of ggbs or fly ash. Such information may not be available when using the recently published European standards for low-heat cements. To provide design data for these materials, cements just meeting the limiting heats of hydration for the low-heat and very low-heat classes were simulated. Temperature rises were predicted by a computer program that applied heat of hydration models to general heat flow theory with parameters to account for cement content, formwork type and section thickness.

1. INTRODUCTION

The advisability of controlling the temperature rise and fall in concrete at early age is well recognised as one of the major factors preserving long-term performance and durability of structures. However, when the difference between the peak temperature inside the concrete core and the restraining concrete is large, temperature gradients across the concrete section can initiate cracking on the surface. If these cracks are not minimised and crack widths controlled, cracking may seriously affect serviceability, particularly with respect to water-retaining structures. Thermal cracking may be controlled by reducing the thermal movement or by reducing the restraint, but in most circumstances the use of distribution reinforcement parallel to each face of the member is the most economical and convenient method of crack control.[1] The amount of differential reinforcement required to control cracking is generally considered to be directly proportional to the difference between the peak temperature of the section and the temperature of the restraining concrete (usually assumed to be mean ambient temperature): this difference in temperature is often known as the T_1 value. In selecting the amount of crack control reinforcement required, engineers need to predict the temperature rise in concrete, and to this end they use guidance documents[1–4] that allow predictions of T_1 based on knowledge of cement type, cement content, formwork type, section size, ambient temperature and placing temperatures.

To minimise the amount of crack control reinforcement, it is necessary to minimise the T_1 value, and, in addition to other means, it is usual to select a cement with a low rate of heat evolution.[5,6] Indeed, blended cements or combinations consisting of Portland cement (PC) and ground granulated blast-furnace slag (ggbs) or fly ash are widely used because they have low heat of hydration while producing concrete with excellent long-term strength and durability.[7–9]

To assist engineers in specifying a cement with an appropriate rate of heat evolution, heat classes have been incorporated into the European standards BS EN 197-1,[10] BS EN 197-4[11] and BS EN 14216.[12] BS EN 197-1 and BS EN 197-4 have a single class of low heat cement, known as *low heat* and denoted as LH. The heat of hydration requirement, determined in accordance with EN 196-9 (semi-adiabatic method)[13] or EN 196-8 (heat of solution method),[14] is for a maximum characteristic heat of hydration of 270 J/g.

BS EN 14216 defines very low-heat special cements, which are cements that, through composition, fineness and reactivity of constituents, have a slower early hydration process than low-heat common cements. They must meet a requirement for a lower heat of hydration (220 J/g) than low-heat cements, and are denoted as VLH (very low heat). Very low-heat special cements are particularly suitable for dams and other massive constructions where the dimensions of the structure have a low surface/volume ratio. For blastfurnace cement, the minimum ggbs content allowed for a very low-heat special cement is 66% by mass.

When using factory-blended low-heat cements, the ggbs or fly ash content may not be exactly known, and the current guidance[1–4] used by UK engineers to predict early-age temperature rises in concrete is not applicable, as these documents may be used only where the ggbs or fly ash content of the cement is known explicitly. However, engineers may request details of the composition from the cement producer (BS EN 197-1 NB.3[10]), and although BS 8500[15] does not require the furnishing of similar information on any combination produced by a concrete supplier, engineers can insist on its being agreed in the specification for their concrete.

This paper describes a study carried out to provide data for predicting the early temperature rises for concrete containing cements meeting the LH and VLH classes. Cements characteristic of factory-made blended cements, or concrete combinations of the same composition, currently available in the UK, were produced by combining PC with various proportions of ggbs or fly ash. Although factory blends are likely to have a somewhat higher gypsum content than combinations of PC and addition, it was felt that this would not have a significant effect on the relationship between heat of hydration and temperature rise. Cements just meeting the limiting heats of hydration for the low-heat and very low-heat classes were determined for the materials tested. Temperature rises were predicted by a computer program that applied heat of hydration models to general heat flow theory with parameters to account for cement content, formwork type and section thickness.

2. PROGRAMME OF WORK

The work was carried out in the following steps

(*a*) a systematic series of semi-adiabatic calorimeter tests to identify cements just meeting the requirements for the LH and VLH classes in BS EN 197-1 and BS EN 14216 respectively
(*b*) development of a heat calculation program to determine the early-age temperature rises in concrete based on general heat flow theory and heat of hydration models
(*c*) calculation of temperature rises for concrete (up to 1000 mm section thickness) containing cements just meeting the limits for the LH and VLH classes.

2.1. Materials

A single Portland cement, strength class 42·5N conforming to BS EN 197-1,[10] was used throughout. Two sources of ggbs, denoted GA and GB, and two sources of fly ash, FA and FB, were used to prepare different blended cements. The physical and chemical properties are shown in Table 1. GA and FA were finer than GB and FB respectively.

2.2. Cements and test programme

To determine combinations of PC, ggbs and fly ash that just met the limiting characteristic heats of hydration for LH and VLH classes, semi-adiabatic tests were carried out for a range of cements, including 100% PC, eight different ggbs contents, 20%, up to 90% by mass, and five fly ash contents, 15–65% by mass.

3. SEMI-ADIABATIC CALORIMETRIC TEST RESULTS

Semi-adiabatic heat of hydration was measured in accordance with EN 196-9,[13] which consists in introducing a box containing mortar (1050 g CEN standardised sand, 175 g water and 350 g cement) into a calorimeter in order to determine the quantity of heat emitted on the basis of the temperature development. The calorimeter consists of an insulated flask sealed with an insulated stopper and encased in a rigid casing. At any given time the heat of hydration of the cement contained in the sample is equal to the sum of the heat accumulated in the calorimeter and the heat lost into the ambient atmosphere. The temperature of the mortar is subtracted from the temperature of an inert reference calorimeter of equivalent dimensions containing an inert (at least 12 months old) sample of mortar, to give the temperature rise of the test sample for use in calculations. The temperature rise depends mainly on the characteristics of the cement and is normally between 10°C and 50°C. The test is run for 41 h, at which time the reference heat of hydration (H_{41}) for use in categorising cements in accordance with BS EN 197-1 and BS EN 14216 is achieved.

		ggbs		Fly ash	
Property	PC	GA	GB	FA	FB
Relative density	3·14	2·86	2·88	2·14	2·06
Fineness: m^2/kg	405	602	466	7·2*	35·0*
Particle size distribution: % passing by volume					
125 μm	100·0	100·0	100·0	100·0	97·3
100 μm	100·0	100·0	99·9	99·8	93·0
75 μm	99·8	100·0	99·6	97·7	85·9
45 μm	96·6	98·7	96·6	88·7	69·9
25 μm	81·8	91·2	84·9	70·9	50·7
10 μm	41·2	62·4	53·7	41·6	28·5
5 μm	19·7	41·5	34·5	24·6	16·9
2 μm	7·7	21·4	17·1	10·9	7·7
1 μm	4·3	10·5	8·1	5·5	3·8
0·7 μm	2·4	5·5	4·1	3·0	2·0
0·5 μm	0·8	1·7	1·3	1·0	0·6
0·2 μm	0·1	0·2	0·1	0·1	0·1
Bulk oxide composition					
SiO_2	21·5	35·2	36·3	44·2	46·6
Al_2O_3	5·4	13·1	12·6	29·0	29·3
Fe_2O_3	2·6	0·2	0·5	5·9	6·5
CaO	64·2	41·0	42·1	2·2	2·2
MgO	2·6	8·1	6·9	0·9	0·8
P_2O_5	0·1	0·0	0·0	0·6	0·5
TiO_2	0·3	0·7	0·6	1·5	1·4
SO_3	2·8	—	—	0·6	0·7
K_2O	0·7	0·5	0·3	1·2	1·1
Na_2O	0·3	0·2	0·2	0·2	0·2
MnO	0·0	0·5	0·3	0·0	0·0

*Percentage by mass retained on 45 μm sieve.

Table 1. Properties of cements and additions used in study

Relationships between cumulative heat of hydration and time are shown in Fig. 1. The H_{41} value for the PC (338 J/g) fell towards the lower end of the range of UK Portland cements as tested by the authors (327–372 J/g). The curves for Portland cement and low fly ash or ggbs contents show an S-shape relationship that is typical of Portland cement hydration.[16] However, with very high fly ash or ggbs contents (particularly ggbs contents $> 70\%$ by mass), the relationships between heat of hydration and time approach an apparent linearity: that is, the ratio between the heat of hydration at the midpoint of the test (20 h) and that at the end (41 h) approaches a value of 0·5 as the ggbs content increases (Fig. 2). This means that approximately 40–50% of the heat of hydration when using high-content ggbs cements occurs after 20 h, compared with Portland cement ($H_{20}/H_{41} = 0{\cdot}8$), for which 80% of the heat at 41 h is generated in the first 20 h. It may be concluded from this 'apparent linearity' that the test (up to 41 h) is insufficient for deriving the total heat of hydration of PC/ggbs cements. Although this means that the test is unsuitable for generating data for use in predictive modelling, it does distinguish clearly between cements containing different percentages of fly ash and ggbs. For this reason, it appears

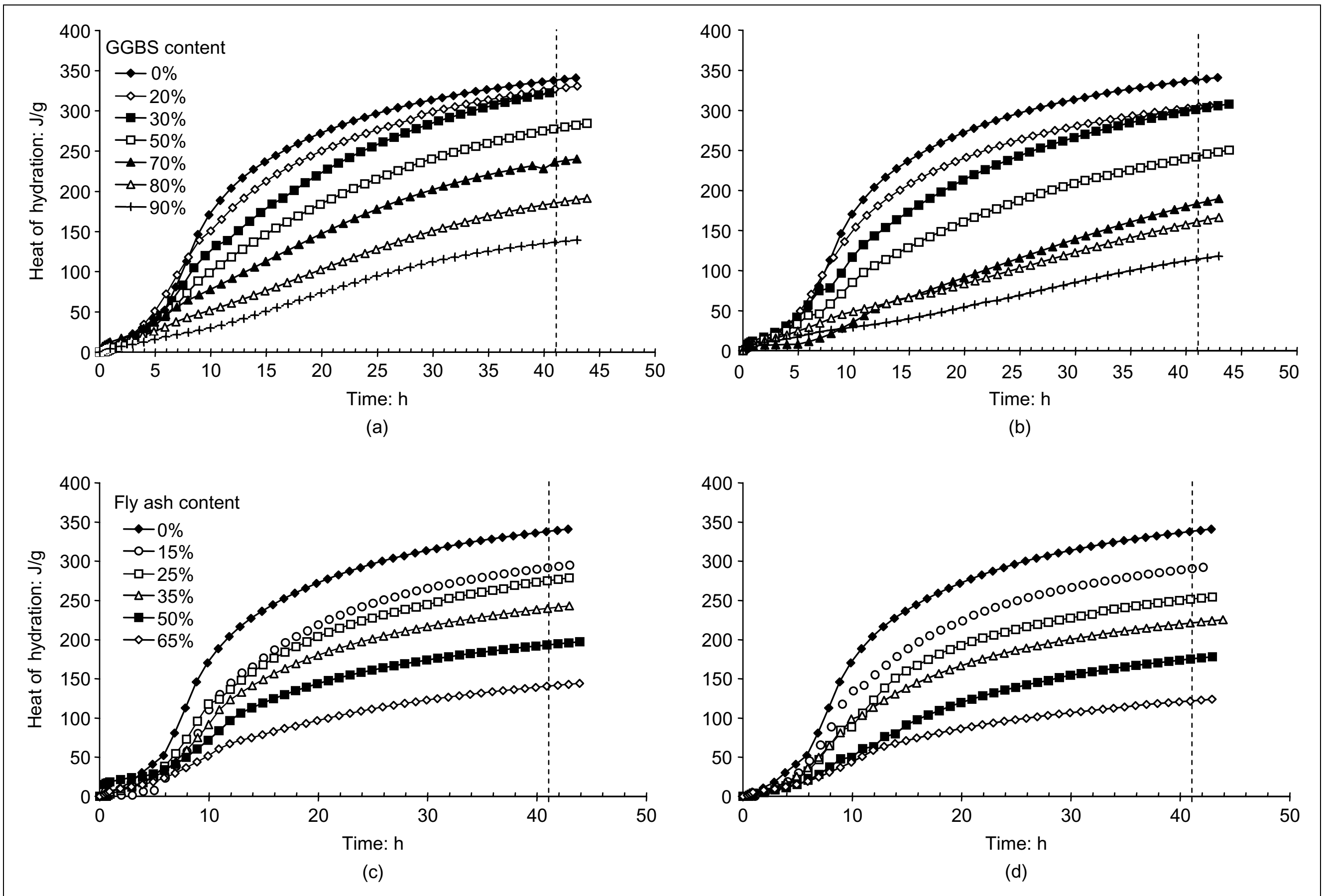

Fig. 1. Effect of ggbs content and fly ash content on cumulative semi-adiabatic heat of hydration: (a) PC/GA; (b) PC/GB; (c) PC/FA; (d) PC/FB

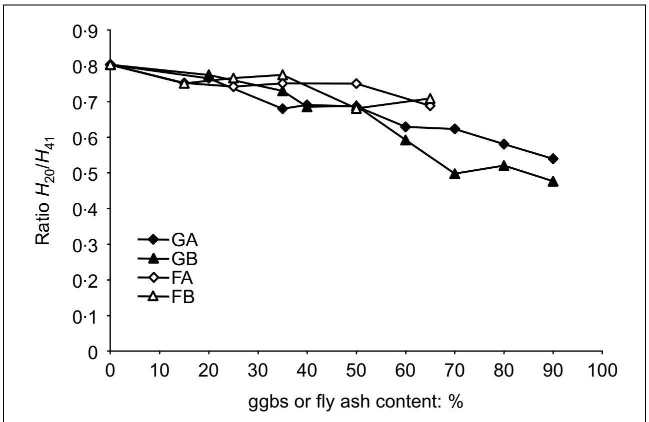

Fig. 2. Effect of ggbs content and fly ash content on ratio of heat at 20 h to that at 41 h

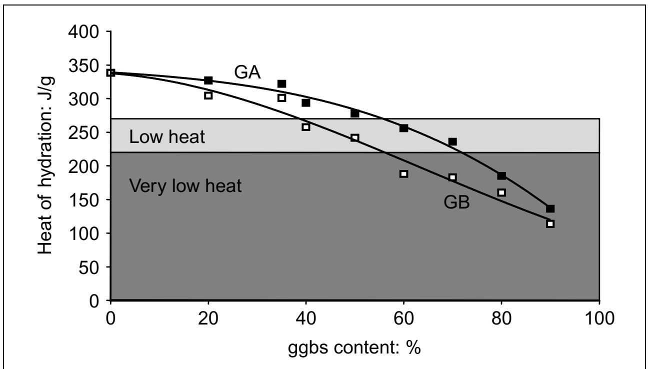

Fig. 3. Effect of ggbs content on semi-adiabatic heat of hydration

suitable for use as a simple and efficient means of categorising cements based on heat of hydration.

3.1. PC/ggbs cements

Figure 3 shows the effect of ggbs content on the heat of hydration after 41 h. It is clear that, as the ggbs content increased, the measured heat of hydration reduced, and that cements made with the finest ggbs (GA) gave off greater heat for a given content, the maximum difference being 69 J/g for a ggbs content of 60% by mass. Consequently, there were differences in the ggbs content necessary to meet the requirements for LH and VLH classes between cements containing GA and GB, as shown in Table 2. For example, only 40% of GB was required to meet the LH class, but when GA was used, the LH class was not met until more than 50% ggbs was used.

This difference is significant, because ggbs is typically used in cements in the range 40–50% by mass of cement. The results show that a blast-furnace cement made by factory-blending GA with the current PC would need to contain over 50% by mass of GA in order to be classified as a low-heat cement.

3.2. PC/fly ash cements

Figure 4 shows the effect of fly ash content on the heat of hydration after 41 h. As with ggbs, the measured heat of hydration reduced with an increase in fly ash content, and

Heat class	ggbs content: %		Fly ash content: %	
	GA	GB	FA	FB
LH	56	39	25	20
VLH	72	56*	43	36

*Note that by definition the minimum ggbs content for a very low-heat special cement is 66% by mass.

Table 2. Lower limits on addition content to meet LH and VLH classes

cements made with the finest material (FA) gave off greater heat for a given content. However, the differences were small: only 24 J/g for a fly ash content of 25% by mass. Subsequently, there were smaller differences in the PC/fly ash cements meeting the requirements for LH and VLH classes (Table 2) than for the PC/ggbs cements. For example, only 20% of FB was required to meet the LH class, compared with 26% when using FA.

Note that fly ash used at 30–35% by mass of cement, which is common in the UK, would be classified as a low-heat cement for both fly ashes used in this study.

The dotted line in Fig. 4 shows the theoretical heat generated by a cement containing PC and a completely inert fly ash. It can be seen that the results for PC/FB cements are only slightly above this line. From this it may be suggested that FB is practically inert with regard to its contribution to heat at early ages for the temperature investigated.

4. CALCULATION OF EARLY-AGE TEMPERATURE RISES

For controlling early-age thermal cracking in concrete, most design guidance is related to the difference in temperature between the peak temperature of the centre of section and the temperature of the restraining concrete (taken to be mean ambient temperature), sometimes known as the T_1 value. This is not in fact the critical temperature difference in early-age concrete,[2] but as a design assumption has proven to be a good basis on which to estimate the appropriate crack control reinforcement. The temperature rise in a section depends on the balance between the heat generated during the hydration reactions and the heat lost from the concrete, and can be calculated through general heat flow theory.

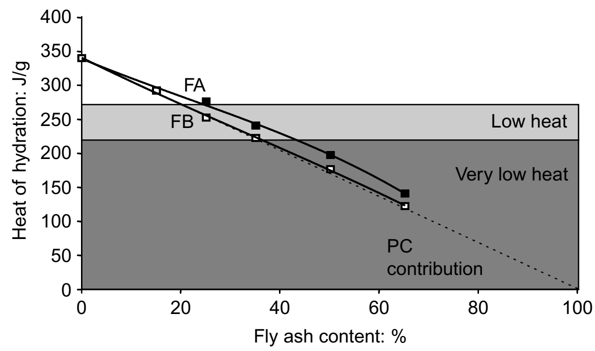

Fig. 4. Effect of fly ash content on semi-adiabatic heat of hydration

4.1. Heat flow calculations

General heat flow theory is well established,[17,18] and in a solid material—a concrete wall, for example—heat flows from an area of higher temperature to an area of lower temperature. At the same time, the concrete temperature will increase owing to internally or externally generated heat, and may decrease due to heat lost at the surface. Therefore, at any point in time, the temperature distribution in a concrete cross-section is the dynamic heat balance between the heat generated inside the concrete and the heat lost to, or gained from, the ambient. The temperature distribution within a concrete body or the momentary heat flow within the boundaries of the body is governed by the well-known Fourier Law.[7] However, only in some very special conditions can theoretical solutions for Fourier differential equations be found. Generally, for solving the Fourier differential equation, finite-difference methods (as used in this study) or finite-element methods are used.

The development of a subroutine was based on an earlier program that used a finite-difference method.[19] Fig. 5 shows the simplified concrete model for temperature calculation. One element was considered for the formwork and the concrete wall was divided into n elements from the concrete surface to the centre.

During calculations, temperature values T_n at time step $m+1$ are calculated based on the results obtained at the previous time step m, and the calculation formulas are as follows.

$$
\begin{aligned}
T_1^{m+1} &= T_1^m - \frac{2\Delta t}{\Delta x_1 \rho_1 c_1}\left[\frac{K_1\left(T_1^m - T_2^m\right)}{\Delta x_1} + a_1\left(T_1^m - T_e^m\right)\right] \\
T_2^{m+1} &= T_2^m - \frac{2\Delta t}{\Delta x_1 \rho_1 c_1 + \Delta x_2 \rho_2 c_2} \\
&\quad \times \left[\frac{K_1\left(T_2^m - T_1^m\right)}{\Delta x_1} + \frac{K_2\left(T_2^m - T_3^m\right)}{\Delta x_2} - \frac{\Delta x_2}{2}\Delta QC\right] \\
T_i^{m+1} &= T_i^m - \frac{\Delta t}{\Delta x_2 \rho_2 c_2} \\
&\quad \times \left[\frac{K_2\left(T_i^m - T_{i-1}^m\right)}{\Delta x_2} + \frac{K_2\left(T_i^m - T_{i+1}^m\right)}{\Delta x_2} - \Delta x_2 \Delta QC\right] \\
&\quad (\text{for } i = 3 \text{ to } n-1) \\
T_n^{m+1} &= T_n^m - \frac{2\Delta t}{\Delta x_2 \rho_2 c_2}\left[\frac{K_2\left(T_n^m - T_{n-1}^m\right)}{\Delta x_2} - \frac{\Delta x_2}{2}\Delta QC\right]
\end{aligned}
\tag{1}
$$

where Δt is the time interval; a_1 is the heat transfer coefficient for formwork to air; K_1, ρ_1 and c_1 are the thermal conductivity, density and specific heat of formwork; K_2, ρ_2 and c_2 are the thermal conductivity, density and specific heat of concrete; Δx_1 and Δx_2 are the element thicknesses of formwork and concrete

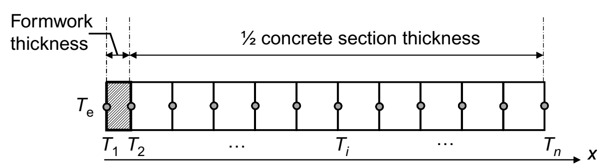

Fig. 5. Division of concrete wall into elements

Constant	Concrete	Timber	Steel
Thermal conductivity: W/mK	1·8	0·18	50
Specific heat: J/gK	0·88	1·63	0·42
Density: kg/m^3	2400	650	7800
Heat transfer coefficient to air: W/m^{2}K	17	17	17

Table 3. Physical constants used in the program

respectively; ΔQ is the heat generated in the concrete element during the time interval; and C is the cement content of the concrete.

Calculations used to determine ΔQ in equation (1) were based on heat of hydration models established through isothermal calorimetry tests carried out on cements containing the same PC, fly ash and ggbs.[7] The hydration model was based on the Arrhenius function and refined De Schutter functions,[20] and was developed to allow the effect of cement composition to be taken into account. The total heat of blended cements was considered to be the sum of three components

(*a*) an initial PC reaction
(*b*) a latent hydraulic ggbs reaction
(*c*) co-reactivity effects between the PC and ggbs, or fly ash.

4.2. Predicted temperature rises

A computer program was written, based on equation (1), to calculate the early-age temperature profile for concrete made with PC, PC/ggbs and PC/fly ash cements. The variable parameters were: cement content; formwork type and section size; ambient temperature; and placing temperature. The physical constants used in the program are given in Table 3. Monitoring of early-age temperatures in a number of new massive constructions was carried out to verify the profiles and temperatures obtained by the program against real data, including the National Stadium, and Heathrow Airside Road Tunnel.[21] In addition, several specially made specimens were cast in order to measure the effect of cement type (PC/ggbs or PC/fly ash), ggbs or fly ash content, cement content (250 kg/m^3 or 400 kg/m^3), formwork type (plywood or steel), and section thickness (250, 500 or 750 mm) and compare these results with the model. Fig. 6, for example, shows measured T_1 values with those predicted by the computer program for PC/ggbs concretes. These results suggest that the model gives a good approximation, with most of the elements tested giving maximum T_1 values within ± 2°C of the estimated value.

A comparison of the T_1 values for PC concrete predicted by the program and those in CIRIA Report 91[2] is given in Table 4. The range of T_1 given in CIRIA Report 91 is shown with shaded background; ambient temperature is assumed to be 15°C and the placing temperature to be 5°C higher. The program was found to predict T_1 values that were on the higher side for plywood formwork, and somewhat above the CIRIA Report data range for steel formwork. It is believed that this difference may be caused predominantly by the difference in PC hydration properties: for example, the maximum isothermal heat of hydration at 24 h was 179 kJ/kg for the PC used in this study,[7] compared with five PCs with values between 107 and 181 kJ/kg used to generate the data given in CIRIA Report 91.[2]

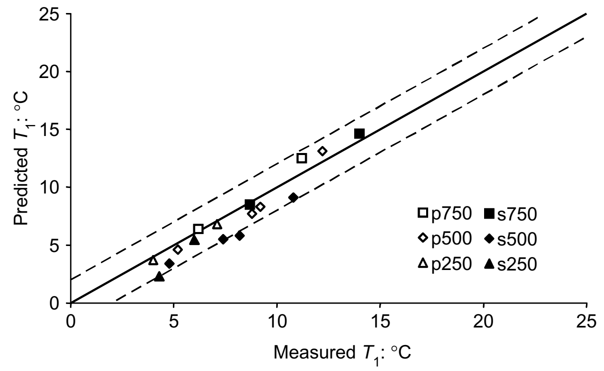

Fig. 6. Comparison of measured data with those predicted by model for PC/ggbs cements. p, plywood formwork; s, steel formwork; numbers are section thickness in mm

5. T_1 VALUES FOR LOW-HEAT AND VERY LOW-HEAT SPECIAL CEMENTS

T_1 values for ggbs contents 0%, 35%, 50%, 70% and 90% were generated by the computer program for concretes of different section thicknesses, constructed with two types of formwork (18 mm plywood and steel) and four cement contents (220 kg/m^3, 290 kg/m^3, 360 kg/m^3 and 400 kg/m^3) in order to be consistent with tables provided in CIRIA Report 91.[2]

Figure 7 shows the calculated T_1 values for a 500 mm thick concrete section constructed with 18 mm plywood formwork at all four cement contents. From interpolation of this, and similar figures, it was possible to determine the T_1 values appropriate to the Portland cement/ggbs cements just meeting the requirements for the LH and VLH classes (Table 2).

For example, from interpolation of Fig. 7(a), it can be calculated that concrete comprising a PC/GA low-heat cement (ggbs content = 56% by mass), at a cement content of 400 kg/m^3, gives a T_1 value of 26°C. Likewise, concrete containing a PC/GB cement (ggbs content = 39% by mass) gives a T_1 value of 30°C (Fig. 7(b)).

Based on these data, a design T_1 range of 26–30°C can be given for low-heat ggbs cement at a cement content of 400 kg/m^3 and section thickness of 500 mm (plywood formwork). Design data for other cement contents and section thicknesses can be calculated similarly (Table 5), as may values for very low-heat special cements based on minimum ggbs contents of 72% (GA) and 66% (GB). It should be noted that, for PC and GB, a ggbs content of 56–65% will not satisfy the definition given in BS EN 14216 for very low-heat special cements (i.e. minimum ggbs content of 66%).

T_1 values appropriate to PC/fly ash cements just meeting the requirements for the LH and VLH classes were determined through figures similar to that of Fig. 7. The results are given in Table 6.

A comparison of T_1 values for the four cements meeting the LH class (i.e. PC and 56% GA, 39% GB, 25% FA, and 20% FB) is shown in Fig. 8. T_1 values estimated from the use of these four cements differ significantly. Indeed, a difference in T_1 of 10°C is given between PC/GA and PC/FB, despite both cements having the semi-adiabatic heat of hydration (270 J/g) at 41 h: that is, a

Section thickness: mm	Steel formwork				18 mm plywood formwork			
	Cement content: kg/m^3				Cement content: kg/m^3			
	220	290	360	400	220	290	360	400
300	8·5	11·7	15·5	18·0	13·6	18·8	24·9	28·9
	5–7	7–10	9–13	10–15	10–14	14–19	18–26	21–31
500	14·7	20·2	26·8	31·1	19·1	26·3	34·7	40·1
	9–13	13–17	16–23	19–27	15–19	20–27	27–36	31–43
700	19·6	26·9	35·5	41·0	23·1	31·7	41·6	47·8
	13–17	18–24	23–33	27–39	18–23	25–32	34–43	40–49
1000	24·9	34·2	44·7	51·3	27·5	37·5	48·8	55·7
	18–23	24–32	33–43	39–49	22–27	31–37	42–48	47–56

Ambient temperature = 15°C; placing temperature = 20°C.

Table 4. Comparison of T_1 values with those in CIRIA Report 91 for PC concrete: °C (shaded sections are from the CIRIA report)

PC/fly ash cement just meeting the LH class will give a T_1 value higher than that of a PC/ggbs cement just meeting the LH class. This is because, in addition to the total heat of hydration, the rate of hydration plays a significant role in temperature rise. For example, from Fig. 2, cements that have a low ratio of H_{41}/H_{20} (all PC/fly ash cements) have a higher rate of heat evolution, and subsequently will tend to give higher T_1 values.

Tables 5 and 6 are similar to those in CIRIA Report 91 and can be used in the same way. They require engineers to know only the cement type, including heat of hydration class, but not the specifics of the cement blend. For example, take a 700 mm wide concrete section made with a low-heat ggbs cement content of 360 kg/m^3 constructed in 18 mm plywood formwork. Table 5 gives a T_1 value between 29°C and 34°C (i.e. a peak temperature between (29 + 15) and (34 + 15) °C), depending on the fineness of ggbs. If the source and composition of the cement are not known, then the higher value of T_1 (34°C in the example given) should be used in the calculations for crack control.

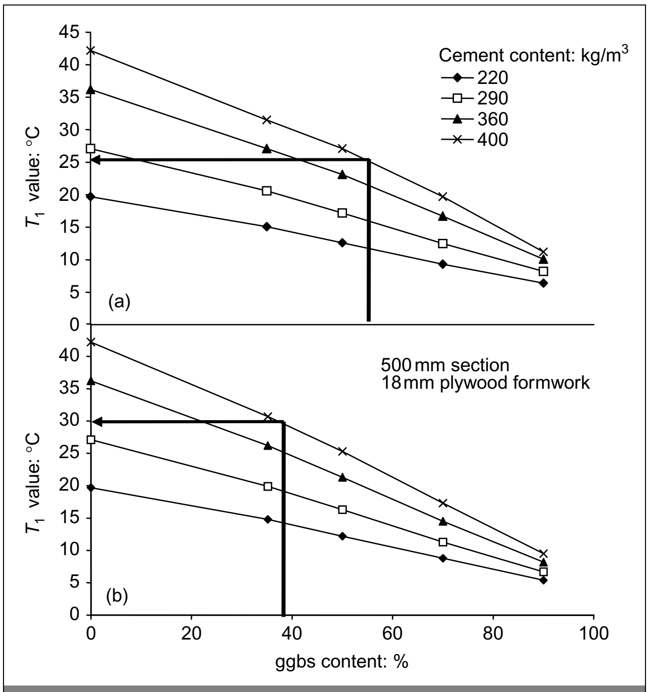

Fig. 7. Calculation of T_1 values for PC/ggbs cements meeting the LH class: (a) PC/GA; (b) PC/GB

The values given in Tables 5 and 6 are the maximum possible T_1 values for cements meeting the LH and VLH classes. As the types of ggbs and fly ash used were chosen to be representative of the extremes of the range of ggbs and fly ash permissible for use in concrete, T_1 values calculated can be regarded as representative of the values that will be obtained using most ggbs and fly ash. However, it should be noted that the highest T_1 values given relate to the use of the least 'reactive' ggbs and fly ash (i.e. GB and FB respectively). As shown in Fig. 4, FB was almost inert with regard to its contribution to early-age heat, and thus the highest values given in Table 6 approximate to the maximum possible T_1 values when using an LH or VLH class cement.

6. DISCUSSION AND CONCLUSIONS

From semi-adiabatic calorimetric tests carried out on PC/ggbs and PC/fly ash cements, cements just meeting the limits for the LH and VLH classes have been determined. For PC/ggbs cements it was shown that the composition of the blend meeting the respective classes was significantly affected by the fineness of the ggbs. However, the fineness of the fly ash had less effect on PC/fly ash cements.

T_1 values applicable to these cements were determined using a computer program based on a heat of hydration model. It was observed that there was no single T_1 value relating to a particular heat of hydration class; values depend both on cement type and on the fineness of the fly ash or ggbs. This suggests that European cement standards that classify blended cements based on composition ranges, and on strength and heat of hydration classes (rather than explicit knowledge of the composition), may be less than useful, unless specific details of the composition of the cement blend are also provided. It should be noted that engineers are able to request details of the composition from the cement producer, and can insist on it being agreed in the specification for their concrete. However, data of the type given in Tables 4 and 5 provide an accessible means of obtaining the best information for predicting the early-age temperature rises in concrete. The data may be used independently, or to complement current guidance,[1–4] depending on the particular circumstances. For example, Tables 4 and 5 give the worst-case values, but CIRIA Report 91 may be used as a final check on the maximum temperature fall should the specific details of the composition of the cement blend become known.

Section thickness: mm	Steel formwork				18 mm plywood formwork			
	Cement content: kg/m^3				Cement content: kg/m^3			
	220	290	360	400	220	290	360	400
LH class								
≤300	5–6	7–8	9–11	10–12	8–10	11–14	14–18	16–19
500	9–11	12–15	15–19	17–21	12–15	16–20	22–26	26–30
700	12–15	17–20	22–26	26–30	16–19	22–26	29–34	34–40
≥1000	17–20	24–27	31–35	36–40	20–23	28–32	34–39	36–42
VLH class*								
≤300	5–6	6–7	7–9	8–10	7–8	7–11	10–14	12–16
500	8–9	9–12	11–15	13–17	10–12	13–16	17–22	20–25
700	10–11	13–14	16–17	19–20	13–15	18–22	24–29	29–33
≥1000	14–15	18–20	24–27	28–31	17–20	24–27	28–33	32–36

Ambient temperature = 15°C; placing temperature = 20°C.
*Data apply only to cements containing a minimum ggbs content of 66% by mass.

Table 5. T_1 values for PC/ggbs cements meeting the LH and VLH classes

Section thickness: mm	Steel formwork				18 mm plywood formwork			
	Cement content: kg/m^3				Cement content: kg/m^3			
	220	290	360	400	220	290	360	400
LH class								
≤300	7–8	10–11	13–14	15–16	11–12	16–17	21–22	24–25
500	13–14	17–18	22–24	26–27	16–17	23–24	30–32	35–36
700	16–18	23–24	31–32	35–37	20–21	28–29	37–39	43–44
≥1000	22–23	31–32	40–42	46–48	25–26	34–35	43–44	44–46
VLH class								
≤300	6–7	8–9	11–12	12–13	10–11	13–14	17–18	19–21
500	11–12	14–15	18–20	21–23	14–15	19–21	25–27	30–31
700	14–15	20–21	26–28	30–32	18–19	25–26	33–35	38–40
≥1000	20–21	28–29	36–38	41–43	22–23	21–32	38–40	40–42

Ambient temperature = 15°C, placing temperature = 20°C.

Table 6. T_1 values for PC/fly ash cements meeting the LH and VLH classes

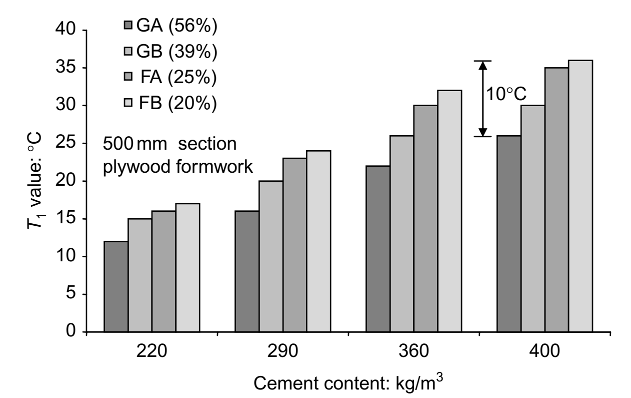

Fig. 8. Effect of cement type and content on T_1 value

It is possible that similar variations in heat of hydration will arise where cement constituents are from different sources. Further work is being carried out to investigate the effect on T_1 of PC from different works; this will enable the variability of T_1 to be determined and provide greater confidence in the values given in Tables 5 and 6.

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