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Minimising the risk of thermally induced cracking in mass concrete structures through suitable materials selection and processing

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ABSTRACT

The hydration of cement is an exothermic reaction which generates around 300 kJ/kg of cement hydrated. In mass concrete structures such as dams and large foundations, this heat of hydration causes a significant rise in temperature in the internal sections of the concrete. If thermal gradients between the internal sections and the near-surface zone of the concrete element are sufficiently large, the thermal stress can cause cracking of the concrete. This cracking may cause functional or structural problems in the operation of the structure. In order to minimise the potential for such cracking, it is necessary to minimise the rate and amount of heat that is evolved, particularly during the early period of the hydration process. This can be achieved by design engineers and concrete technologists through judicious selection and processing of concrete-making materials. This paper presents the observations and results obtained over a number of years from adiabatic testing of concretes, computational modelling of temperature development in large concrete structures and direct temperature measurements in actual structures, with a view to understanding the effects of concrete-making materials on temperature development in concrete. The paper considers the effects of different types of rock aggregates, different types of Portland cement, fineness of grinding of the cement, the addition of supplementary cementitious materials and variations in the concrete starting temperature on temperature development in a large concrete element over time. The results indicate that using a coarser ground cement, adding significant amounts of supplementary cementitious materials and cooling the concrete mixture before placing has a more significant effect in reducing the risk of cracking than varying the aggregate type of the Portland cement type.

INTRODUCTION

The design and construction of large concrete elements requires attention to the particular problem of the potential for thermally induced cracking that may compromise the serviceability of the structure. This problem derives from the fact that the hydration reactions between cement and water are exothermic while the concrete itself has a relatively high thermal inertia. In large concrete elements, or in elements of modest dimension but high cement content, the high rate of heat production during the early stages of hydration, together with the slow rate at which heat is able to flow toward the surface of the structure, results in significant temperature increases in the inner sections of the concrete element.

During the early stages of hydration, when the internal temperature of the immature concrete is increasing, the cooler surface zone is subjected to tensile stresses and surface cracks, usually fairly shallow, occur within a few days after casting. At later ages, after the peak temperature has been reached and the internal concrete enters the cooling phase, the increased stiffness of the surface zone now acts as a restraint to the thermal shrinkage of the internal concrete. Internal sections are therefore subjected to tensile stresses and significant internal cracking is possible during this period [1]. In this phase of decreasing internal temperature, the surface sections experience compressive stresses and the surface cracks formed earlier may well reduce in width.

Since thermal stresses in such concrete elements are the result of temperature differences between different sections within the concrete, the most effective way to minimise the risk of thermally-induced cracking is to minimise the maximum temperature that is likely to be obtained in the concrete as a result of the heat of hydration. The focus of this paper is to consider the effects of the controllable parameters related to selection and processing of the concrete-making materials in the design and construction of large concrete elements.

This paper draws on experimentation and development work conducted over the past 15 years to indicate the likely effects of parameters such as the type of Portland cement, the type of supplementary cementitious material (SCM), the aggregate type and the initial temperature of the concrete on the time-temperature profiles of a hypothetical concrete element that is infinitely long and 4 m wide x 3 m high in cross section, cast on a rock foundation with steel formwork on the vertical surfaces for the first 18 hours after casting. The paper also considers the effect of the fineness of grinding of the cement on the maximum temperature likely to be developed as a result of the heat of hydration.

The analyses and results presented in this paper are mainly based on a finite-difference computational solution to the Fourier equation, developed by Ballim [2] and later verified using in situ concrete temperature measurements [3]. Experimentally determined heat rate profiles for different concrete binders were used as input into the model in order to predict the time-temperature profiles in a concrete element up to the time of the maximum internal temperature. The model results were then used to consider the likely effects of different controllable materials variables on the potential for unintended cracking in large concrete elements.

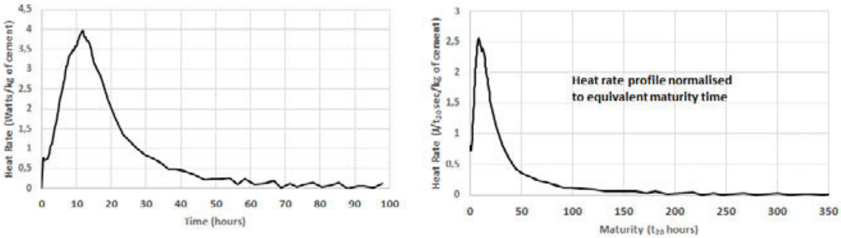
BACKGROUND

Using a purpose-built adiabatic calorimeter for determining the heat of hydration of cement [3, 4], it has been possible to develop an understanding of the effects of variations in the crystal chemistry and physical characteristics of Portland cements on the heat released during the early stages of cement hydration. The results of this work has been reported over the years [5, 6, 7]. The work also provided experimental justification for an approach to normalising the adiabatic heat-rate function of cement using Arrhenius maturity to account for variations in the time-temperature history of a particular section of a large concrete element [8].

The adiabatic calorimeter test generates a heat-rate profile as a function of time (see Fig. 1a). This profile is then normalised to a maturity heat rate using the Arrhenius equation to determine the equivalent maturity at 20 ^{o}C, as illustrated in Fig. 1b. This normalised heat rate function can then be used in a solution approach to the Fourier equation (in 2-dimensions):

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \frac{\partial q}{\partial t} \tag{1}$$

to determine the development of temperature over time in a in a concrete element as a result of the heat of hydration of the cement binder. In Equation 1, ρ = density of the concrete; C_p = the specific heat capacity of the concrete; T = temperature; t = time; k = thermal conductivity of the concrete; x and y are the coordinates at a particular point in a structure, q is the heat evolved by the hydrating cement and $\frac{\partial q}{\partial t}$ is the time rate of heat evolution at point (x, y) in the structure.



a

b

Figure 1: An example of a heat-rate profile as determined from an adiabatic calorimeter test (a); and the same profile expressed in normalised maturity form (b) for use in a computational solution of the Fourier equation

Ballim [2] has proposed a finite difference model together with in-situ verification of the model [3] that incorporates the normalised heat-rate function to predict the early-age time-temperature profiles in a large concrete element. The heat-rate profile of the concrete mixture used in the structure, with the actual aggregates, binder and admixtures to be used, is experimentally determined in an adiabatic calorimeter. The normalised heat rate function, as indicated in Fig. 1, is then used in step-wise calculations to determine the heat rate at a particular time and position as:

$$\left[\frac{\partial q}{\partial t}\right]_{t,x,y} = \left[\frac{\partial q}{\partial M}\right]_{t,x,y} \cdot \left[\frac{\partial M}{\partial t}\right]_{t,x,y} \tag{2}$$

where M is the Arrhenius maturity of the concrete at position (x,y) at time t.

This model was used to assess the effects of changes in the concrete-making materials used for the construction of large concrete elements of modest compressive strength. Construction methodology variables such as element size, construction sequencing or internal cooling systems were not considered in this analysis.

CONCRETE PARAMETERS AND VARIABLES ASSESSED

Table I below shows the parameters used in the model to assess the likely effects of concrete materials variables on temperature development in a large concrete element. Some parameters were kept constant, such as the size of the element and the aggregate, binder and water contents. However, the following parameters were varied as indicated in the table:

- Aggregate type
- Type of Portland cement (PC)
- Fineness of grinding of the PC
- Type and proportion of fly ash (FA) or ground granulated blastfurnace slag (GGBS) blended with PC in the binder
- Concrete temperature at time of casting

Table I: Concrete mixture, construction and environmental parameters used in the model analysis, including variable parameters used.

FIXED PARAMETERS	
Section Size	4 m wide x 3 m high
Formwork type	Steel
Minimum day temperature	10 ^oC
Maximum day temperature	30 ^oC
Time of casting concrete	10h00
Concrete mixture design:	
Binder	300 kg/m^3
Water	180 kg/m^3
Course aggregate	1100 kg/m^3
Fine aggregate	820 kg/m^3
Liquid admixture	10 kg/m^3
VARIABLE PARAMETERS	
Aggregate Type	Quartzite; Granite; Basalt
Portland cement type	High, medium and low peak heat rate cements
Portland cement fineness	2660 and 4940 cm^2/g
Blended cement type	60% PC/40% FA; 60% PC/40% GGBS
Concrete starting temperature	10 ^oC; 20 ^oC; 30 ^oC

RESULTS AND DISCUSSION

Effect of the type of aggregate

The geological type of aggregate used has a significant effect on the thermal conductivity of the resulting concrete. Three aggregate types were used in the analysis and Table 2 shows values for concrete thermal conductivity in relation to the aggregate type.

It should be noted that there can be a range of thermal conductivity values for aggregates which are nominally the same. The values presented in Table II are guide values for the different aggregate types are intended to provide a first estimate of the temperature likely to be developed in the structure.

Table II: Thermal conductivity of concrete in relation to aggregates type (adapted from [9])

Aggregate Type	Concrete Thermal Conductivity (W/m.°C)
Quartzite	3.5
Granite	2.7
Basalt	2.1

The model was used to estimate the temperature in the concrete block described in Table 1. In the case of all three aggregate types, the heat rate profile of the binder was taken as that of a 100% PC as received from a local manufacturer and the casting temperature of the concrete was 15 °C.

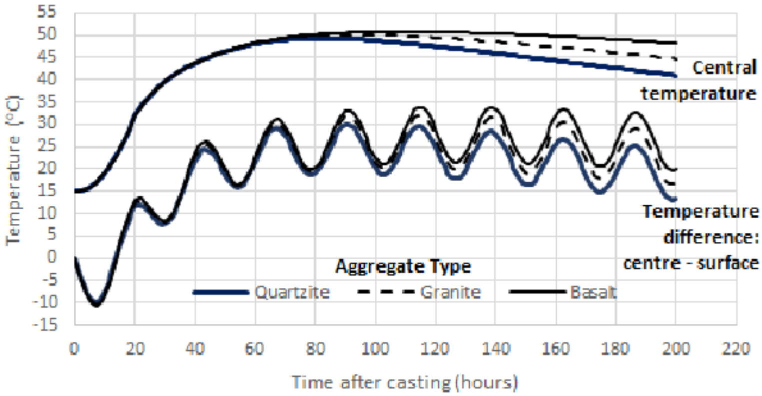


Figure 2: Variation in concrete temperature and temperature difference (relative to the surface) at the centre of the block for concrete with different aggregates

The results of this analysis are shown in Figure 2. It is clear that the most significant effect of the different aggregate types is in the rate of cooling after the peak temperature has been reached at the centre of the concrete element. As expected, the concrete with the highest thermal conductivity (quartzite aggregate) cools fastest. But it should be noted that the time to reach the peak temperature increases as the thermal conductivity reduces.

Figure 2 also shows the temperature difference between the centre of the concrete element and the side surface. The sinusoidal shape of the temperature difference curves is a result of the assumed sinusoidal variation in daily environmental temperature.

As mentioned earlier, temperature differences indicate the magnitude of strain that is likely to occur in the concrete and consequently, the likelihood of thermally-induced cracking in that section of the concrete element. Again, at the peak temperature differences, up to around 100 hours in this analysis, the different aggregates have only a small effect in reducing the temperature differences. While the effect remains modest, it does become larger during the cooling phase at later ages.

<u>Effect of type of Portland cement</u>

Samples of Portland cement clinker were collected from three production plants in South Africa. Each of these production plants manufacture Type 1 cement which satisfies the requirements of the local standard specification [10]. A single sample of gypsum was used and, based on a chemical analysis of the gypsum and the clinkers, the amount of gypsum added to each of the clinkers was adjusted so that each cement had an SO_3 content of 2.3%. Each clinker with the appropriate amount of gypsum was ground in a laboratory ball mill. The mill was periodically stopped and the specific area of the sample was determined using the Blaine test [11]. Grinding was stopped when the measured specific surface area of the sample was 3200 ± 50 cm^2/g. Each of these cements were then used to prepare concrete samples for testing in an adiabatic calorimeter. More detail of the sampling and testing procedure can be found in reference 5.

The results of the adiabatic tests, presented in maturity form, are shown in Fig. 3. The cements show distinctly different peak heat rates, in the magnitude, the timing and in the duration of the peak. These heat profiles were used as input into the temperature prediction model to consider the effects of variations in the chemistry of cements, resulting in very different peak heat-rate characteristics, on the temperature development in a large concrete element. It should be noted that none of these cements were assessed against the requirements for classification as a "low heat" cement. In modelling the effects of the PC type, the model parameters were set to: 100% PC as binder, granite aggregate and a concrete temperature of 15 ^{o}C at the time of casting.

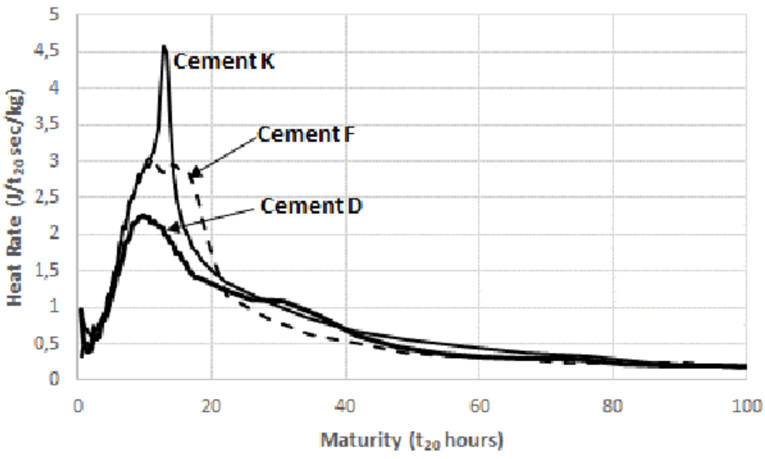


Figure 3: Heat-rate profiles of the three Portland cements used in the model analysis.

Figure 4 shows the model results for the temperature distribution and temperature differences at the centre of the concrete block. The figure shows that Cement D, with the lowest peak heat rate, gave the lowest initial absolute temperature and temperature differences. However, after around 100 hours, the more vigorous post-peak hydration of this cement caused the peak temperature to occur later and to have a slower cooling rate after the peak temperature. The results show similar effects in the temperature difference profiles. Nevertheless, the lower peak heat rate cement does cause a 5 ^{o}C lower maximum temperature and marginally lower temperature differences in the concrete.

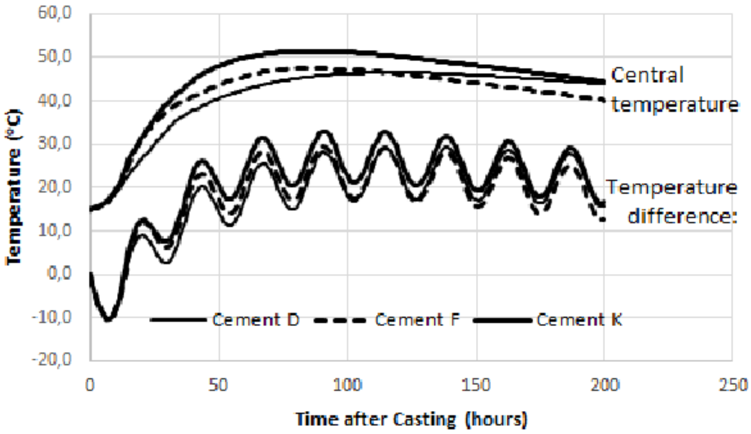


Figure 4: Variation in concrete temperature and temperature differences (relative to the surface) at the centre of the block for concrete with different Portland cement types

Effect of fineness of grinding of Portland cement

A Portland cement clinker was obtained from a cement manufacturing facility in South Africa in order to prepare the cement for this part of the assessment. The clinker was purposely selected on the basis of its nominal status as being a "medium heat" clinker.

A small, laboratory-scale ball grinding mill was used to grind the clinker. Based on chemical analyses of both the clinker and the available gypsum, sufficient gypsum was added before grinding to give a cement with an SO_3 content of 2.53%.

One sample of the cement and gypsum mixture was milled for 41 minutes, to produce a cement with Blaine fineness of 2660 cm^2/g. A second sample was milled for 150 minutes to produce a cement with Blaine fineness of 4943 cm^2/g. The two cements were then used to prepare concretes for testing in the adiabatic calorimeter.

The heat rate profiles for the two fineness cements as determined from the adiabatic calorimeter tests are shown in Fig. 5. Comparing with the heat-rate profiles shown in Figure 3, the peak heat-rates of the cements shown in Fig. 5 are similar to that of Cements D and K. However, the difference here is that the gross chemistry and crystallography of the two cements are the same and the differences of the heat profiles are the result only of the fineness of grinding, with finer fractions producing more vigorous hydration reactions of the cement at early ages. It is also interesting to note that the peak heat rates occur at around the same Arrhenius maturity time (approximately 11 t_{20} hours). This indicates that, in the finer grinding of the cement, there does not appear to be a preferential grinding of a markedly more (or less) reactive component of the cement. Had this been the case, it would be expected that the timing of the peak heat rate would change because the finer fractions of cement have a strong influence of the early reactions.

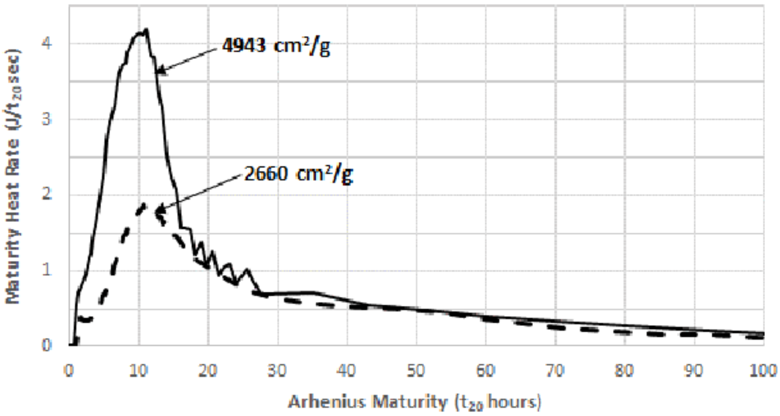


Figure 5: Heat-rate profiles for the cement ground to two different fineness levels.

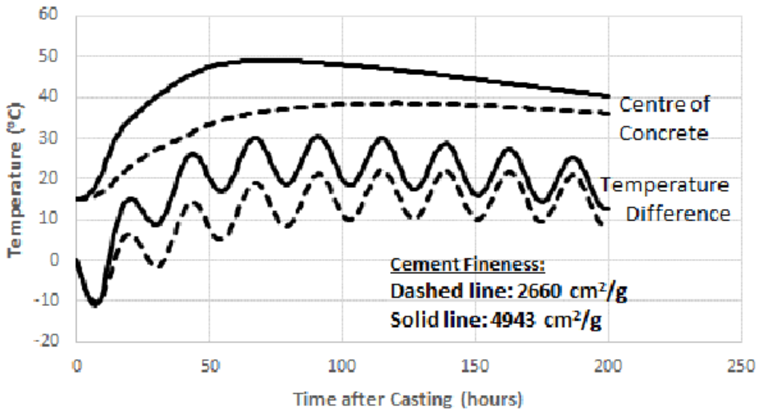


Figure 6: Variation in concrete temperature and temperature differences (relative to the surface) at the centre of the block for concrete with Portland cement ground to different fineness levels

The results of the modelled temperature and temperature gradients at the centre of the block using concretes with the same cement but at different fineness, are shown in Fig.6. In modelling the effects of the fineness of grinding of PC, the model parameters were set to: 100% PC as binder, granite aggregate and a concrete temperature of 15 °C at the time of casting.

The results shown in Fig 6 indicate that the fineness of grinding of cement has a significant effect on both the maximum temperature and the maximum temperature difference obtained in the concrete. The maximum temperature is reduced by around 12 °C and the time of this peak temperature occurs around 60 hours later for the more coarse cement. The maximum temperature difference is reduced by around 10 °C and this too occurs somewhat later than in the case of the finer ground PC. The effect of a coarser clinker cement in the binder is to significantly reduce the potential for thermally induced cracking in large concrete structures.

Effects of supplementary cementitious materials

The temperature profiles in the concrete block were also modelled for the situation where supplementary cementitious materials are added to Portland cement to form a blended binder. In this modelling exercise, the measured heat-rate profiles of concretes containing 100% PC, 60% PC with 40% GGBS and 60% PC with 40% FA were used as input into the model. In undertaking the modelling exercise, the model parameters were set to: granite aggregate and a concrete temperature of 15 ^{o}C at the time of casting. Importantly, the fixed parameters shown in Table 1 were left unchanged and the possibility of (say) decreasing the water content because of the workability effect of FA, was not considered.

Fig. 7 shows the results of the temperature prediction model for the concrete block considered. This figure shows the significant benefit in using GGBS or FA in reducing the likelihood of cracking in large concrete structures. In this case, the maximum temperature is reduced by up to 20 ^{o}C while the maximum temperature difference is reduced by around 12 ^{o}C. The effect of the FA is marginally better than that of the GGBS but this difference may become unimportant when considerations of equivalent strength and workability are brought into adjustments for the concrete mixture design.

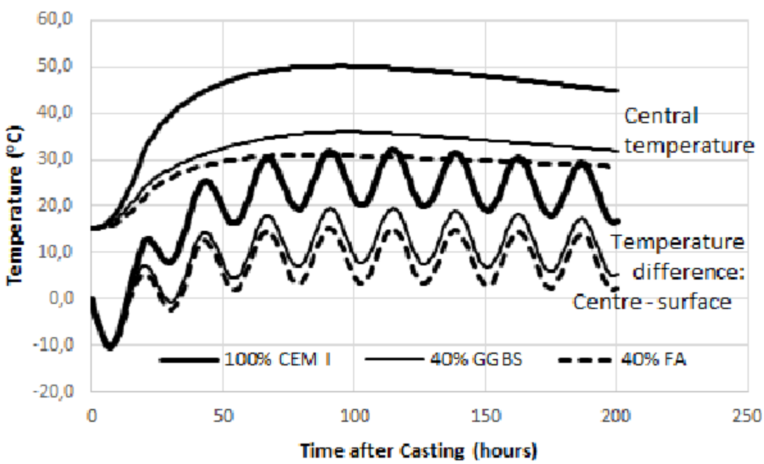


Figure 7: Variation in concrete temperature and temperature differences (relative to the surface) at the centre of the block for concrete with FA and GGBS as part of the binder, compared with plain PC as binder

Effect of changes in the casting temperature of the concrete

There are a number of construction methodology approaches that are used to minimise the risk of cracking caused by the heat of hydration in large concrete structures.

These approaches include reducing the size of the element constructed in a single concrete casting, including a network of conduits in the structure for circulating chilled water to remove the heat generated during hydration or thermally insulating the surface of the concrete to reduce the temperature gradients. However, one of the relatively low-cost approaches is to reduce the temperature of the concrete at the time of casting. This can be achieved by shading the aggregate stockpiles, wetting the aggregate stockpile to take advantage of evaporative cooling and using chilled water or ice flakes as concrete mix water.

In this part of the assessment, the temperature model was used to assess the impact of reduced concrete casting temperature on the temperature profile and temperature gradients in the concrete block. In modelling the effects of the different initial concrete temperatures, the variable model parameters were set to: 100% PC as binder with granite aggregate.

The model results for initial concrete temperatures of 10 °C, 20 °C and 30 °C are shown in Fig. 8. This figure illustrates the significant benefit in reduced cracking potential that can be obtained by reducing the initial casting temperature of the concrete. The maximum temperature and the maximum temperature difference is both reduced and delayed when the concrete placing temperature is reduced. The effect of this parameter on concrete temperature decreases at later ages but the positive effects are pronounced at early ages when the risk of cracking is higher. Of course, this benefit of reducing the initial temperature of the concrete can be expected to reduce as the concrete section dimensions increase because of the high thermal inertia of the concrete.

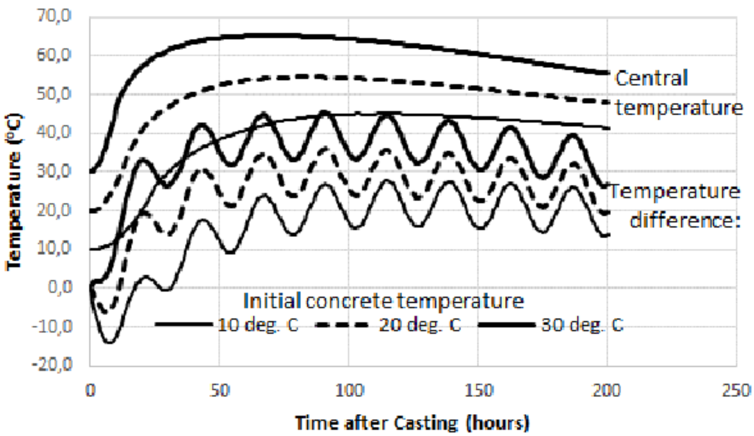


Figure 8: Variation in concrete temperature and temperature differences (relative to the surface) at the centre of the block when the temperature of the concrete at the time of casting is varied.

Conclusions

The objective of the analysis presented in this paper was to consider the effects variations in concrete-making materials parameters on the potential for thermally-induced cracking in large concrete structures as a result of the heat of hydration of the cementitious binder. The following conclusions are drawn based on the results presented:

a. Varying the rock type used as aggregate in concrete to take advantage of an increased concrete thermal conductivity has only a marginal benefit in reducing the maximum temperature and the maximum temperature difference in the concrete. However, the benefit may well lie in a higher rate of concrete cooling at later ages with the consequent benefits of reduced construction times.
b. The magnitude of the peak heat rate of a Portland cement, on its own, is not a sufficient indicator of the likely impact on the temperature development in concrete made with the cement. In this study, three Portland cements with different peak heat rates showed only marginal differences in the temperature profiles obtained for the modelled concrete block.
c. Very significant benefits in reducing the risk of thermally-induced cracking in large concrete structures are to be had by:
    i. Using a more coarsely ground Portland cement, which may also be cheaper to manufacture
    ii. Using significant proportions of supplementary cementitious materials like GGBS or FA as part of the binder in concrete
    iii. Taking measures to reduce the initial temperature of the concrete at the time of casting.

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