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Effect of *in situ* temperature on the early age strength development of concretes with supplementary cementitious materials

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HIGHLIGHTS

- *In-situ* temperature histories from blocks, walls and slabs cast during winter and summer.
- Temperature sensitivity of supplementary cementitious materials.
- Effect of supplementary cementitious materials on the peak temperature of structural members.
- Early age *in-situ* strength development as affected by geometry, size, ambient conditions and type of binder.
- Accuracy of maturity functions, Nurse–Saul and Arrhenius based, in estimating *in-situ* strength development.

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ABSTRACT

A UK based project which involved casting of blocks, walls and slabs, during winter and summer, provided *in situ* temperature histories that could be simulated in the laboratory using a computer controlled temperature match curing tank. The concretes which were of 28-day target mean strengths of 50 and 30 MPa also had partial cement replacement with supplementary cementitious materials (SCMs) such as ground granulated blast-furnace slag (GGBS) and pulverised fuel ash (PFA). The SCMs were effective in reducing the peak temperature especially when there was heat dissipation. The contribution to early age strength by SCMs increased with the high *in situ* temperatures especially in blocks cast during summer. The accuracy of strength estimates obtained from maturity functions was examined. The temperature dependence of the Nurse–Saul function was not sufficient to account for the improvement in early age strengths resulting from the high temperatures in blocks cast during summer. The Arrhenius based function, was better at estimating the early age strengths as it assumes that the concrete strength gain rate varies exponentially with temperature.

1. Introduction

The Concrete Society in the UK carried out an investigation into the relationship between core strength and standard cured (i.e. 20 °C) cube strength [1], which involved casting concrete blocks, walls and slabs, see Fig. 1, with mixes incorporating a wide range of cementitious materials [2]. Casting for the units for the winter phase was in February–March 1997 and continued with the summer phase in June-July 1997. The aim was to obtain data on the strength of concrete cores to assist in updating the Concrete Society Technical Report 11 (TR11) entitled "Concrete core testing for strength" which was first published in 1976 and re-published with an extensive addendum in 1987 [3]. The project had been carried out by the Concrete Society under a Partners in Technology Scheme, partly funded by the Department of Trade and Industry (DTI) – formerly the Department of Environment, Transport and the Regions (DETR). It has become known as the "DTI project" and that is how it is referred to in this paper.

The project was designed to provide the information needed to enable the potential strengths of concretes with supplementary cementitious materials (SCMs) to be derived, taking into account age at test, thermal history, cement type and concrete strength. The results could then be compared with standard cured cube strengths obtained from each of the mixes. It was hoped that the difference between *in situ* and standard cube strength would assist in the updating of TR11 [3] and providing data so that cements not currently covered by TR11 could be included.

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Fig. 1. Structural elements used in the DTI project [2].

The data generated has been very extensive although aimed at potential strength, i.e. long-term strengths rather than early age strengths. The temperature histories obtained from the blocks, walls and slabs could be simulated in the laboratory using computer controlled temperature matched curing tanks. The aim of doing so was to determine the effect of temperature on the early age strength development of concrete mixes with SCMs. Improved compressive strengths due to higher than 20 °C temperatures in the structural elements were expected. In order to benefit from these improved strengths, a contractor would need to be able to estimate these from the expected temperature history in a structural element. This can be achieved with maturity methods which account for the combined effect of time and temperature on the strength development of concrete [4–8].

Carino [9] has reviewed the historical development of maturity functions in great detail and only a summary of this is included here. It was proposed that the measured temperature history during the curing period could be used to compute a single number that would be indicative of the concrete strength. Saul [10] called this single factor "maturity":

$$M = \sum_t (T - T_0) \cdot \Delta t \quad (1)$$

where M is the maturity (°C-days), T is the average temperature (20 °C for standard curing) over the time interval Δt (°C), T_0 is the datum temperature (°C), Δt is the time interval (days).

This equation has become known as the Nurse–Saul function and assumes that the rate of strength development is a linear function of temperature. It can be used to convert a given temperature–time curing history to an equivalent age of curing at a reference temperature as follows:

$$t_e = \frac{\sum (T - T_0)}{(T_r - T_0)} \cdot \Delta t \quad (2)$$

where t_e is the equivalent age at the reference temperature (days), T_r is the reference temperature (°C).

Equivalent age represents the duration of the curing period at the reference temperature that would result in the same maturity as the curing period at other temperatures. The equivalent age concept, originally introduced by Rastrup [11], is a convenient method for using other functions besides Eq. (1) to account for the combined effect of time and temperature on strength development. Eq. (2) can be written as:

$$t_e = \sum (\beta \cdot \Delta t) \quad (3)$$

where:

$$\beta = \frac{(T - T_0)}{(T_r - T_0)}$$

The ratio β, which is called the "age conversion factor", is used to convert a curing interval Δt to the equivalent curing interval at the standard reference temperature.

Functions described above are for calculating a maturity index (temperature–time factor or equivalent age) based on the temperature history of the concrete. Several functions have also been proposed to relate concrete strength to the maturity index [12–19]. The following S-shape function proposed by Carino [20] (Eq. (4)) is the one recommended in the ASTM Standard [21] procedure.

$$S = \frac{S_u \cdot k \cdot (t - t_0)}{1 + k \cdot (t - t_0)} \quad (4)$$

where S is strength at age t (MPa), S_u is ultimate strength at temperature T (MPa), k is the rate constant (1/days), t is test age (days), t_0 is age at which strength development is assumed to begin (days).

Regression analysis is needed to provide for each curing temperature the rate constant, k, the ultimate strength, S_u, and the setting time, t_0, of the mortar mixture.

In order to calculate the apparent activation energy, E_a, the ASTM Standard's recommendation [21] is to plot ln(k) against $1/T_{abs}$ (given in 1/Kelvin), where T_{abs} is the absolute curing temperature. The slope of the trend line is equal to $-Q$ and the activation energy (E_a) for the mixture will be equal to $Q \cdot R$, where R is the universal gas constant equal to 8.31 J/K·mol. The assumption that the rate of strength development obeys the Arrhenius equation leads to the maturity function (referred to as Arrhenius function in this paper):

$$t_e = \sum e^{-E_a/R \cdot \left(\frac{1}{T_a} - \frac{1}{T_s}\right)} \cdot \Delta t \quad (5)$$

where t_e is the equivalent age (days), T_a is average temperature of concrete during time interval Δt (K), T_s is specified reference temperature (K), E_a is apparent activation energy (J/mol), R universal gas constant (J/K·mol).

Apparent activation energies can be determined using "equivalent" mortar specimens, as described in ASTM Standard C1074-98 [21] and the results applied to the concrete under investigation. The equivalent mortars need to have the same water to binder ratios and superplasticiser dosages as the concretes. The sand to binder ratios also need to be equal to the coarse aggregate to binder ratios of the concretes. These requirements are to ensure that the strength development of the mortar specimens is similar to that of the corresponding concrete mixtures.

The aims of the work described here were therefore to:

(a) Determine, using data from the DTI Core Project[1], the effects of: (i) environmental conditions (summer or winter concreting), (ii) size and type of structural element (blocks, slabs and walls), (iii) concrete compressive strength (30 MPa and 50 MPa), and (iv) partial cement replacement with SCMs (pulverised fuel ash (PFA) or ground granulated blast furnace slag (GGBS) at 30% and 50% cement replacement levels, respectively) on the early age temperature history exclusively.

(b) Investigate, in the laboratory using replicated mixes, the effect of particularly high early age temperatures on the *in situ* strength development of concrete for a selection of structural elements and concrete mixes, based on the above.

[1] Data from the DTI Core Project were provided to the authors by Dr. L.K.A Sear who was directly involved with the project.