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Maturity testing of lightweight self-compacting and vibrated concretes

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HIGHLIGHTS

- SCMs and fillers in low energy lightweight self-compacting and vibrated concretes.
- Predicting lightweight concretes activation energies from isothermal strength data.
- Predicting strength development under non-isothermal curing from activation energies.
- Activation energies for lightweight and normal aggregate concretes are similar.

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ABSTRACT

A series of laboratory tests were carried out to investigate the effect of temperature on the early-age strength development of lightweight self-compacting and vibrated concrete mixtures. These had been developed at Queen's University Belfast as part of a Technology Strategy Board funded project aimed at developing lightweight and low energy concretes. The new mixtures incorporated high volumes of pulverised fuel ash (PFA), ground granulated blast furnace slag (GGBS), and limestone powder (LSP). Activator, i.e. sodium sulphate, was used to improve the early age strength development of vibrated concrete mixtures proportioned with PFA and GGBS. For each mixture, concrete cubes were manufactured and cured under isothermal (20 °C, 30 °C, 40 °C and 50 °C) as well as adiabatic conditions. The temperature rise under adiabatic curing conditions was also measured. The resulting isothermal strength data were analysed to determine the apparent activation energies of the binders/mixtures used. The suitability of maturity methods for predicting concrete strength development of these low energy lightweight self-compacting and vibrated concrete mixtures under non-isothermal, i.e. adiabatic, curing was assessed.

1. Introduction

Novel low energy mixtures with self-compacting and/or lightweight properties were developed at Queen's University Belfast as part of a Technology Strategy Board funded project [1–6]. These were intended for use by precast concrete manufacturers for products such as coffered slab units for office buildings and individually cast voussoirs of the FlexiArch™ bridge units [7]. Products with low carbon footprint are sought after for the construction of new buildings, which increases ratings of such buildings in environmental assessment methods and rating systems, e.g. BREEAM [8]. The new mixtures incorporated high volumes of pulverised fuel ash (PFA) and ground granulated blast furnace slag (GGBS). Selected vibrated mixtures, proportioned with PFA and GGBS, were activated with sodium sulphate in order to improve their early age strength development. Such mixtures are more sensitive to temperature than Portland cement mixtures. There was therefore the need to establish whether maturity functions could be used to monitor early age strength development. These could be used by the precast concrete manufacturer to (a) control the temperature of the casting bed to the required one to obtain the early age strengths needed for lifting the units, (b) identify strength variations along the depth of the element, since the heating was on the underside only, so as to avoid weak concrete at the top and subsequent failures during lifting, and (c) possible quality control assurance, i.e. for ensuring the strengths required are achieved, even in extreme cold weather situations, before lifting.

The need for estimating the effects of steam curing treatments on strength development led, in around 1950, to the development of maturity methods which aimed at accounting for the combined effect of time and temperature on the strength development of concrete. 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

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Table 1
Activation energy values found in the literature.

Concrete mixture identifier	Source	w/b	Activation energy (kJ/mol)
CEM I (C25/30[a])	Hatzitheodorou [27]	0.66	22.851 and 37.382
CEM I (C40/50[a])	Hatzitheodorou [27]	0.46	18.063 and 29.698
Type I cement	Carino and Tank [20]	0.60	48.000
Type I cement	Carino and Tank [20]	0.45	61.100
General for type I cement (without admixtures)	ASTM C1074-98 [21]	–	40.000–45.000
CEM I + 30% PFA (C25/30[*])	Hatzitheodorou [27]	0.53	19.440 and 22.539
CEM I + 30% PFA (C40/50[*])	Hatzitheodorou [27]	0.35	27.309 and 34.506
Type I cement + 20% PFA	Carino and Tank [20]	0.60	36.600
Type I Cement + 20% PFA	Carino and Tank [20]	0.45	33.100
CEM I + 30% GGBS (C25/30[a])	Hatzitheodorou [27]	0.65	53.265 and 59.600
CEM I + 30% GGBS (C40/50[a])	Hatzitheodorou [27]	0.46	41.296 and 41.606
Type I cement + 50% GGBS	Carino and Tank [20]	0.60	51.300
Type I cement + 50% GGBS	Carino and Tank [20]	0.45	42.700
CEM I + 10% microsilica (C70/85[a])	Hatzitheodorou [27]	0.25	38.999 and 50.997

[a] Concrete compressive strength class according to BS EN 206-1:2000 [28].

Table 2
Concrete mixture proportions.

Concrete mixture identifier	LW-PC control	LW-PFA	LW-PFA-activated	LW-GGBS	LW-GGBS activated	NWSCC-PC control	LWSCC-GGBS	LWSCC-LSP
Mixture constituents	Quantity kg/m^3							
CEM I	450	225	225	225	225	460	424	419
PFA	–	154	154	–	–	–	–	–
GGBS	–	–	–	211	211	–	181.5	–
LSP	–	–	–	–	–	–	–	180
Lytag 4–14 mm	561	561	561	561	561	–	351	351
Sand	787	787	787	787	787	818	818	818
Granite	–	–	–	–	–	896	–	–
Na_2SO_4	–	–	15.15	–	17.43	–	–	–
SP1	2.25	1.89	1.89	2.18	2.18	–	–	–
SP2	–	–	–	–	–	1.611	3.3	3.3
Free water	189	159	159	183	183	208	210	208
Free w/b	0.42	0.42	0.42	0.42	0.42	0.45	0.35	0.35

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 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:

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

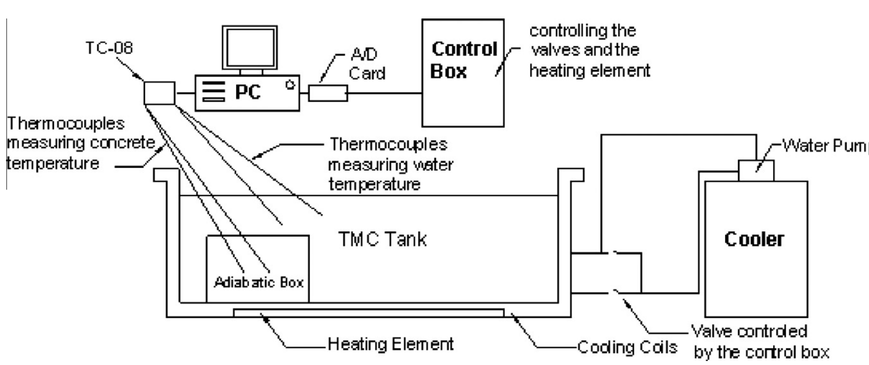

Fig. 1. Adiabatic test apparatus setup – S chematic diagram.