Construction and Building Materials 168 (2018) 931–945

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Statistical validation of new maturity functions for high-strength self-consolidating concrete mixes

J. Vilar Fernández [a], C. Vázquez-Herrero [b,*], C.J. Mendoza [c], Roberto Meli Piralla [c], C. Aire Untiveros [c]

[a] Department of Mathematics, Universidade da Coruña (University of A Coruna), Campus de Elviña SN, 15071 La Coruña, Spain
[b] Center for Technological Innovation in Construction and Civil Engineering, Universidade da Coruña (University of A Coruna), Campus de Elviña SN, 15071 La Coruña, Spain
[c] Instituto de Ingeniería UNAM, Ciudad Universitaria, Delegación Coyoacán, Ciudad de México, CP 04510, Mexico

HIGHLIGHTS

- High-strength self-consolidating concretes of prestressed column footings were characterized.
- Internal concrete temperatures at prestressed column footing at an early age ranged from 5 to 90 °C.
- ASTM C1074-11 not valid, provides an excessively wide range of activation energy values.
- New maturity functions got for equivalent mortars based on hyperbolic and logarithmic models.
- New maturity functions provide better predictions than ASTM C1074-11 and solve cross-over effect.

ARTICLE INFO

Article history:
Received 29 November 2017
Received in revised form 12 February 2018
Accepted 13 February 2018

Keywords:
Regression models
Concrete maturity method
Non-destructive-testing
Mass concrete
Self-consolidating
Accelerated Bridge Construction

ABSTRACT

A research project was performed to characterize both the setting and hardening of three high-strength self-consolidating concrete mixes used in the production of precast combined pile-cap and column footings (column footings) of the Elevated Highways in Mexico City. By monitoring an eighteen-meter-high column footing during its production, the wide range of internal concrete temperatures experienced by this massive structure at an early age was registered, from 5 to 90 °C. Concrete maturity method was applied to the equivalent mortars after ASTM C1074-11. The analysis of the experimental results allowed the statistical validation of new maturity functions for the equivalent mortar mixtures, which provided better predictions for the relative strength than the deterministic procedure of ASTM C1074-11 for the concrete ages and the wide range of curing temperatures tested. The maturity functions make up the cross-over effect, namely the influence of the internal temperature experienced by concrete on its long-term compressive strength.

1. Introduction

The motto of the project managers, so as to obtain maximum profit, could be summarized as to build on-time, on-budget, in a safe way and meeting quality standards. Therefore, when building a structure dominates the critical path of a building project, the main goal is to minimize its construction time because its deadline determines variable costs and, consequently, the budget of the project. In general, concrete quality is evaluated according to its mechanical properties and its durability [1–4].

Eurocode EN1990: 2002 + A1 2005, in its Section 6.4.2, “Verification of equilibrium and strength,” establishes the equation for the verification of static equilibrium and strength, which is reformulated in this article through Eq. (1), which accounts for the dependence of concrete strength on both the elapsed time since concrete mixing and the internal concrete temperature history [5].

$$min(t')/E_d(t') \leqslant S_d(t') \tag{1}$$

being:

t': Elapsed time since concrete mixing
$min(t')$: Minimum elapsed time since concrete mixing
$E_d(t')$: Design value of the effect of the actions at an early age, t'
T': Internal concrete temperature history up to age t'
$S_d(t', T')$: Design value of the corresponding strength at an early age, t', taking into account the internal temperature history.

---

* Corresponding author.
E-mail addresses: juan.vilar@udc.es (J.V. Fernández), cvazquezh@udc.es (C. Vázquez-Herrero), cjm@Pumas.Iingen.Unam.Mx (C.J. Mendoza), rmep@Pumas.Iingen.Unam.Mx (R.M. Piralla), aire@Pumas.Iingen.Unam.Mx (C.A. Untiveros).

https://doi.org/10.1016/j.conbuildmat.2018.02.074

Eq. (1) reflects the aim of this research, which is to obtain the minimum elapsed time, t', necessary for a concrete structure to reach a given strength required to withstand the effects of an action applied at an early age, such as the transfer of prestress in pretensioned concrete structures, application of post-tensioning, or loads applied during construction.

Thus, the focus of this research is on the term $S_d\,(t',T')$ of Eq. (1), i.e., the concrete compressive strength growth as a function of both time and internal concrete temperature, which is the aim of the concrete maturity method [6]. A minimum compressive concrete strength is necessary to achieve the required ductility of the column footings studied at the plastic hinge that could be formed in the connection between the column base and the foundation concrete pile cap (called a footing) during an earthquake.

The application of the concrete maturity method and other non-destructive tests allows the reduction of construction deadlines (Eq. (1)) and/or the minimization of the amount of cement per cubic meter used in concrete mixes for a given deadline, along with their consequent economic and environmental benefits [7–9].

This research undertook a statistical analysis of the evolution of the compressive strength of the equivalent mortars of three self-consolidating high-strength concrete mixes as a function of both time and curing temperature, based on the concrete maturity method [6,10–12].

Table 1 shows the variables, reported by previous research, that condition the acquisition of strength at early ages as a function of both time and internal temperature for cement-based materials. This table makes reference to relevant research related to each of the factors, also detailing the variables considered in this research.

Different standards regulate the concrete maturity method, such as ASTM C1074-11, widely used in North America [12]. The limitations of this standard are as follows:

- Only three curing temperatures are considered, which do not allow us to statistically analyze the variability of the limiting strength and the rate constant with respect to the curing temperature. (Section A1.2).
- The model of strength growth proposed to obtain both activation energy and datum temperature is the linear hyperbolic model [6]. There are alternative models in other regulations, such as the logarithmic model proposed by Plowman in 1956 [6] and the exponential model included in Eurocode 2, 3.1.2 [2].
- The procedure to estimate both the activation energy and datum temperature is deterministic (Section A1.1.8.1.). Consequently, Section 10, Precision and Bias, is not developed in ASTM C1074-11 [30].
- It is allowed to obtain the activation energy and datum temperature from the equivalent mortars [6,24]. Therefore, researchers have adopted the hypothesis that the rate of hardening of the equivalent mortar is the same as that of the concrete object of study.
- This regulation does not take into account the cross-over effect, i.e., the effect of high temperatures on concrete's long-term strength [6].

Table 1
Factors of concrete maturity method studied in previous research and in this paper.

Variables affecting maturity method	Variables studied in this research (X)
Time and internal temperature [13,14]	X
Initial setting time [15–19]	X
Final setting time [16–20]	X
Air temperature [21]	X
Air relative Humidity [22]	
Elapsed time until curing temperature is applied [23]	
Equivalent mortar representative of concrete [24–26]	X
Effect of applied pressure [27,28]	
Strength vs. maturity models [29]	X
Limit states theory [30]	
Different apparent activation energy during setting and hardening [16]	
Effect of variable curing temperature over time [31–33]	
Effect of different temperatures between zones [7–9,34]	
Apparent activation energy varies with time [23]	
Apparent activation energy during setting [17,18]	
Cross-over effect [17,29]	X
Alternative maturity formulations [29,32,35]	X
Application to building works [7–9,20,21,30,35–39]	X
Heat flux experiments and models [40–43]	
Time to peak Tª [32]	X
Other non-destructive testing methods [9,44–46]	
Special Concretes, SCMs and AAMs [7–9,29,33,47,48]	X

2. Existing problem

This paper is part of a research project aimed at applying the concrete maturity method and other NDTs to the production of concrete structures, in this case the precast combined pile-cap and column elements (from now on, column footings) of the Elevated Highways in Mexico [7–9]. This investigation considered Standard ASTM C1074-11 to reduce the column footings' construction deadline and consequently their economic and environmental cost [12].

The specific goal of this research was to analyze the combined effect of time and temperature on the evolution of the actual compressive strength of the column footings, which are prestressed, pretensioned concrete structures that provide stability and strength to the elevated highways with respect to both vertical loads and horizontal loads (i.e., earthquake). The condition required in the project to transfer prestress is that at least 80% of the specified strength (in this case, 60 MPa) has been attained.

Thus, the internal temperature of the column footing ZC-049 was registered during its production in the precast concrete plant in several zones (see Fig. 1), using internal concrete temperature sensors developed at the University of A Coruña [30].

One of the records of the internal concrete temperature of the column footing ZC049 appears in Fig. 2 (solid line), together with the temperature of the air that surroundedthe structure during the whole production process (dashed lines).

If the air temperature curves recorded to monitor the curing environment (dashed lines in Fig. 2) are observed, the curing process starts at approximately 0.85 days and ends 1.3 days after the time of origin. The air temperature was maintained between 50 and 65 °C in moisture-saturated conditions for about 0.5 days.

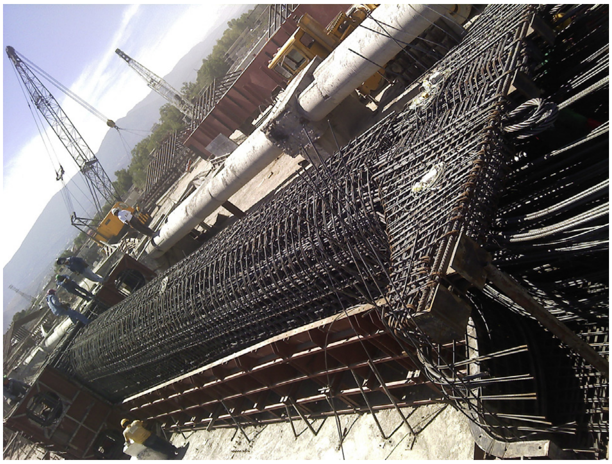

Fig. 1. Monitoring column footing ZC049 during its production.