Construction and Building Materials 189 (2018) 192–204

Contents lists available at ScienceDirect

Construction and Building Materials

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

Accelerated electric curing of steel-fibre reinforced concrete

Domenico Cecini [a,*], Simon A. Austin [b], Sergio Cavalaro [b], Alessandro Palmeri [b]

[a] Loughborough University, Centre for Innovative Construction Engineering (CICE), Epinal Way, Loughborough LE11 3TU, UK
[b] Loughborough University, School of Architecture, Building & Civil Engineering, Epinal Way, Loughborough LE11 3TU, UK

HIGHLIGHTS

- Similar effectiveness to steam curing in accelerating strength development.
- Slightly detrimental effect on the composite mechanical behaviour performance.
- A more porous microstructure at the fibre-matrix interface.

ARTICLE INFO

Article history:
Received 3 May 2018
Received in revised form 14 August 2018
Accepted 27 August 2018

Keywords:
Direct electric curing
Steam curing
Steel fibre reinforced
Concrete
Microstructural analysis

ABSTRACT

This paper evaluates the effect of electric curing on the mechanical properties and microstructure of steel fibre reinforced concrete. Specimens subjected to electric curing, steam curing and without curing were tested for compressive and residual flexural tensile strengths at different ages. The fibre-matrix contact area after pull-out was characterized by means of scanning electron microscopy. Although electric cured specimens had consistently smaller residual flexural strengths than steam cured specimens, differences were not statistically significant. Results derived from this study confirm the feasibility of applying electric curing for the production of elements made with steel-fibre reinforced concrete.

1. Introduction

Curing conditions play a crucial role in the hydration of the binder and in achieving the performance expected from the hardened material [1]. In the precast industry, curing is often synonymous with the application of heat to shorten demoulding times and to increase productivity. One can appreciate the importance of accelerated curing to the manufacturer's rate of production by considering that to reach the demoulding strength in some cases requires more than a day (several days for prestressed concrete) as opposed to hours when accelerating curing is adopted, and thus the economic viability of precast plants significantly relies on accelerated curing [2].

Steam Curing (SC) is the most common method used in precast plants to achieve high temperature cycles while ensuring abundant moisture supply [2]. Although reliable and relatively easy to control, SC has poor energy efficiency and generates temperature gradients inside the elements, thus inducing internal stresses. In other words, SC suffers the limitations of being a surface-heating method, therefore it is physically limited by thermal conductivity of the medium and maximum permissible temperature. Moreover, its on-site deployment is unfeasible in most cases due to the large equipment required (steam generators, ducts and conveyors, etcetera).

Electric methods are relatively unexplored alternatives, which generate heat by means of the Joule effect [3,4]. Indirect or direct methods can be distinguished. For the indirect method, surface or embedded electric resistors (or the reinforcement bars) are deployed to supply heat; however, regardless of the actual positioning of the heating elements, indirect electric curing remains a surface-heating method, with the physical limitations mentioned above. Conversely, for the direct method electricity is run through the concrete, either by applying a voltage to the reinforcement bars (i.e. using them as electrodes) or by means of purposely embedded electrodes [3]. The direct Electric Curing method (EC) has received relatively little attention with regard to research and it is the focus of this study.

---

* Corresponding author.
E-mail addresses: D.Cecini@Lboro.ac.uk (D. Cecini), S.A.Austin@Lboro.ac.uk (S.A. Austin), S.Cavalaro@Lboro.ac.uk (S. Cavalaro), A.Palmeri@Lboro.ac.uk (A. Palmeri).

https://doi.org/10.1016/j.conbuildmat.2018.08.183
0950-0618/

EC is a volume-heating method, with virtually no limitation to the power density that can be provided, in this being similar to microwave heating [5]. As heat is not transferred through the mould, it can be insulated and EC can achieve high energy efficiency. Also, EC requires relatively compact machinery with no moving parts, hence it is reliable, simple to maintain and compatible with on-site applications [4]. On the downside, the implementation of EC requires significant electrical power and specific engineering know-how about how fresh concrete conducts electricity.

The largest market of Steel Fibre Reinforced Concrete (SFRC) is in industrial flooring and ground bearing slabs thanks to its enhanced crack control and local redistribution capacity [6]. Structural applications where the fibre reinforcement completely replaces conventional bars have also appeared in recent years. The prime example is found in precast tunnel lining segments [7,8] along with other precast elements. Significantly, the enhanced bulk electrical conductivity of SFRC allows lower working voltages and/or higher power densities, favouring the use of EC.

Despite that, to the authors' best knowledge, only one published paper [9] (in French) has addressed the application of EC to SFRC. Although no detrimental effect of EC was observed on compressive and flexural (cracking) strengths, the study did not evaluate the influence of EC on the post-cracking residual strength provided by the combined mechanical action of the fibres and the matrix. This might well be a critical aspect, as the higher conductivity of the metal could induce differential temperature and electrochemical phenomena around the fibres, thus affecting the microstructural characteristics and post-cracking mechanical performance of the composite which are essential for the design of elements in service and ultimate limit states. Inevitably, the lack of scientific knowledge and of solid experimental evidence remains to date a barrier to the use of EC in practice.

The aim of this paper is to evaluate the effects of direct EC on the mechanical properties and microstructural characteristics of SFRC in comparison with SC and Normal (unaided) Curing (NC). An extensive experimental campaign was undertaken envisaging realistic application scenarios. In total, 108 prismatic specimens measuring 150x150x550 mm^3 were cast and subjected to curing regimes with either EC, SC or NC. An EC rig, specially designed and built for this study, allowed matching of the temperature evolution attained inside the concrete specimen during SC in a climatic chamber, which enables a fair comparison between the two accelerated curing methods (SC and EC).

Thermal and electrical data were collected throughout the curing process. After that, the flexural behaviour of the beams was assessed according to [10], paying special attention to the residual tensile response. Then, cubes were sawn from the beams and characterized through the inductive method to assess the content and orientation of fibres [11–13], in order to determine the influence of variations in fibre distribution between specimens in the comparisons. The cube specimens were later used in compressive tests [14] and Barcelona indirect tension tests (the latter test is described in [15] and adapted according to [16–18]). Finally, Scanning Electron Microscopy (SEM) was undertaken along with Energy-Dispersive X-ray spectroscopy (EDX) to investigate the microstructure at the fibre-matrix interface.

This study improved our understanding of the consequences of EC on concrete elements, with and without steel fibres. It also serves as a reference for future scientific research; the results presented in this paper may prompt further exploration of the potential for practical applications of EC in SFRC elements. An example can be found in novel applications of self-compacting concrete proposed by Reymann [19] and Cecini et al. [20] for precast and cast-in-situ, respectively.

2. Literature review

Direct EC (Electric Curing) has been used on a commercial scale in Russia since 1933, both in precast plants and for in-situ casting, although no reported use for elements made with SFRC was found. A wide body of literature addressing EC from the former Soviet Union is reported by Krylov [21], along with his own research undertaken at the NIIZhB (Research Institute of Concrete and Reinforced Concrete). In comparison, studies and applications in the Western world have been scarcer and limited to precast elements, perhaps due to the generally warmer climate.

Bredenkamp [22] investigated the effect of EC on Portland cement-based concrete in comparison to NC, measuring the compressive strength evolution from 4 h to 28 days, with the goal of optimising curing strategies. Constant intensities of electric field ranging from 300 to 500 V/m were examined. EC was finished either after a given exposure time or upon reaching a total input energy of 76 kWh/m^3. However, in neither case was the control based on the temperature. Despite reaching about 50% of 28-day strength in just 4 h, the strength of specimens subjected to EC was lower compared to that of specimens subjected to NC after 80 h. Even though the magnitude of the detrimental effect in terms of the strength difference after 28 days was not reported, it was deemed acceptable.

Wilson [23] performed tests using a variable transformer and real-time adjustment of the input power by temperature-controlled closed-loop. This work provided a detailed report of the electrical parameters involved in EC. The initial resistivity of fresh concrete was about 8 Ωm and, thanks to insulation applied to the specimens, a total energy input of less than 40 kWh/m^3 was sufficient to complete the temperature cycle. Nevertheless, only 24-h compressive strengths were reported, ignoring any subsequent strength evolution. Heritage [24] also conducted testing of temperature-controlled EC with target temperatures of 60 and 80 °C achieved through a linear rise of 40 °C/h, after a 3 h delay before heating. No reduction of the 28-day compressive strength compared to NC was observed at 60 °C, while about 10% lower values were reported when the target temperature was 80 °C.

Kafry [4] addressed the industrial aspects of deploying EC with case studies on precast tunnel segments and in-situ casting of a multi-storey building, pointing out potential productivity gains for on-site construction. More recently, Wadhwa [25] also reported the potential use of EC both on- and off-site and provided data from an experimental campaign. In addition to assessing the compressive strength of cubes, the authors tested half-scale reinforced slabs and checked compliance with the relevant local code.

None of the previous studies performed a back-to-back comparison of EC and SC under approximately equivalent conditions, nor did they consider the possibility of applying EC on SFRC. The only exception is the paper of Paillere and Serano [9] in French, who applied EC to $100 \times 100 \times 400$ mm^3 beams containing 0.0, 0.5, 1.0 or 1.5 vol% of steel fibres. These fibres were straight, had a length of 30 mm and an aspect ratio (length-to-diameter) of 75. Normal or lightweight aggregates were used to produce the concrete that was tested at ages in the period of 1–90 days after casting for flexural cracking and compressive strengths (however, post-cracking residual strengths were not assessed). Also, several slabs up to $100 \times 1200 \times 1600$ mm^3 were cast to compare heating effectiveness, collect resistivity data and measure required voltages.

EC showed better homogeneity of the temperature field inside the specimen than SC, but the rate of temperature rise was faster near the electrodes. At a fibre volume of 1%, an eight-fold reduction of resistance in comparison with Plain Concrete (PC) was reported, and the strength of the electric field required for curing ranged