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Heat treatment of fresh concrete by radio waves – Avoiding delayed ettringite formation

Björn Höhlig [a,*], Christof Schröfl [b], Simone Hempel [b], Ina Noack [b], Viktor Mechtcherine [b], Detlef Schmidt [c], Ulf Trommler [a], Ulf Roland [a]

[a] Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany
[b] TU Dresden, Germany
[c] Leipzig University of Applied Sciences, Germany

HIGHLIGHTS

- Precisely tunable heat treatment of concrete with radio waves.
- Avoiding the exceeding of temperature limitations.
- Minimising the risk of long-term damage caused by delayed ettringite formation.

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ABSTRACT

Heat treatment of concrete during the early stages of hydration using the new radio wave technology enables a uniform energy supply at distinct rates under steady, closed-loop temperature control. This precise control of temperature makes it possible to implement accurately and uniformly any heat treatment regime based on existing or future guidelines over the entire volume of a concrete element. The article at hand presents this new technology briefly and focuses on the issue of possible delayed ettringite formation which might compromise concrete durability. By means of ESEM- and XRD-analysis the influence of the different heat treatment temperatures on the concrete microstructure could be comprehensively investigated. It was found that a maximum temperature of 60 °C should not be exceeded because higher temperatures cause severe delayed ettringite formation. Dielectric heating as such had no additional influence on microstructural damage, especially on the extent of the formation of delayed ettringite.

1. Introduction

The formation of delayed ettringite in hardened concrete may crop up as a consequence of improper heat curing. Frequently an uncontrolled heating rate or excessively high maximum temperatures result in such unfavorable heat treatment of fresh or young concrete locally or over the entire concrete element under preparation. The strict control of starting time with respect to concrete mixing and placing, heating rate, and maximum temperature makes it possible to avoid delayed ettringite formation and thus markedly improve concrete quality. A direct and well-governed energy input by using radio waves (RW) provides the technical possibilities for such steady, well-controlled heat treatment [1].

Conventionally, heat treatment of pre-cast concrete elements is carried out using convectional heating methods such as hot air or hot steam treatment or, alternatively, by infrared radiation. Under such treatment, the energy input occurs on the concrete surface, followed by inward thermal conduction. Due to the relatively low thermal transfer coefficient and the moderate thermal conductivity of concrete, this heat transport is relatively slow and, thus, does not enable the achievement of a speedy temperature increase and uniform temperature distribution over the entire volume of the concrete elements. These limitations make it difficult or even impossible to control adequately the local temperature conditions in the concrete element and to avoid overheating, especially in regions near the surface. Such improper heating of fresh or young concrete is often followed by durability problems. The most prominent mineralogical reason for subsequent concrete damage is the

* Corresponding author at: Helmholtz Centre for Environmental Research – UFZ, Permoserstr. 15, 04318 Leipzig, Germany.
E-mail address: bjoern.hoehlig@ufz.de (B. Höhlig).

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formation of delayed ettringite, a problem which has already been thoroughly studied over several decades, *e.g.* by [2–4].

Elevated temperature during the heat treatment of fresh or young concrete leads to increased early-age strength and allows a significantly accelerated production pace in pre-cast plants. In the long-term, however, the strength of heat-treated concrete is significantly lower when compared to untreated concrete. The reason for such lower strength values after the end of the main hydration process is higher porosity, which is caused by the different (*i.e.* coarser) morphology of the C-S-H phases, see *e.g.* [5,6]. This general knowledge holds true also for heat treatment using radio wave technology [1].

In addition to its effect on morphology, increases in temperature during the hydration process influence the chemistry of reaction products in concrete. In particular, elevated temperatures during the early stage of hydration change the ratio of monosulfate to ettringite to a higher content of monosulfate and less ettringite in the hardened concrete. Furthermore, Lothenbach et al. [7] observed increased SO_4^{2-} content in the pore solution of heat-treated concrete, a consequence of the decomposition of primary ettringite. The widely accepted temperature limitation in order to avoid the conversion of primary ettringite to monosulfate is 75 °C. However, cement's alkalinity requires decreasing this limitation to 60 °C, that is, the maximum safe concrete temperature [8]. The precipitation of monosulfate is the main precondition for the formation of delayed ettringite and represents an internal sulfate attack on the entire concrete volume [4]. Other preconditions for its formation are fluid water or high humidity in the environment of the concrete element and micro-cracks or high capillary porosity as well for the possible penetration of water into the concrete. The availability of all preconditions causes the formation of delayed ettringite, which is accompanied by volumetric increase by the factor of 2.4 based on the volume of the monosulfate [8]. The resulting crystallization pressure inside the concrete microstructure can finally lead to surface cracking and severe damage to the concrete structure.

The work at hand describes the heat treatment of concrete during the early stage of hydration with RW technology using a frequency of 13.56 MHz [1]. The energy input is fed back by using internal temperature sensors in the concrete element for maintaining the desired temperature level. In this way heating occurs at distinct rates and each intermediate temperature is thoroughly controlled. Such temperature control enables consideration of the temperature increase using input intensity mirrors. For instance, the release of heat of hydration is undoubtedly recognized and accordingly the steering of the energy supply adjusts itself in order to keep within the default temperature and rate limitations. These limitations are a prerequisite for avoiding uncontrolled temperature elevation leading to damage caused by the formation of delayed ettringite. In the investigation presented, such precise control of temperature during the heat treatment enabled accurate adherence to given characteristic temperature-time curves with varying maximum temperatures. The focus is directed at the durability of the heat-treated concrete in conjunction with the possibility of the formation of delayed ettringite. The testing procedure included the alternating drying and wetting of the specimens and accompanying measurements of their volume changes. Furthermore, ESEM- and XRD-analysis were performed to investigate the influence of the different heat treatment temperatures and the subsequent alternating wetting-drying exposures on the concrete microstructure. One important goal of the investigation was ascertaining whether the temperature limitations for heat treatment as prescribed in the literature apply also to the curing of concrete by means of radio wave technology.

2. Experimentation

2.1. Controlled heat treatment and temperature measurement

The general procedure of the automated, temperature-controlled heating of fresh or young concrete with RW was recently described in detail by Höhlig [9]. The crucial features regarding the present experimental series can be described as follows: For heating compacted, fresh concrete utilising RW technology, a special plastic mould ($150 \times 150 \times 150\ mm^3$) equipped with two parallel radio-frequency (RF) electrodes was built. The RF electrodes were connected via an electronic matching network (PFM 10,000) by copper bands and further with an RF generator (TruPlasma RF 3003, fixed frequency 13.56 MHz, maximum power 3 kW, both from Hüttinger Elektronik Freiburg/Brsg., Germany) using a coaxial cable. The matching network allowed the complete transfer of the RF energy to the load, *i.e.* the sample to be heated (see, *e.g.*, [10,11]). By applying RF voltage at the RF electrodes, a homogeneous electromagnetic field is established, which leads to the uniform, dielectric heating of the entire concrete volume. The heat treatment was monitored using at least 6 fibre-optical temperature sensors (Neoptix, Quebec/CA, for details see [12]) to obtain an appropriate temperature distribution within the concrete volume. The immediate feedback from these temperature sensors allowed the regulation of the RF energy input depending on the release of hydration heat. Thus, the interplay of the two inner heat sources, hydration and external dielectric heating, allowed the exact input of the required RF energy for heating concrete along the targeted temperature curve.

For all experiments in this work, a typical mixture composition for some arbitrary, ordinary concrete was used with either Portland cement (CEM I 42.5 R, Schwenk, Bernburg/Germany) or a blended cement containing limestone powder and ground granulated blast furnace slag (GGBS; CEM II/B-M (S-LL) 42.5 R, Schwenk, Bernburg/Germany); see Table 1. Blended cements will become much more important in the construction industry in the very near future as they have a significantly reduced content of energy-intensive clinker in the cement. This results, however, in a decrease of the heat of hydration, in this case by approximately 30%, and thus a potential delay in strength development [9]. Therefore, an appropriate heat treatment might be necessary to an even greater extent for concretes produced with such cements than for concretes made of Portland cement.

The compressive strength values for this concrete without heat treatment were 49.3 MPa (CEM I 42.5 R) and 51.1 MPa (CEM II/B-M (S-LL) 42.5 R), respectively, at an age of 28 days. The effect of the dielectric heat treatment on the development of compressive strength was reported in [1]. In this investigation, heat-treated samples as well as non-heat-treated (reference) concrete specimens (cubes, 150 mm edge length) were produced for investigating durability.

2.2. Cracking and strain development of heat-treated concrete during alternating storage

The long-term behaviour of heat-treated concrete is a crucial factor in its use in the construction and building industry.

Table 1
Concrete composition.

Constituent	Content
Cement (CEM I 42.5 R or CEM II/B-M (S-LL) 42.5 R)	300 kg/m^3
Water (for w/c = 0.5)	150 kg/m^3
Aggregates (Grading curve A/B 16)	1956 kg/m^3
Admixtures	None