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# Potential of Microwave Curing for Precast Concrete Manufacture

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**ABSTRACT:** In this paper, an ongoing research sponsored by Innovate UK on developing an intelligent microwave system for manufacturing concrete products is introduced. The key features of this microwave system include using optical fibre Bragg grating (FBG) sensors to control the temperature and the humidity inside concrete and microwave oven cavity, respectively. Using this tailor-made microwave system, research is ongoing in the Advanced and Innovative Materials (AIM) Group at University College London to explore the potential of curing two types of low-carbon cementitious systems, namely high-volume fly ash (HVFA) and alkali-activated fly ash (AAFA). In both systems, thermal curing is essential for the strength development, in particular, early strength development. Their results indicate that, by using the microwave curing technique, the low-carbon performance can be achieved from both systems whilst the early strength was not affected. The current results also demonstrate a good potential of microwave curing for manufacturing low-carbon precast concrete elements in the future.

**KEYWORDS:** ACCELERATED CURING, LOW-CARBON, LOW-ENERGY, MICROWAVE CURING, PRECAST CONCRETE

## INTRODUCTION

Accelerated curing has been extensively adopted to facilitate the development of early strength of Portland cement (PC)-based precast concrete elements, as it can lead to a more frequent reuse of the forms, casting beds and curing facilities, reducing the overall cost. On the other hand, in the case of some other cementitious systems, such as alkali-activated fly ash (AAFA), due to the nature of the chemical reaction involved, accelerated curing is actually essential for initiating the chemical reaction at the first instance before any strength could even be developed.

The most widely used accelerated curing method in industry is steam curing[1,2,3]. Primarily dependent on thermal conduction mechanism, under steam curing, heat is transferred by following an 'outside – in' path, i.e., from the surface to the core of the concrete elements. However, as concrete is not a good thermal conductor due to its low thermal conductivity of 2.267 J/m$^2$s°C/m, steam curing is a slow and inefficient heat transfer process. Moreover, when large or thick concrete products are cured by steam curing, it may lead to thermal stress due to non-uniform heating, which is detrimental to the strength development of concrete products [4]. Moreover, although production time can be decreased by applying steam curing, the energy consumed during the curing process is a major concern, which inevitably increases the production cost and causes some concerns over the sustainability of precast concretes. As a result, alternative curing methods with low energy consumption are needed.

Different from steam curing which is dependent on the thermal conduction, microwave heating relies on energy conversion, which can result in a fast volumetric heating. As all the components of concrete are dielectric materials, particularly water, they can absorb microwave effectively and electromagnetic energy can thus be instantly converted into thermal energy. Although microwave has been well-established in the wood and plastics industry, only limited efforts have been made in the past to employ microwave as an alternative to conventional accelerated curing techniques used in concrete industry. The use of microwaves to accelerate the curing of concrete was first reported in 1968[5]. Following this, some other pilot research were carried out to cure various cementitious products [6,7,8]. Whilst all these work have proved that microwave curing could be a promising alternative accelerated curing method for the production of precast concrete with shorter curing duration and lower energy consumption, neither the curing temperature nor the relative humidity was well controlled during microwave curing process, which may cause long-term strength loss and durability problems in the future.

To address these issues, a research consortium was formed between University College London, City University of London, Industrial Microwave Systems and Macrete (Northern Ireland) in 2013, sponsored by a £1.08 Innovate UK project, to develop a smart microwave system for curing concrete over the past three years. The key features of this microwave system include using optical fibre Bragg grating (FBG) sensors to control the temperature and the humidity inside concrete and microwave oven cavity, respectively. Using this tailor-made microwave system, research has been conducted in the Advanced and Innovative Materials (AIM) Group at University College London to explore the potential of curing two types of low-carbon cementitious systems, namely high-volume fly ash (HVFA) and alkali-activated fly ash (AAFA). In both systems, thermal curing is essential for the strength development. Details of the microwave system developed in this project, together with the results obtained from both HVFA and AAFA systems, are reported below.

## DEVELOPMENT OF A SMART MICROWAVE SYSTEM FOR CURING CONCRETE

A typical curing cycle for the manufacture of precast PC-based products is shown in Figure 1, which generally consists of four stages: delay period, temperature rise period, curing period at maximum temperature and cooling period [2]. A delay period is a period between the casting of concrete and the start of thermal curing which is adopted to allow the concrete to gain some initial strength after mixing in order to better resist the thermal stresses in the subsequent thermal curing stages. Although, in theory, the delay period should last until the concrete reaches its final setting, in practice, the delay period is usually controlled between two hours and five hours in order to allow the concrete to develop sufficient early strength to resist the expansive forces generated during heating. During the temperature rise period, the most important factor that needs to be controlled is the rate of temperature rise, which is, somehow, dependent upon the delay period. In general, it has been agreed that a lower rate of temperature rise can benefit the strength gain with less decrease of strength at a later age [9,10,11]. However, the mix design, the size and shape of concrete products also need to be taken into consideration when the rate of temperature rise is determined. Nonetheless, in industrial applications, a rate of temperature rise of 20°C/hour is widely adopted. The maximum temperature is usually 70°C in most industrial applications [12], in order to prevent the conversion of AFt phase to AFm phase at higher temperature and the subsequent delayed ettringite formation (DEF) at later age[13,14]. On the other hand, as strength gain of concrete is primarily attributed to the hydration of cement, a minimum moisture level should be maintained to allow the maximum hydration of cement and the established belief is that the hydration rate is not adversely affected at a RH level above 80% in the capillary pores of concrete[11]. Therefore, it becomes evident that, to develop a microwave curing system for industrial applications, accurate controls of temperature, the rate of temperature change and the moisture level are essential.

A thorough review of the literature indicated that most of the previous work were carried out in domestic microwave ovens with a fixed power output ranging from 650W to 850W which was too high for the specimens being cured. In an attempt to control the temperature and the rate of temperature rise, extra water (referred to as water load in these studies) was introduced into the microwave oven [15]. Alternatively, pulsed regime (i.e., by turning on and off the microwave generator) was adopted. Although some improvements were made in laboratory studies with these measures, real-time temperature monitoring was not available during the curing process and the power output of microwave could not be regulated in response to the rate of temperature rise and maximum curing temperature. As a consequence, the samples could be subjected to overheating and possible damage under microwave curing.

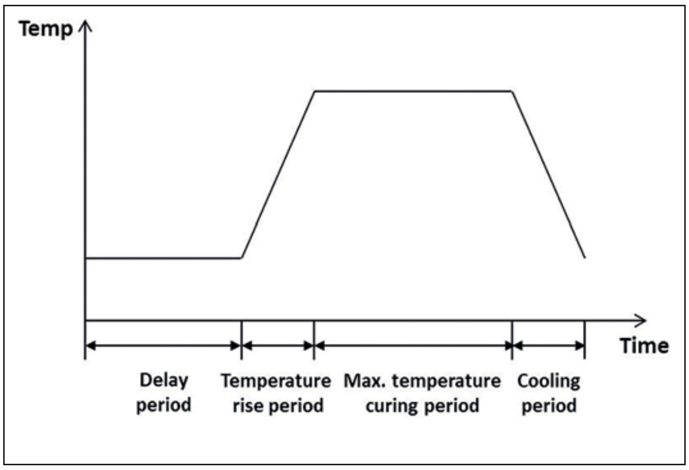


**Figure 1: Typical curing cycle in manufacturing precast concrete products (ACI, 1980).**

Due to the limitations of domestic microwave ovens, efforts have been made by some researchers to develop tailored microwave systems for curing concrete [16,17,18,19].The concept of 'temperature feedback control' was adopted to achieve the desired temperature profile. However, thermocouple was used to monitor the temperature in these studies. To avoid 'sparking' caused by the electromagnetic interference on the metallic surface of the thermocouple, special shielding was employed which can cause undesirable reflections, leading to the formation of 'hot' and 'cold' spots within the concrete. If a suitable shielding was not available, glass tubes were cast in concrete so that thermocouple could be inserted at intervals during which the microwave power was off and the oven door was opened. It is obvious that this system cannot be used to achieve continuous control. Additionally, a strength decrease of 10%-12.6% was found in a sample with an embedded thermocouple in comparison with a sample without a thermocouple [20] which was attributed to the interference caused by the metallic thermocouple to the electromagnetic field of microwave.

As highlighted before, in addition to the temperature control, the concrete products should also be cured under a moisture higher than 80% R.H. level in order to ensure the quality and long-term performance of concrete products. However, in the previous work, no moisture control was adopted which is considered to be inadequate, even if there are some evaporation during the microwave heating process.

To address the above issues, in the current project, optical FBG temperature sensors developed by the Research Centre of Photonics and Instrumentation at City University of London were incorporated into a bespoke dual-frequency solid-state microwave oven (SS500) manufactured by Industrial Microwave Systems in Milton Keynes (see Figure 2). This FBG temperature sensor can provide real-time temperature profile within the concrete at different depth. The highest temperature within the concrete is used for the 'temperature feedback control'.

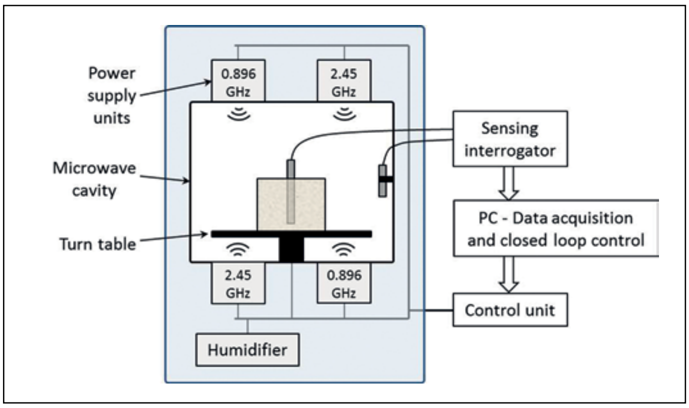


**Figure 2: Schematic of smart microwave oven system.**

Compared to the metallic thermocouple, FBG sensors are immune to microwave radiation. They are also much smaller in size and easier to multiplex in concrete. Automatic control of the microwave oven is then accomplished using the software LabVIEW Version 5.5 (Figure 3). Through a Proportional-Integral-Derivative (PID) algorithm, the microwave power was then regulated to maintain the target curing temperature within the set range based on the temperature obtained from the FBG sensor embedded in the concrete sample. A humidifier, which can be controlled by the FBG humidity sensor, is also integrated into the microwave oven in order to maintain a humidity above 90% R.H. For the first time, non-invasive measurements could be taken at different depths using a single probe in a microwave environment (see Figure 4). Another feature which should be highlighted is the distribution of the microwave power. In order to achieve a uniform distribution of microwave power, the power supply units have been distributed inside the oven, i.e., two units on the top and two at the bottom. In addition, to ensure sufficient penetration of microwave power can be achieved, in particular, when concrete is still fresh, power supply units with different frequencies have been used in this tailored microwave oven. There are two 2.45 GHz power supply units and two 0.896 GHz units. Depending on the type and the geometry of the concrete products to be cured, an appropriate frequency could be applied. Additionally, power meters were installed for the microwave oven and the thermal oven to monitor the energy consumption during each curing process (Figure 5).

Making use of this fully automated, tailor-designed microwave system, two types of low-carbon cementitious systems, namely HVFA and AAFA, have been manufactured and cured in the AIM Group at University College London. The preliminary results obtained from their study are reported in the following sections for each system, respectively.

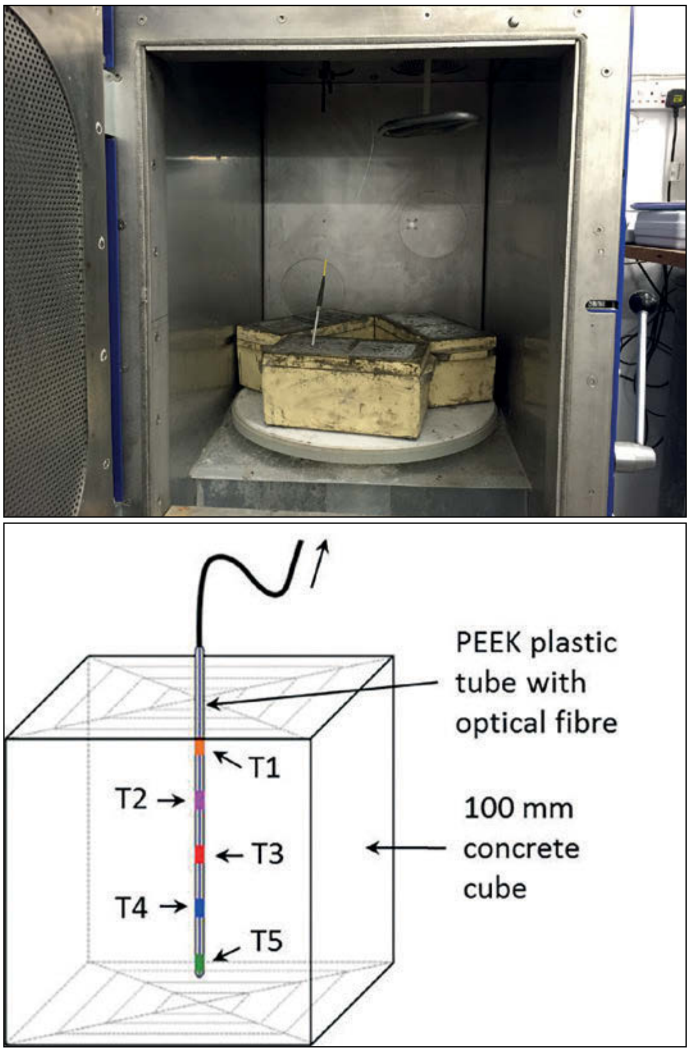


**Figure 4: (a) Concrete cube in smart microwave oven at University College London. (b) Schematic of the five-point multiplexed FBG temperature probe developed at City University of London.**

Min power (W) 5

Start temperature (C) 25

P 1 I 0.01 D 0

P1 (2.45 GHz Top)
P2 (2.45 GHz Bottom)
P3 (896 MHz Top)
P4 (896 MHz Bottom)

Operating mode
○ Manual
○ On/Off cycles
● PID control loop
○ Power profile

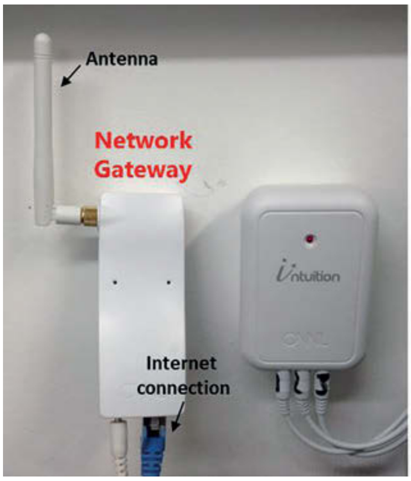
| P1 | P2 | P3 | P4 | T max | t1 | t2 |
|---|---|---|---|---|---|---|
| 0 | 0 | 380 | 380 | 50 | 30 | 184 |
| 0 | 0 | 380 | 380 | 70 | 30 | 236 |

Total time (min) 08:00:00
ETA (min) 00:00:00

P 1 6.0
P 2 6.7
P 3 166.3
P 4 156.6

T max 70.0
T fbg 71.4

**Figure 3: Automatic control interface for the smart microwave oven system.**



19 °C Partly Cloudy
Humidity: 83% Wind: 12 mph Cloud Cover: 75%

Network OWL 0068ec
System Online

0 Watts
0.0p /hr

| | Total Energy Used | Net Cost |
|---|---|---|
| Today | 0.0 kWh | £0.19 |
| Yesterday | 4.2 kWh | £0.68 |
| Last 7 Days | 4.4 kWh | £0.89 |
| Last 30 Days | 4.4 kWh | £0.89 |

P1: 0 Watts
P2: 0 Watts
P3: 0 Watts

| (kWh) | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| Today | 0.00 | 0.00 | 0.00 |
| Yesterday | 3.1 | 1.1 | 0.0 |
| Last Week | 3.2 | 1.2 | 0.0 |
| Last 30 Days | 3.2 | 1.2 | 0.0 |

Electricity Yesterday
Max: 1.06kW
Min: 0.05kW
Ave: 0.17kW

CO2e
Yesterday: 1.63kg
Last Week: 1.70kg
Last 30 Days: 1.70kg

2015 © 2 Save Energy Limited | v2.1.1
Manuals | Privacy Policy | Terms & Conditions

**Figure 5: Power meter for monitoring the energy consumption.**

# CURING HIGH VOLUME FLY ASH CONCRETE WITH MICROWAVE OVEN

With the implementation of *BRE Environmental & Sustainability Standard BES 6001 - Framework Standard for the Responsible Sourcing of Construction Products* [21], UK concrete industry is under the pressure to reduce their carbon footprint. However, as the main constituent material in concrete, PC contributes to the most of the embodied carbon dioxide (E$CO_2$) in concrete, mainly due to the decarbonation of limestone and the consumption of large amount of fuel and energy during its manufacture process. As a result, the E$CO_2$ of PC is 830 kg/t [22] and the global cement manufacture accounts for ~ 5% of the $CO_2$ produced by mankind annually. One way to reduce the carbon footprint of concrete is to replace PC with by-products from other industry because they usually have much lower E$CO_2$ than PC. For example, fly ash only has E$CO_2$ of 10 kg/t [22]. Therefore, replacing PC with fly ash can significantly reduce the E$CO_2$ of concrete, offering a good potential to develop a low-carbon concrete. The current BS EN 197-1[23] and BS 8500-1[24] permit the replacement of PC with up to 55% fly ash in blended cement systems. However, the early strength of the blends with high levels of fly ash is usually low (Bentz, 2010, Bentz and Ferraris, 2010, Kayali and Ahmed, 2013, Atis, 2002). Consequently, the current average replacement level of fly ash across all type of concretes in UK is only approximately 18%. To increase the early strength of HVFA concrete, thermal curing can be employed. However, thermal curing can significantly increase the E$CO_2$ of the final concrete products, offsetting the benefit could be achieved from fly ash. Making use of the tailored microwave system developed in our Innovate UK project, a high volume fly ash concrete (55% of Portland cement was replaced by a low calcium fly ash) was cured in the microwave oven (at 70 °C and ≥ 90% R. H.) and its energy consumption and strength immediately after microwave curing were compared with those obtained in an environmental chamber (at 60 °C and ≥ 90% R. H.). It should be noted that, due to the fully automated control system available in the microwave system, the 70 °C in microwave curing was the highest temperature inside the concrete samples whilst in the case of the environmental chamber, 60 °C was the chamber temperature in order to simulate the industry practice – this also demonstrates the advantage of the microwave system in controlling the temperature profile inside concrete. To make a fair comparison, the curing duration of the concrete samples in the environmental chamber has been determined based on equal maturity as that in microwave curing. From the results in Table 1, it can be seen that whilst similar compressive strength was obtained from both systems after a nearly eight hours thermal curing in both cases, the energy consumption in the microwave system was much lower, representing a 73% reduction in energy consumption. Furthermore, the total curing duration (including both the delay time and thermal curing time) was only nine hours for microwave curing, which is much shorter than the 14 hours and 27 minutes needed for the concrete samples cured in environmental chamber. These results clearly demonstrate that, compared to conventional thermal curing, microwave is a fast and low-energy alternative curing technique for manufacturing HVFA-based precast concrete products.

**Table 1: Compressive strength and energy consumption of HVFA from different curing methods.**

| Curing method | Delay time (hr: min) | Duration of thermal curing (hr: min) | Total Duration (hr: min) | Total energy consumption (kJ) | Compressive strength (MPa) | Energy consumption (kJ/MPa) |
|---|---|---|---|---|---|---|
| **Environmental chamber** | 6:45 | 7:42 | 14:27 | 65808 | 14.76 | 4459 |
| **Microwave oven** | 1:00 | 8:00 | 9:00 | 18731 | 15.56 | 1204 |

# CURING ALKALI-ACTIVATED FLY ASH WITH MICROWAVE OVEN

In addition to the HVFA concrete which is based on PC system, another approach to develop low-carbon cementitious material by utilising the low carbon footprint of fly ash is through AAFA. Different from HVFA, in AAFA system, no PC or PC clinker is needed. In this system, fly ash (100%) is activated by alkaline activators [29]. Compared to PC system, AAFA generates lower $CO_2$ emission, consumes less energy and possesses superior durability [30,31]. However, the strength development of AAFA is very slow under room temperature and thermal curing is essential for the initiation of the chemical reaction and then subsequent strength gain [32,33]. Currently, the prevailing curing method for AAFA is thermal curing at 85°C, which normally takes more than 8 hours to obtain an early strength of above 20 MPa [33]. The main drawback of this thermal curing is, again, its high energy consumption, offsetting the environmental benefits which could be obtained from AAFA itself.

Using the tailored microwave system, a multi-stage microwave curing regime has been developed in AIM Group at University College London [34]. Table 2 shows the results obtained from an 8M sodium hydroxide activated fly ash system. Both microwave oven and electric oven have been used. The energy consumption during each curing process was also monitored by the power meter. It can be seen that, with 4.5 hours' multi-stage curing, the microwave cured AAFA (MW AAFA) obtained higher strength than that cured by the electric oven (OV AAFA), i.e. 35.66 MPa as compared to 28.10 MPa, which is around 27% increase. More importantly, the energy consumption per strength gained (kJ/MPa) was only 191.81 KJ/MPa for the MW AAFA whereas this was 330.92 KJ/MPa for the OV AAFA, representing a 42% reduction in the energy consumption from the microwave curing as compared to the conventional thermal curing.

# CONCLUSIONS

Compared to conventional accelerated curing techniques, such as steam curing, microwave curing is a fast and more energy efficient alternative curing technique. By incorporating the advanced optical fibre sensor system and the state-of-the art microwave technology, a fully automated microwave curing system has been established at University College London for manufacturing low-carbon concretes. The two low-carbon systems currently investigated at UCL, namely, high volume fly ash concrete and alkali-activated fly ash, indicate that, by using the microwave curing technique, the low-carbon performance can be achieved from both systems whilst the early strength was not affected. The current results also demonstrate a good potential of microwave curing for manufacturing low-carbon precast concrete elements in the future.

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**Table 2: Compressive strength and energy consumption of AAFA from different curing methods.**

| Curing method | Delay time (hr: min) | Duration of thermal curing (hr: min) | Total energy consumption (kJ) | Compressive strength (MPa) | Energy consumption (kJ/MPa) |
|---|---|---|---|---|---|
| **Electric oven (OV AAFA)** | 1:00 | 4:30 | 9299 | 28.10 | 330.92 |
| **Microwave oven (MW AAFA)** | 1:00 | 4:30 | 6840 | 35.66 | 191.81 |

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