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Application of fibre Bragg gratings for the optimization of microwave-cured concrete

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***Abstract*—In this paper, the suitability of using 'intelligent' fibre Bragg gratings (FBGs) as sensors for the temperature feedback control of concrete cured in a microwave environment has been presented and experimentally demonstrated. In this novel approach, the temperature data provided by the embedded FBGs are processed on the fly (using a feedback control algorithm) in order to regulate the microwave power so that an internal curing temperature of 70°C is maintained. The immunity of the FBGs to microwave radiation ensures that the embedded sensors remain stable, unlike conventional metallic/electrical probes.**

***Index Terms*—Fibre Bragg gratings, temperature monitoring, microwave curing.**

I. INTRODUCTION

At present, conventional heating by steam-curing is generally the preferred approach for accelerating the strength development of pre-fabricated concrete elements. The heat energy provided by the steam significantly increases the rate of cement hydration, thus enabling the concrete to reach a higher strength in a shorter time period while maintaining a moist curing environment. While established as a favourable means of accelerating the strength development of precast concrete, concerns remain over the heating efficiency and precision of temperature control achieved by using conventional heating methods.

The use of microwave power as an alternate, energy-efficient source of heat energy has recently triggered interest in the U.K. Not only can significant improvements in efficiency be made, the precise control of microwave power can ensure that an optimum internal temperature is maintained. The failure to control the internal heating rate can cause undesirable effects such as the boiling of mixing water or phase transformations in the hardened state (e.g. the transition of ettringite to monosulfate above 70°C). Therefore, in order to maximise the benefits of microwave heating, a robust control system must be established.

After some initial studies in the 1980s, the advantages of heat-curing concrete using microwave energy were quickly recognized [1]. In this early work, curing was carried out using a domestic-type microwave whereby the fixed power was pulsed in order to achieve a desired average power output. Further studies in the 1990s explored the concept of 'temperature feedback control' in order to improve the curing efficiency [2-4]. The authors noted that by using microwave heating, the concrete was heated uniformly, unlike the occurrence of temperature gradients when conventional methods are used. For the internal temperature measurement, a thermocouple with appropriate shielding was used in order to avoid 'sparking' caused by the electromagnetic interference on the metallic surface. With this arrangement, however, additional bulk is added which may become intrusive, particularly if multiplexing is required. Moreover, the thermocouple shielding can cause undesirable reflections to take place thus forming 'hot' and 'cold' spots within the concrete being cured.

Unlike conventional metallic thermocouples, fibre Bragg gratings (FBGs) are immune to microwave radiation. They are also much smaller in size and easier to multiplex. With these considerations, FBGs are expected to offer improved stability and versatility in the design of temperature probes for use in industrial microwave environments.

II. PRINCIPLE OF MEASUREMENT

FBGs are in-fibre sensing devices which can be 'inscribed' into photosensitive optical fibres by using a precision UV laser. A schematic of an FBG is shown in Fig 1. The inscribed grating pattern incorporates a periodic change in the refractive index of the fibre core thus enabling light to be reflected at a particular wavelength, λ_B, and monitored as a peak of light intensity. This can be explained using Bragg's relationship [5]:

$$\lambda_B = 2n_e\Lambda$$

where n_e is the effective refractive index of the fibre core and Λ is the periodic spacing of the grating.

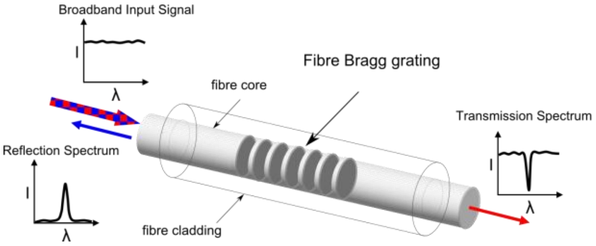

Fig. 1 Schematic of FBG

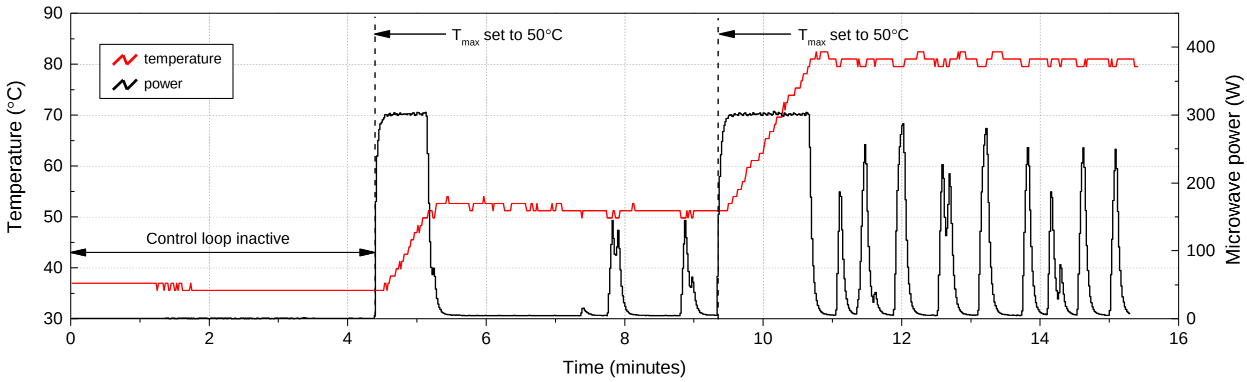

Fig. 2 Demonstration of FBG temperature feedback control system for new laboratory microwave (FBG immersed in water)

Changes in the environmental temperature cause a peak ‘shift’ to occur which has been found to be directly proportional to the temperature change [5]. Multi-point sensing can be achieved by inscribing additional FBGs (with different Λ) thus enabling intensity peaks to be discriminated and monitored independently without the need for separate ‘wires’ (fibres).

III. MICROWAVE WITH FBG FEEDBACK CONTROL

For this work, a bespoke microwave oven was manufactured by Industrial Microwave Systems (IMS), U.K. The design enabled interfacing with a computer to allow full control over the microwave power (unlike a domestic microwave). The temperature feedback control software was written in Labview which incorporated a proportional-integral-derivative (PID) control algorithm.

Trials with water were carried out in order to demonstrate the feasibility of using FBGs for temperature feedback control of the microwave power. With the positioning of 1 x FBG in a beaker of water, the control loop was set to achieve a target water temperature of 50°C and subsequently 80°C, with the maximum microwave power set at 300 W. Figure 3 illustrates the success of the FBG feedback control system whereby the precise regulation of temperature is achieved through low-energy pulsing of the microwave power.

IV. SENSOR ARRANGEMENT AND TEST SETUP

A series of FBGs (x 5) were inscribed onto one optical fibre strand to produce a new type of multi-point, microwave-transparent temperature probe. The new probe design consists of an optical fibre encased in a bespoke housing manufactured using polyether ether ketone (PEEK) (shown schematically in Fig. 3). To enable the transfer of temperature, some perforations were incorporated at each grating position. The software was modified to only use the highest temperature reading for the PID control.

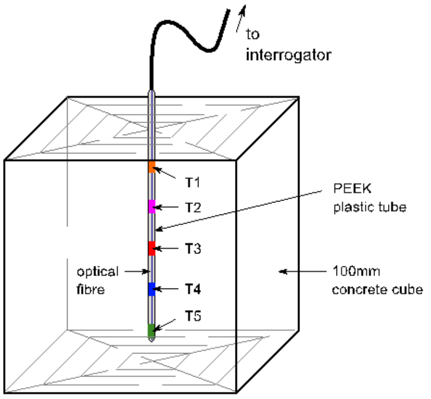

Fig. 3 FBG probe layout

For the concrete, a typical formulation was recommended by industry (Macrete, Ireland) which included pulverized fuel ash (PFA) as a cement replacement material (25% w.t. of Portland cement). The mix quantities are shown in Table 1. A 100 mm cube mould was manufactured in PEEK plastic for containing the freshly mixed concrete (Fig. 4). To maintain 100% RH, a low-energy ultrasonic ‘fog generator’ was placed outside the microwave with a feed incorporated via the roof of the oven. In order to compare with a traditional heat curing technique, concrete cubes were cast in steel moulds and cured at 100% RH using a conventional oven set at 60°C. For both microwave and conventional curing, the cast concrete was allowed to sit for 2 hrs under constant environmental conditions (20°C, 100% RH) prior to the curing regime. For the microwave feedback control, a maximum microwave power of 400 W was set in conjunction with a maximum internal temperature of 70°C. As an additional control, concrete cubes from the same batch were cast and cured under normal curing conditions (20°C, 100% RH) for 24 hrs.

TABLE I. CONCRETE MIX DESIGN (1 M^3)

Portland cement	**PFA**	**20 mm coarse aggregate**	**10 mm coarse aggregate**	**Medium sand**	**water**
330 kg	110 kg	640 kg	320 kg	810 kg	190 kg

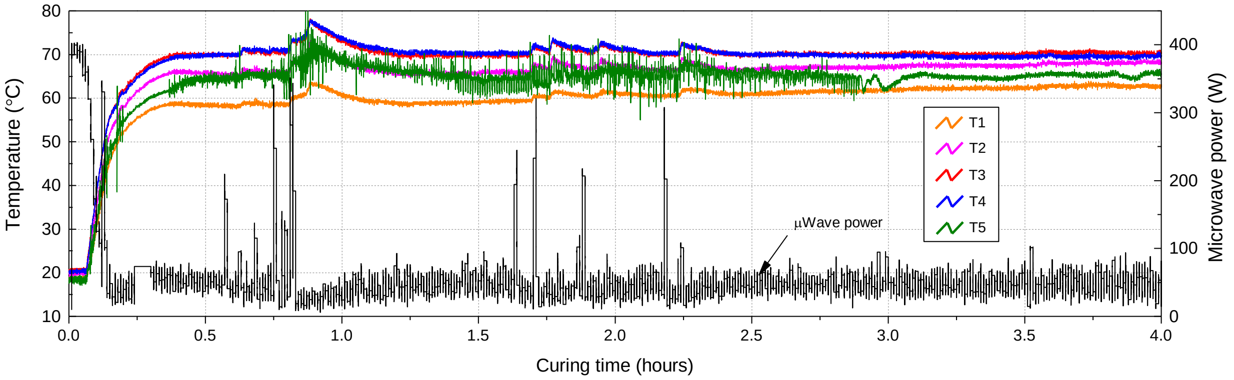

Fig. 5 Temperature feedback control of concrete cube cured for 4hrs (max internal temperature of 70°C)

Fig. 4 Photo of 100 mm concrete cube cast in PEEK mould in microwave

V. EXPERIMENTAL RESULTS

The microwave data obtained over the 4 hr test duration is shown in Fig. 5. It is interesting to observe the outcome of the temperature feedback control, particularly the response and hence dramatic reduction of microwave power within 0.25 hrs of curing. The data also reveals that the temperature gradient is very low, thus highlighting a major advantage of the microwave technique. Overall, the target internal temperature of 70°C was precisely maintained, with the exception of a ~7°C temperature rise at around 0.8 hrs. This suggests that further refinement of the PID control will be necessary in order to eliminate temperature 'overshooting'.

At the end of the 4 hr test period, the concrete cubes from both conventional heating and microwave heating were tested for strength using a compression machine. It was found that the microwave cured concrete had a marginally higher strength than the conventionally cured cube (see values in Fig. 6). Calculations also revealed that the microwave curing method used a mere 6% of energy in comparison to the conventional oven at 60°C (see values in Fig. 7).

VI. SCALED-UP TRIAL

Finally, a scaled-up trial, as shown in Fig. 8, was carried out within an industrial-scale microwave at IMS U.K. For this trial, a larger 150 mm cube mould was manufactured using polypropylene (PP) plastic (Fig. 9). As external interfacing was not incorporated into the industrial-scale microwave, it was necessary to use the 'power history' trace in Fig. 5 as a guide while manually controlling the microwave power using a control knob. Three additional 100 mm cubes were cast alongside the 150 mm cube as specimens for compressive strength testing. Due to time constraints, the curing regime was shortened by 2 hrs in comparison to the laboratory study (i.e. 2 hr rest + 2 hr microwave curing). At the end of the trial, the concrete cubes were immediately demoulded and after inspection by Macrete it was found that the 150 mm cube had achieved the minimum 'demoulding strength' required for precast concrete. Later testing of the 100 mm cubes in

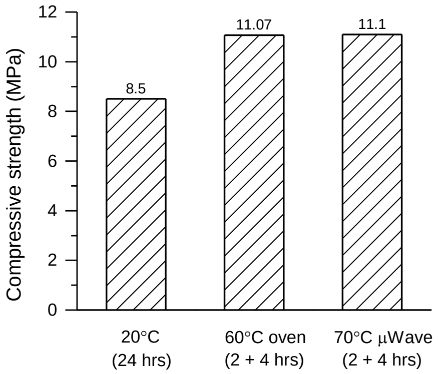

Fig. 6 Compressive strength results of concrete cured under different heating conditions

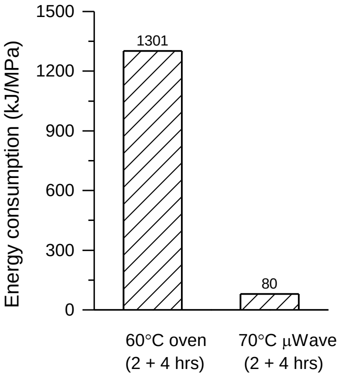

Fig. 7 Energy consumption of thermal curing techniques

Fig. 8 Scaled-up trial of microwave-cured concrete

Fig. 9 Photo of 150 mm concrete cube cast in PP mould in microwave

University College London revealed that a strength of 7.82 MPa had been achieved (after an additional 2hrs transport at ambient temperature). As well as the reduced power consumption, the microwave curing technique shows excellent promise in terms of heating efficiency thus enabling a faster turnover of product.

VII. CONCLUSION

This preliminary study has demonstrated the benefits of using FBGs as temperature sensors in a microwave environment. Not only does the probe provide microwave-immune readings, this simple principle enables multiple sensors to be incorporated thus providing useful information on the heating profile of concrete in a microwave environment. Combined with the suitable control system, FBGs enable the precise monitoring and feedback necessary for the optimisation of microwave-cured concrete.

Future studies will focus on the development of a larger microwave incorporating full temperature feedback control using FBGs.

VIII. ACKNOWLEDGEMENT

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