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Microwave system for in-situ curing of concrete repair

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ABSTRACT: This paper presents some results of the FP7 MCure project on the development of a prototype system for microwave curing of concrete and concrete repair. Microwave curing of concrete provides higher early age strength compared to normally cured concrete. A prototype microwave curing system has been developed based on laboratory results on microwave curing of concrete repair materials. Subsequently, field trials were carried out to validate the Pre-Industrial Prototype system by testing elements of four commercial repair materials and a CEM II cement concrete. The prototype control system was used to record data such as surface temperature of concrete, moisture content of concrete and output power of the magnetron. In addition, the relationships between microwave output power, temperature and volume of repair of the field trials were derived and compared with the laboratory results. The prototype microwave system performed effectively. Slabs of dimensions 1 m x 1 m and depths up to 64 mm were microwave cured to temperature up to 45 ^{o}C for the predetermined time.

1 INTRODUCTION

Patch repair is one of the most common types of repair in concrete structures. It can be classified as non-structural or cosmetic repair in which load carrying capacity is not a major issue and structural repair in which the repair patch is expected to carry load (Plum 1991). Emmons (1992) provides a detailed description of the various stages involved in the execution of a patch repair.

In the case of runway, bridge and car park repairs, high early age strength may be required to minimise delays, disruption and financial costs for the users and owners of the structure. Cold weather repair application is another example in which high early age strength is required to avoid the detrimental effects of low temperatures on long-term compressive strength (Neville 2011). However, under normal curing conditions, it may take 24 hours or more for most cementitious repair materials to harden and it may take several days before sufficient compressive strength is developed to carry the applied loads (Leung & Pheeraphan 1995).

Microwave heating based on dissipation of internal energy due to the excitation of water molecular dipoles when exposed to a rapidly alternating electromagnetic field (Leung & Pheeraphan 1995) can be used to reduce curing time and increase early age strength of cement-based repair materials. This has been shown by various studies performed on cement-based mortars using different types of cement and w/c ratios (Wu et al. 1987, Hutchison et al. 1991, Leung & Pheeraphan 1995, Leung & Pheeraphan 1997, Sohn & Johnson 1999, Lee 2007, Rattanadecho et al. 2008, Makul & Agrawal 2011). Significant reduction in disruption, delays and costs can be achieved by shortening the required curing time of patch repairs in concrete structures and airport runways.

The MCure project funded by the EC FP7 programme has been developed to facilitate rapid and durable patch repairs to concrete structures and pavements. A microwave curing prototype has been developed to accelerate in-situ concrete repairs and to enable repair application in cold weather.

2 MCURE PROTOTYPE DESCRIPTION

2.1 *MCure prototype systems*

The MCure prototype (Fig. 1) is comprised of the following six systems:

- Microwave system
- Temperature monitoring system
- Moisture monitoring system
- Remote control system
- Electrical system
- Microwave radiation safety system

Figure 1. The MCure prototype.

2.2 *MCure prototype operating software*

Software based on two different algorithms specifically developed for the MCure system is used to operate the machine. It provides the user with the option of selecting either manual or automatic mode control for operating the machine. Parameters such as the movement pattern of the antenna over the microwave cured area, microwave power, target temperature and total heating time can be input before the start of operating the machine by using the touch screen panel shown in Fig. 2. The movement of the antenna is subdivided into step by step and continuous movement patterns. The step by step movement pattern means that the antenna will move to the next position only when the temperature of the current position achieves the target temperature. The continuous movement pattern means that the antenna will continuously move over the concrete surface with constant speed/power.

Figure 2. The touch screen display panel.

2.2.1 *Manual mode*

Microwave curing parameters such as position of the antenna, microwave power and heating time should be determined by the operator in the manual mode of the machine. The target temperature can be reached using either continuous movement or a step by step approach. In the first case, the antenna moves at a constant speed along a pre-determined path using fixed power and the temperature is recorded. This procedure can be repeated as many times as needed to achieve the target temperature. In the second case, the antenna is positioned above a pre-determined location and remains fixed until the area directly beneath the antenna has reached the target temperature. Once the target temperature is reached, the antenna is moved and positioned at the next area to be microwave cured. By using this approach, it is possible each time to microwave cure an area slightly larger than the projected area of the antenna.

2.2.2 *Automatic mode*

When in automatic mode, only the movement pattern of the antenna is determined by the operator. The target temperature of the microwave cured patch repair is achieved by using either a Proportional Integral Derivative (PID) algorithm or a Fixed Time Power Regulating (FTPR) algorithm specifically developed for the MCure system. The algorithm is used to regulate the required microwave power of the antenna at a specific position. Once the target temperature at this position is achieved, the antenna is moved and positioned over the next area to be microwave cured.

2.2.2.1 *PID algorithm*

The Proportional Integral Derivative (PID) controller (Minorsky 1922) is a control loop feedback mechanism. It has become the most commonly used closed-loop controller in all types of industrial control systems due to its simplicity and excellent performance (Astrom & Murray 2010). In a PID controller its input signal is the error $e(t)$ between a user defined set point $r(t)$ and a measured plant/process variable $y(t)$ as shown in Equation 1. The terms plant and process refer to the object or the process that is being controlled by the PID controller. In the case of MCure system the process is the microwave heating of the repair patch and the error $e(t)$ is the difference between the measured temperature $y(t)$ and the target temperature $r(t)$ (40 to 45 ^{o}C) (Mangat et al. 2015, Mangat et al.2016.). The output signal $u(t)$ of the PID controller in time t-domain is given by Equation 2.

$$e(t) = r(t) - y(t) \tag{1}$$

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \tag{2}$$

where $e(t)$ = error signal; $r(t)$ = set point value for temperature; $y(t)$ = plant/process variable (measured temperature); $u(t)$ = PID output signal; K_p = proportional gain (a tuning parameter); K_i = integral gain (a tuning parameter); and K_d = derivative gain (a tuning parameter).

In the MCure system, the PID controller continuously measures the error and attempts to minimise it over time by only adjusting the microwave power supplied to the surface of the repair patch. Consequently, the required heating time to reach the target temperature cannot be controlled. Too much microwave power can lead to excessive rates of temperature increase, which in turn can result in plastic shrinkage and cracking, significantly reducing later age strength (Mangat et al. 2015, Mangat et al.,2016.). In order to overcome the above limitation, a second algorithm (Fixed Time Power Regulating (FTPR) algorithm) has been developed for use with the MCure system. In FTPR algorithm the target temperature is achieved at the end of microwave curing (Mangat et al. 2015, Mangat et al. 2016.).

2.2.2.2 *FTPR algorithm*

The aim of this algorithm is to provide adequate microwave power for reaching the target temperature at the end of a fixed period of microwave curing. Prior to the application of microwave curing the rate of temperature increase for the entire curing cycle is determined based on the initial (ambient) temperature of the repair surface. At the start of the curing cycle an initial microwave power P_1 is applied for an incremental period t_1 and the temperature of the repair surface T_1 is measured at the end of t_1. Next, the rate of temperature increase during period t_1 is compared to that for the entire curing cycle. If the rate of temperature increase during t_1 is higher or lower than the rate of temperature increase for the entire curing cycle the microwave power is either reduced or increased accordingly to a new value P_2.

2.3 *Microwave radiation safety system*

The microwave radiation safety system of MCure prototype consists of a microwave safety enclosure in the form of a rectangular cuboid cage, four microwave leakage sensors and one microwave safety automatic power-off switch. The safety enclosure fully covers the microwave system and is used to confine the emitted and reflected microwave energy within its boundaries (Fig. 3). The walls and roof of the enclosure consist of a semi-transparent stainless steel fabric supported by an aluminum frame. The enclosure is able to provide effective shielding against electromagnetic waves and complies with BS EN 60519-6 (BSI 2011) which limits microwave leakage to 50 W/m^2. It also offers the chance to observe the prototype when in operation. The four microwave leakage sensors are installed on top of each enclosure wall (external face) and continuously monitor the level of microwave leakage. Each sensor is connected to the main control system in such a way that it can individually shut down the whole system by detecting microwave leakage in excess of 50 W/m^2 during its operation. The automatic power-off switch ensures that the whole prototype is automatically switched off once the maintenance door of the enclosure is opened while the prototype is in operation.

Figure 3. The microwave safety enclosure.

2.4 *System integration*

All MCure prototype systems were assembled, integrated and verified as a single operational unit. For this purpose, software developed specifically for the MCure system was used to integrate individual components in the whole system and then verify the whole system as a single unit. In addition, the integrated system was verified for microwave safety. The integrated and verified system was then used to perform trials on large slabs cast using different repair materials.

3 EXPERIMENTAL PROCEDURE

3.1 *Test programme*

A test programme was performed to microwave cure scaled up elements of concrete repair using the MCure prototype system. Tests were carried out to validate the operating and control parameters of the microwave prototype system and to assess their reliability. The results were analysed to validate the basic microwave curing relationships developed for repair patches (Mangat et al. 2015, Mangat et al. 2016.).

3.2 *Repair materials*

The following commercial repair materials were used in this investigation:

- Repair Material 1: A concrete with CEM II/A-LL 32.5 R cement conforming to BS EN 197-1 (BSI 2011), coarse sharp sand (50% passing a 600 μm sieve) and uncrushed river gravel (maximum size of 20 mm) with w/c ratio of 0.45. Density of fresh mix was 2350 kg/m^3.
- Repair Material 2: A low shrinkage polymer modified cement mortar, fibre-reinforced with corro-

sion inhibitor. Density of the fresh mix was 2100 kg/m^3 (Sika MonoTop-412).

- Repair Material 3: A polymer modified cement mortar. Density of the fresh mix was 2050 kg/m^3 (Sika MonoTop-613).
- Repair Material 4: A polymer modified cement mortar with corrosion inhibitor. Density of the fresh mix was 1900 kg/m^3 (StoCrete GM P).
- Repair Material 5: A polymer modified cement mortar. Density of the fresh mix was 2200 kg/m^3 (StoCrete TG 204).

3.3 *Details of slabs*

Five slabs were cast in timber moulds of 1000 x 1000 x 105 mm internal dimensions for microwave curing trials of the above repair materials. The mix proportions of each repair material were based on the manufacturer's recommendations. Details of all slabs are shown in Table 1.

Table 1. Details of repair material slabs

Slab	Area (m^2)	Depth (mm)	Repair material	Pre-curing time (min)
S6	1	58	1	43
S7		62	2	40
S8		59	3	46
S9		61	4	38
S10		64	5	41

3.4 *Mixing and casting of slabs*

The quantity of each repair material (concrete and commercial repair materials of slabs S6 to S10) and water were mixed together in a concrete pan mixer to produce the required volume of mix for the slab element. Each mix was cast in the mould and compacted by hand tamping and trowelled as shown in Figs. 4, 5. The slab specimens were then placed inside the MCure prototype system and microwave cured. Microwave curing was started at 38 to 46 minutes (pre-curing time) after commencing mixing the repair materials, to simulate the typical time taken on construction sites to apply a repair patch.

Figure 4. Compaction of newly cast mix.

Figure 5. Surface finishing of material.

3.5 *Microwave curing*

Slabs were cast with dimensions of 1 m x 1 m and microwave cured. The surface of each slab was divided into strip areas to heat. The slab surface exposed to microwave power was not covered during curing. The microwave curing was controlled manually. Each strip area was microwave cured for 2.5 minutes at a power of 1700 Watts by locating the microwave antenna above the strip. The projected area of the antenna, with some spread of the microwave energy, was heated at each location. After 2.5 minutes the antenna was moved manually over the next strip. The total microwave curing time of each slab was 50 minutes.

3.6 *Internal temperature monitoring*

The internal temperature of each slab was measured by a single type T thermocouple which was located at the base of the timber mould of the slabs. Fig. 6 shows an installed thermocouple (top right corner) in a typical slab mould. Temperature measurements were taken every 5 seconds using a Data Taker DT85G digital logger.

Figure 6.Thermocouple placed on the base of the mould.

3.7 *Surface temperature measurement*

In addition to the temperature sensors of the MCure prototype, the surface temperature of the slabs was measured using a FLIR i7 thermal camera (Fig. 7). The accuracy of the camera is 0.2% or ±2 °C and gives a resolution of 140 x 140 pixels. The camera provides an image of temperature distribution, maximum and minimum temperature range at a selected area and a spot point temperature.

Figure 7. Thermal camera for monitoring the surface temperature of the slabs.

4 RESULTS AND DISCUSSION

A significant temperature increase ΔT was achieved at the end of microwave curing in all slabs. The mid-point temperature increase recorded by the thermal camera at the end of microwave curing is shown in Table 2.

Table 2. Slab details.

Slabs	Repair material	Volume (l)	Mid-point temperature increase ΔT (°C)
S6	1	58	12.6
S7	2	62	19.1
S8	3	59	16.6
S9	4	61	14.6
S10	5	64	24.4

The results of slab S9 which are typical of all slabs S6-S10 are described in detail below.

A typical photo of a slab (S9) immediately after the end of microwave curing is provided in Fig. 8, which shows signs of phase change from fluid to solid state. Microwave curing significantly accelerated the setting of the repair slabs and the surfaces were free from plastic shrinkage cracking. Thermal images of slab S9 at the start and at the end of microwave curing are shown in Figs. 9a, b respectively. Finally, details of slab S9 temperature development during successive microwave curing of its strip areas obtained using the embedded thermocouple and the MCure prototype temperature sensors are shown in Table 3.

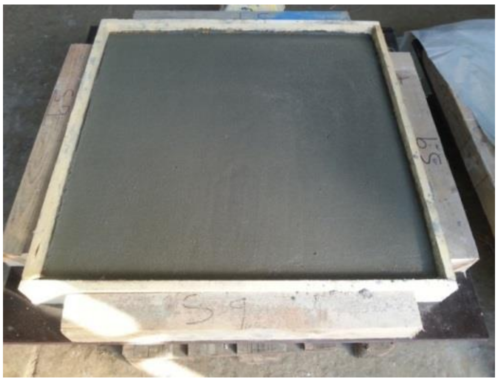

Figure 8. Slab S9 at the end of microwave curing.

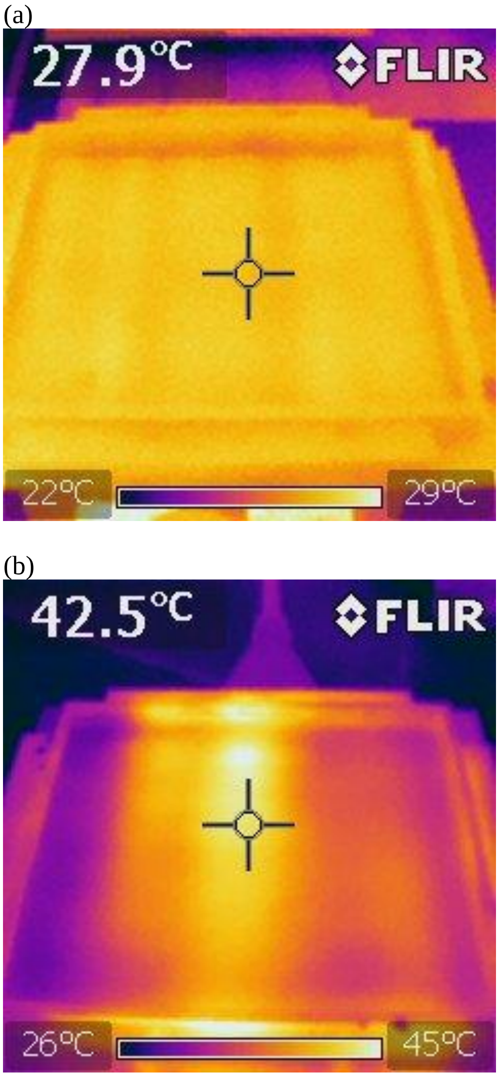

Figure 9. Slab temperature distribution (a) before the start of microwave curing and (b) after the end of microwave curing.

Finally, it should be noted that negligible microwave leakage was detected during curing of all test slabs.

Table 3. Slab S9 temperature development.

Microwave curing progress	Thermocouple temperature[1] (°C)	Sensor av. temperature[2] (°C)	Sensor max. temperature[3] (°C)
At the start of the operation	29.5	30.2	30.9
After microwave curing first quarter of slab	34.7	36.5	39.0
After microwave curing second quarter of slab	37.1	38.9	44.0
After microwave curing third quarter of slab	36.8	39.1	44.3
After microwave curing fourth quarter of slab	36.5	40.5	46.2

1-Thermocouple located at mid-point of first quarter of slab, 2-Average temperature reading of the sensors, 3-Maximum temperature of the sensors.

5 CONCLUSIONS

- The microwave prototype system provides sufficient heat to microwave cure concrete repair slabs of dimensions 1 m x 1 m and depths up to 64 mm.
- All systems of the MCure prototype functioned satisfactorily.
- The prototype enclosure provides satisfactory shielding of microwave radiation (less than 50 W/m^2)
- Microwave curing significantly accelerates the setting of the repair slabs and the surfaces of the repair remain free from plastic shrinkage cracking.

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