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Microwave System for Accelerated Curing of Concrete Repair

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Abstract:

This study presents a novel prototype microwave system developed to accelerate the curing of concrete repair patches. The system incorporates a 2 kW magnetron, a radiation safety enclosure and a temperature monitoring unit to ensure safe and controlled operation. The prototype advances beyond prior microwave curing systems by incorporating real-time temperature feedback, automated data acquisition and power modulation to minimize non-uniform heating and prevent localized overheating. Field trials were undertaken on concrete slabs of varying thicknesses, up to 80 mm, including both proprietary repair materials and conventional cementitious concrete. Each slab was exposed to microwave heating for approximately one hour at constant power levels ranging from 1500 W to 2000 W. Resulting temperatures ranged from 40.4 °C to 48.5 °C across specimens, with one exceptional maximum of 76.5 °C for a predetermined time. The estimated energy consumption was 25 kWh/m³. Data obtained from these trials were employed to validate a previously developed predictive equation for temperature rise in concrete specimens, originally derived from laboratory investigations. The findings indicate that microwave heating can rapidly increase the temperature of concrete repairs, thereby effectively accelerating the curing process for slabs up to 80 mm in thickness. The Proportional Integral Derivative (PID) algorithm was used to control the power supply and temperature in the field trials. A Fixed Time Power Regulation (FTPR) algorithm is presented as a proposed refinement intended to further improve power distribution and temperature uniformity. The results demonstrate that microwave heating can rapidly and efficiently accelerate curing for slabs up to 80 mm thick, supporting the potential for energy-efficient, cold-weather concrete repair applications.

Keywords

Microwave curing, concrete repair, power control algorithm, prototype trials

Highlights

- Prototype microwave system has been developed to microwave cure repair concrete
- Algorithm for the control system has been derived
- Design and development parameters of the prototype system validated by field trials

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1. Introduction

Microwaves are a form of electromagnetic radiation with frequencies ranging between 300 MHz and 300 GHz (Osepchuk 1984). The ability of microwaves to penetrate and cause heating of dielectric materials was discovered accidentally by Percy Spencer an American Engineer and it led to the manufacture of the first commercial microwave oven (Williams 2017). There has been extensive research since, to enhance the efficiency of microwave heating and improve the uniform distribution of heat within the heated materials (He et al. 2020; Yang and Chen 2022; Zhou et al. 2023; Li et al. 2025).

When a material is subjected to conventional heating, thermal energy is transferred to the material through convection, conduction and radiation mechanisms. On the other hand, when microwave heating is used, microwaves penetrate the material and deliver energy directly to the material through molecular interaction with the electromagnetic field. As such, microwaves can achieve rapid and more uniform heating, especially when it comes to materials with substantial thickness (Thostenson and Chou 1999). Additional advantages of microwave heating over conventional heating include use of portable equipment, quick start/stop process, no direct contact between the heated material and the heating source, higher temperatures, selective heating of materials, low energy consumption and a cleaner and more environmentally friendly energy source (Thostenson and Chou 1999; Jones et al. 2002).

While domestic microwave ovens used for heating and cooking food represent by far the largest market, microwave heating applications in other fields are quite extensive. Examples include heating/drying paper, wood, textiles, ceramics and lather (Ayappa et al. 1991; Egorov et al. 2022; Miao et al. 2024; Suer and Dericioglu 2024; Krikkis 2025), oil extraction from tar sand (Ayappa et al. 1991), synthesis, crosslinking and processing of polymer materials (Ayappa et al. 1991; Rattanadecho 2006; Caminata et al. 2020; Dua et al. 2025; Ojo et al. 2025) and

sterilization, pasteurization and thawing in the food industry (Ayappa et al. 1991; Viji et al. 2022; Bhatnagar et al. 2025; Gholamhosseinpour and Hashemi 2025; Qian et al. 2025; Tian et al. 2025; Wang et al. 2025).

Commonly used frequencies for microwave heating include 0.915, 2.45, 5.8, and 24 GHz (Ong and Akbarnezhad 2018). Lower frequencies, such as 0.915 GHz and 2.45 GHz are widely used due to their ability to penetrate deeply, making them suitable for heating materials with substantial thickness. Conversely, higher frequencies like 5.8 GHz and 24 GHz dissipate more quickly within dielectric materials, resulting in localized heating. While localized heating can be unsuitable for applications such as food processing or microwave curing of concrete, it is highly beneficial for tasks such as cutting, drilling, and breaking through hard materials like rock (Mohammadi et al. 2024; Ahmadihosseini et al. 2025; Gao et al. 2025; Lu et al. 2025; Xu et al. 2025).

The applications of microwave technology in the construction industry are numerous. These include microwave furnaces for the production of cement clinkers (Jianmiao and Shizong 2005; Buttress et al. 2015; Vermeiren et al. 2024), recycling of concrete demolition waste (Bru et al. 2014; Sheng et al. 2024; Wei et al. 2024; Zheng et al. 2025), decontamination of radioactive concrete (Bažant and Zi 2003; Akbarnezhad and Ong 2010), cutting/drilling of concrete (Jerby et al. 2002) and non-destructive monitoring of concrete structures (Wahab et al. 2019).

In addition to the above applications, significant research in microwave curing of cementitious materials has been performed (Leung and Pheeraphan 1997; Makul and Agrawal 2011; Mangat et al. 2016a; Grigoriadis et al. 2017; Mangat et al. 2017; Mangat et al. 2021; Abubakri et al. 2024a). However, most studies have been limited to laboratory experiments using domestic microwave ovens and conventional Portland cement concrete mixes. Recently, efforts have shifted toward developing industrial-scale microwave systems for concrete curing (Mangat et al 2016b; Morozov et al. 2016; Rattanadecho et al. 2016). For example, Morozov et al.

(Morozov et al. 2016) reported an experimental investigation of applying microwave energy to heat concrete before transferring the mixture into moulds. They have introduced a prototype and claimed that a microwave power of 50 kW increases the temperature of concrete by 6 °C. The prototype can heat up to 10 m^3 of concrete per hour.

The authors (Mangat et al. 2016a) have previously identified the key parameters influencing the microwave curing of concrete repair as microwave power, duration of exposure, and volume of the repair patch. These parameters significantly influence the temperature rise in concrete exposed to microwave energy. Based on laboratory experiments with concrete repair materials, a statistical best-fit equation was developed to describe the relationship between these parameters (Mangat et al. 2016a). This equation is used to design a microwave prototype system and calculate the range of power required to achieve the desired curing temperatures. The design accounted for factors such as temperature increase, curing time and volume of materials being cured, facilitating the in-situ curing for larger repair material volumes.

This study outlines the development of the microwave curing system, including its control parameters, leading to the creation of an automated prototype system for accelerated curing of concrete repairs. In addition, it presents test results from field trials on microwave curing of different proprietary concrete repair materials in slabs of 1 × 1 m^2 simulating patch repairs. This work builds upon our initial prototype and preliminary results reported in the FP7 MCure conference paper (Mangat et al. 2016b),which provided an early demonstration of microwave curing for concrete repairs. The current study significantly advances that foundation by presenting a developed closed-loop power control system integrating a PID control algorithm and a newly developed FTPR control algorithm. It also includes extensive temperature monitoring that captures both surface and internal conditions, as well as validation of the prototype design theory through field trials on slabs of varying thicknesses and repair materials. These rigorous experimental analyses were not covered in the earlier conference publication,

thereby representing a substantial contribution beyond prior work. This study forms part of a broader research effort funded by the European Commission, Framework Programme 7 (MCure project), which aims to advance microwave curing technology of cement-based repair materials and develop a scalable prototype system for in-situ curing of concrete patch repairs. The outcomes align with the United Nations Sustainable Development Goals, particularly Goal 9: Industry, Innovation and Infrastructure and Goal 11: Sustainable Cities and Communities (United Nations 2023). By advancing microwave curing technology for concrete repair, the study supports the development of more efficient, low-carbon construction practices that extend the service life of infrastructure and reduce energy consumption. The proposed in-situ microwave curing system promotes sustainability by minimising downtime during repairs, enhancing the durability of civil structures and reducing reliance on energy-intensive conventional curing methods. Collectively, these findings contribute to the broader objective of creating resilient and sustainable built environments.

2. Description of the prototype microwave system

2.1 Microwave system

The microwave prototype system was designed and manufactured based on the findings from laboratory investigations of microwave curing of different types of proprietary concrete repair materials (Mangat et al. 2016a). The magnetron of the system operates at a frequency of 2.45 GHz and can generate power at increments of 5%, ranging from 10% to 100% of its maximum output of 2000 Watts. A slotted antenna measuring 500 × 100 mm^2 ensures uniform microwave distribution across the concrete surface. Temperature sensors and a moisture sensor were also installed close to the slotted antenna. The microwave antenna along with sensors is mounted onto a 3D Cartesian coordinate robot and can remotely move along the *x*, *y* and *z* axes. The robot can travel a maximum distance of 1500 mm, 1255 mm and 300 mm along the *x*, *y*, and *z*

axes, respectively. The external frame is attached to four wheels to move on the ground and adjust the position of the antenna above a patch repair. The microwave system and external frame are shown in Fig. 1.

2.2 Slot Layout and Design Principle:

The slotted waveguide antenna used in the prototype is based on a uniform linear slot arrangement, designed according to standard rectangular waveguide TE_{10} mode propagation principles. The distributed slot design ensures radiation is spread along the waveguide, which reduces localized heating and supports relatively even energy deposition over the slab surface. This design follows classical formulations (Pozar 2012) and was validated through empirical calibration. To further improve uniformity, the slotted waveguide applicator was mounted on a servo-motor system allowing controlled movement along both the *x*- and *y*-axes during curing, which helps distribute energy evenly across the slab surface.

Surface temperature uniformity was evaluated by combining six-point infrared sensor readings with periodic full-field thermal imaging. The six surface sensors formed an integrated part of the prototype, providing continuous monitoring of slab temperature during curing. These sensors were shielded against microwave interference when the magnetron was active, ensuring reliable readings. For holistic monitoring, a handheld infrared thermal camera was used to capture full-field slab images. Because the camera was not compatible with direct microwave exposure, the microwave source was periodically paused to take thermal images at key stages of heating. These images were then compared with the six-point infrared sensor readings, confirming that the sensor layout captured representative hot spots and cold zones.

This combined approach of servo-driven applicator motion, six-point infrared sensing and independent thermal imaging verification confirmed that the slotted waveguide system achieved sufficiently uniform temperature distribution for practical curing applications.

2.3 Microwave radiation safety system

Microwave technology presents two primary health and safety concerns, first the risks associated with high voltage used by microwave generators and second the exposure to microwave radiation.

Microwave systems typically operate at high voltages with capacitors capable of retaining dangerous electrical charges even when the device is switched off (Gerling 2023). Accidental contact with these high voltages may lead to severe injury or even death (Casini 1998). Therefore, manufacturers are required to securely enclose all microwave-generating components and restrict access to trained personnel only. Safety measures, such as door interlocks, are commonly used to automatically cut-off electric power and discharge stored electrical energy when the system is opened. Thus, ensuring safe operation and maintenance (Gerling 2023).

Over the last 25 years, there has been considerable public concern related to human exposure to electromagnetic fields such as the ones with frequency of 2.45 GHz generated by microwave ovens and mobile phones (Shahab et al. 2018) As such, numerous studies on the risks of cancer and other illnesses due to exposure to electromagnetic fields have been published (Elwood 1999; Kim et al. 2008; Ruediger 2009; Falzone et al. 2011; Kazemi and Ranjbaran 2015; Morgan et al. 2015; Ohtani et al. 2015; Jiang et al. 2016; Kuybulu et al. 2016; Türedi et al. 2017; Altun et al. 2018; Gruber et al. 2018; Son et al. 2018). However, no conclusive evidence currently links exposure to microwave electromagnetic fields with an increased risk of cancer (Shahab et al. 2018; Gerling 2023). Unlike γ and x-ray frequencies, microwave radiation lacks the photonic energy necessary to ionize materials, which significantly reduces its potential for causing cell damage in human body (American Medical Association 1994; Gerling 2023). In addition, regulatory bodies such as the International Commission on Non-Ionizing Radiation

Protection (ICNIRP) (ICNIRP 1997) Institution of Electrical and Electronics Engineers (IEEE) (IEEE 1999) and International Electrotechnical Commission (IEC) (IEC 2022) have established strict safety standards for devices operating in the frequency range between 300 MHz and 300 GHz. For example, IEC 60519-6 standard (IEC 2022) limits power density exposure to 50 W/m^2 or 5 mW/cm^2 from different sources, including medical devices, amateur radio, mobile phone base stations, WiFi networks, microwave ovens and traffic radars. Nevertheless, microwave exposure can cause severe thermal trauma to human tissue, and the degree of danger depends on the frequency, power and period of exposure. In addition, an increase in either the power or the duration of microwaves increases the level of thermal injury. Microwave systems are normally designed with proper shielding to protect the operators against microwave heating.

The prototype microwave system has been designed to operate safely in accordance with IEC 60519-6 standard (IEC 2022) by appropriately shielding any signal above the allowed limit of 50 W/m^2. This limitation in leakage is achieved by using an aluminium shielding frame with metallic fabric to cover the prototype system. The shield traps any reflected microwave energy during microwave curing. In addition, four microwave detector sensors installed at the top of each side of the frame are connected to a Hör Electronic MLT442 microwave leakage tester. Each sensor is directly connected to the main control system and has the capability to shut down the entire system independently if it detects a leakage exceeding 50 W/m^2 during operation. Furthermore, a Voltcraft MWT-2G manual microwave radiation meter is used to monitor the space outside the shielding frame while the prototype is in operating. No leakage above the limit was observed throughout the trials. Fig. 2a shows the microwave safety frame and Fig. 2b shows the microwave leakage sensor.

2.4 Temperature monitoring system

Temperature monitoring of microwave cured repair material is important to provide controlled heating to a repair patch. Surface temperature was selected as the primary control variable for two main reasons. First, for practicality and responsiveness. Infrared pyrometers provide non-contact, real-time surface temperature feedback with high accuracy and minimal latency, making them ideal for dynamic microwave control. Second, for safety and uniformity. Excessive surface heating during microwave curing can cause dehydration or microcracking. Controlling the surface temperature helps to maintain safe limits while allowing sufficient heat to diffuse inward by conduction. The prototype has been integrated with six non-contact infrared temperature sensors to measure spot temperatures ranging from -50 °C to +975 °C with an accuracy of ±1%. The emissivity setting on the infrared pyrometers was set to $\varepsilon = 0.95$, which is commonly used for concrete and recommended in relevant literature (Huh et al. 2018). The infrared pyrometers have a response time in the sub-second range, consistent with typical specifications for this class of industrial sensors (on the order of 0.1-0.2 seconds). The control loop was implemented with a sampling interval of approximately 1 second (1 Hz). At each update step, the system processed the six surface temperature readings, computed the average and safety threshold values. To ensure the accuracy of surface temperature readings, we cross-checked the infrared readings against a type-T thermocouple embedded at the base of the slab and a thermal camera. Fig. 3 shows the arrangement of the six sensors with the actual position related to the slotted wave antenna. The size of the spots is exaggerated to assist the visibility of the location. Among these sensors, B220 and B221 come with laser markers indicating the location of the measurement on the top surface of the concrete. The arrangement of the sensors provides the ability to determine the temperature at different locations of the concrete surface covered by the slotted antenna during microwave curing. The temperature recording system records the minimum, maximum and average temperature at each location.

2.5 Operation of microwave prototype

The prototype microwave system has a guided antenna with a cross-sectional dimension of 500×100 mm^2. In practical applications, however, patch repairs may involve top surface areas of varying sizes, often exceeding the antenna's projected area. Consequently, two methods may be employed to achieve microwave curing over a surface area larger than the antenna. These methods are referred to as the Step by Step (SS) and Continuous Movement (CM) approaches. The SS approach involves positioning the antenna at a specific location and keeping it stationary until the area beneath it, attains the desired temperature. Once this condition is met, the antenna is moved to the next section requiring microwave curing. This technique allows each curing step to cover a slightly larger area than the antenna's projected surface due to the spread of microwave energy. In contrast, the CM approach involves the antenna maintaining a steady speed and power, with the process repeated as often as necessary to achieve the desired temperature. The prototype system is designed to perform microwave curing in either manual or automatic mode.

To microwave cure an element using either of these two approaches, several parameters must be determined by the operator, including the antenna's position, microwave power, heating time and target temperature. The authors accomplished this using two distinct algorithms: the Proportional Integral Derivative (PID) algorithm and the Fixed Time Power Regulating (FTPR) algorithm.

2.5.1 PID algorithm

The Proportional Integral Derivative (PID) control algorithm is a fundamental feedback mechanism extensively used in various industrial control systems due to its simplicity and high performance (Minorsky 1922; Aström and Murray 2010). In this system, the input signal $e(t)$,

represents the difference between a defined target value for temperature $r(t)$, which is set within the range of 40 to 45 °C and the actual measured value of temperature $y(t)$, as outlined in Eq. (1). The controller's output signal $u(t)$ dynamically modifies the system's behaviour to minimise $e(t)$, as mathematically represented in Eq. (1) and Eq. (2). This mechanism allows the PID controller to continuously adjust system behaviour, maintaining the process within desired parameters.

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

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

where $e(t)$ is the input signal; $r(t)$ is the target value for temperature; $y(t)$ is the actual measured temperature; $u(t)$ is the PID output signal; K_p is the proportional gain (a tuning parameter); K_i is the integral gain (a tuning parameter); K_d is the derivative gain (a tuning parameter). The unit of error in this case is °C, microwave power (%)/°C for K_p, microwave power (%)/°C·s for K_i, and microwave power (%)·s/°C for K_d.

The PID controller in the microwave prototype system actively monitors deviations from the target temperature and dynamically adjusts the microwave power to reduce these discrepancies and maintain optimal heating of the repair patch. However, this method lacks the ability to directly control the time required to achieve the target temperature. Excessive microwave power can result in rapid temperature increases, which may cause plastic shrinkage and cracking, ultimately compromising the long-term strength of the material (de Medeiros-Junior et al. 2015; Shen et al. 2016). To overcome this limitation, the authors introduced the Fixed Time Power Regulating (FTPR) algorithm. This algorithm ensures that the repair patch

accurately reaches the target temperature by the end of the microwave curing process, effectively reducing the risks associated with uncontrolled heating rates.

2.5.2 Fixed Time Power Regulating (FTPR) Algorithm

FTRP algorithm aims to supply sufficient power to the concrete repair material to ensure it reaches the target temperature by the end of microwave curing. It is based on an idealised non-linear temperature-time profile shown in Fig. 4, which has been determined as optimum for early strength development of concrete mixes (Leung and Pheeraphan 1997). The patch repair is microwave heated to a target temperature (T_t = 40 °C) as recommended by previous research (Mangat et al. 2016a) within a target period (t = 45 minutes). The basis for the conservative target temperature is to prevent risks associated with moisture loss, thermal cracking, post-curing hydration and long-term durability problems. The duration of 45 minutes of microwave heating would be practical for site curing. The aim of the FTPR control system is to regulate the power in time-increments to generate the temperature-time profile shown in Fig. 4. Three time-increments are given in Fig. 4 (periods I, II and III) but the number can be increased to provide greater accuracy of power control. The algorithm provides heating to any cementitious repair material in a concrete repair patch of a given volume to follow the non-linear temperature-time profile of Fig. 4 (Leung and Pheeraphan 1997).

The values of T_1 and T_2 are determined from the nonlinear relationship of T and t represented in Fig. 4, at pre-determined time increments based on the degree of control required on power supply to accurately follow the temperature profile (Fig. 4). The relationship between T and t is approximated to be linear in each incremental period as shown in Fig. 4. The accuracy of this assumption will be improved by selecting a greater number of smaller time increments. The control system of the prototype provides this facility. For simplicity, the non-linear temperature profile can be replaced by 3 increments of linear temperature-time profiles as

shown in Fig. 4, representing decreasing rates of temperature rise (Periods I to III). The target temperatures at the end of periods I, II and III (T_1, T_2 and T_t) are fed into the control system together with their respective times of t_1, t_2 and t_t. The target values of T_t and t_t (40 °C and 45 minutes respectively) are also recorded in the control system.

Microwave heating of a concrete repair mix of given volume at a constant microwave power results in a linear temperature-time relationship as shown in Fig. 5 (Mangat et al. 2016a). The slope α (°C/s) in Fig. 5 is different for the various proprietary materials used for concrete repair in practice and it increases linearly with an increase in the microwave power as shown in Fig. 6 (Mangat et al. 2016a).

The function of the control system is to provide adequate microwave power to achieve a curing temperature of 40 °C (target temperature) in the repair after 45 minutes (target curing time). This will be achieved by an iterative process providing three or more decreasing rates of temperature increase (Periods I, II, III or more) shown in Fig. 4.

2.5.2.1 *Calculation for Period I:*

At the start of curing (time 0, Fig. 5), a random power P_i is applied for a short duration of time t_i. The initial temperature T_i is then measured (by remote sensing) at the initial incremental time t_i. The values of t_i and T_i will enable characterisation of the linear temperature-time relationship of the repair patch material cured at a constant microwave power P_i by determining the slope α_i (°C/s) from Fig. 5 as follows:

$$a_i = \frac{T_i - T_a}{t_i} \qquad (3)$$

where T_a is the ambient temperature.

Since the slope α versus power relationship of the repair materials is known to be linear (Mangat et al. 2016a), the known values of α_i and P_i provide a point on the linear graph of slope α versus power P for the repair patch material formulation in Fig. 6. The graph can now be used to calculate the slope β (°C/s·W) of the α (°C/s) versus power relationship of the repair patch of Fig. 6 as follows:

$$\beta = \frac{a_i}{P_i} = \frac{T_i - T_a}{t_i P_i} \qquad (4)$$

The temperature-time graph of Fig. 6 at microwave power P_i in the Period I is re-drawn in Fig. 7. The target curing temperature of the repair patch at the end of Period I is T_1 ºC at time t_1 minutes as shown in Fig. 4.

The corrected slope α_1 of the temperature-time relationship required to achieve the target temperature T_1 at time t_1 is calculated from Fig. 7 as follows:

$$a_1 = \frac{T_1 - T_i}{t_1 - t_i} \qquad (5)$$

Hence, the corrected microwave power input P_1 required after the initial curing period t_i to attain the target temperature T_1 of the repair after time t_1 is calculated from Fig. 6 as follows:

$$\beta = \frac{a_1}{P_1} \qquad (6)$$

Substituting from equations 4 and 5, one obtains:

$$P_1 = \left(\frac{T_1 - T_i}{t_1 - t_i}\right)\left(\frac{t_i P_i}{T_i - T_a}\right) \qquad (7)$$

The three linear stages of Temperature-time profile in Fig. 4 which represents the incremental temperature-time curing profile of the repair patch over the total 45-minute period, is presented in Fig. 8.

2.5.2.2 *Calculation for Period II:*

From Fig. 8,

$$a_2 = \frac{T_2 - T_1}{t_2 - t_1} \tag{8}$$

From Fig. 6,

$$\beta = \frac{a_2}{P_2} \tag{9}$$

Substituting for a_2 and β from equations 8 and 4 one obtains:

$$P_2 = \left(\frac{T_2 - T_1}{t_2 - t_1}\right)\left(\frac{t_i P_i}{T_i - T_a}\right) \tag{10}$$

2.5.2.3 *Calculation for Period III:*

Similarly, from Fig. 8,

$$a_3 = \frac{T_t - T_2}{t_t - t_2} \tag{11}$$

and

$$P_3 = \left(\frac{T_t - T_2}{t_t - t_2}\right)\left(\frac{t_i P_i}{T_i - T_a}\right) \tag{12}$$

Eq. (7), Eq. (10) and Eq. (12) form the basis of the Fixed Time Power Regulating (FTPR) algorithm, which is designed to control power to reach the target microwave curing temperature within a specified time. For the integration of this into the control system, it should be noted that α_1 is derived from a single short test pulse, therefore, this stage is more uncertain than subsequent periods. However, for the periods I to III, smaller incremental time intervals will rapidly improve the accuracy of achieving the non-linear temperature-time profile of Fig. 4. The control system will continuously adjust power supply after each increment according to the above procedures of FTPR, which include the α_i, α_1, α_2 and α_3.

The control logic of the system should ensure that only one algorithm, either PID or FTPR, is active at any given time to avoid conflicting commands. While the PID algorithm continuously modulates microwave power based on the temperature error to maintain the target temperature, the FTPR method, developed by the authors and recommended for microwave heating in concrete repair, adjusts power in discrete steps (P_1, P_2, and P_3) according to the rate of temperature increase. This stepwise approach effectively replaces the continuous modulation of PID. The software architecture enforces this mutually exclusively, ensuring consistent and stable system behaviour throughout the heating process.

All temperature profiles reported in this study were obtained using either PID control or constant-power operation throughout heating. Although a FTPR algorithm was subsequently developed to address PID limitations, such as slow response and accurate temperature control over the non-linear curing period, it was not applied in the present trials.

3. Prototype trials

3.1 Test programme

Slab elements, each measuring 1 × 1 m^2 were cast in timber moulds and microwave cured using the mobile microwave prototype system. Throughout the heating process, the top surface

and internal temperature of the slabs were monitored with a thermal camera and thermocouples, respectively. Additionally, the performance of the microwave shield and moisture sensor was evaluated.

3.2 Repair materials

Details of the repair materials are given in Table 1. Material I is a control mortar mix with CEM II/A-LL 32.5R cement. Materials II to V are propitiatory repair formulations containing cementitious materials. Material II is a fibre-reinforced concrete repair material with polymer additives. Material III is polymer-modified and fibre-reinforced cement mortar. Material IV is a polymer-modified concrete repair product designed to repair reinforced concrete structures. Material V is a polymer-modified cementitious mortar which contains an anti-corrosion admixture.

3.3 Details of slabs

Table 2 summarises the details of the 9 slabs prepared for this study. Each slab was cast in a timber mould with internal dimensions of 1000 × 1000 × 105 mm^3. Slab S4 was cast on top of 34 mm hardened concrete to simulate a repair applied to an existing substrate. Slabs S1 to S6 were made using a mortar mix with a w/c ratio of 0.5, while slabs S7 to S10 were prepared using repair materials with varying water/powder (w/p in Table 1) ratios.

3.4 Mixing and preparing slabs

The repair materials and water were mixed on-site using a concrete mixer, then poured into timber moulds, compacted manually using a tamping tool and finished with a trowel. After preparation, the slabs were placed in the microwave prototype for curing, as shown in Fig. 9. The curing process started between 38 to 56 minutes after mixing, which reflects the standard

pre-curing time typically observed on construction sites when applying repair patches. Slab S4 was treated as a composite repair patch element, as it was cast on top of the hardened Slab S3 to simulate the process of repairing an existing concrete substrate.

3.5 Microwave curing

Microwave energy emitted from the magnetron is directed through a slotted antenna measuring 500 × 100 mm^2. To apply microwave curing to the 1 × 1 m^2 surface area of each slab, the surface was divided into 20 strip sections (Mangat et al 2016b), as shown in Fig. 10. Each strip measured 0.5 × 0.1 m^2. During curing, the slab surface remained uncovered, allowing direct exposure to the microwave energy. For slabs S1 to S4, each strip was exposed to microwave energy for 5 minutes at a power of 1500 W, while slabs S4 to S9 were exposed for 2.5 minutes per strip at 1700 W. The S2 strip 20 received an additional 1900 W exposure as part of a supplemental test incorporating embedded reinforcing steel (Ø10 mm rebar). This trial was conducted intentionally to assess localized field performance and electromagnetic interaction with rebar in the slab. The microwave antenna was positioned above each strip, ensuring that the projected area, including the slight spread of energy caused by the angle of the antenna slots, was effectively heated. After completing the curing of one strip, the antenna was manually repositioned to the subsequent strip through the control system. The complete curing process for the 1 × 1 m^2 slab surface required 50 to 90 minutes, depending on the slab and the specific curing parameters.

3.6 Monitoring internal temperature

A T-type thermocouple was positioned at the base of the timber mould at the centre of Strip 2. Fig. 11(a) illustrates the setup, showing a timber mould with the thermocouple installed. For slab S4, which was cast on top of a pre-existing hardened substrate slab (S3), an additional

thermocouple was placed at the interface between the substrate and the repair material, as depicted in Fig. 11(b). This second thermocouple was located on the top surface of the substrate, directly above the thermocouple at the base of the mould. Temperature readings were taken at one-minute intervals using a DataTaker DT85G digital logger.

3.7 Top surface temperature

Along with the temperature sensors integrated into the microwave system, a Flir i7 thermal camera was used to measure the surface temperatures of the slabs. The camera offers an accuracy of ±2°C or 0.2% and captures images at a resolution of 140 × 140 pixels. It can be set to show the temperature distribution across the top surface, highlight the maximum or minimum temperature within a selected area, or provide the temperature at a specific point.

4. Results and Discussion

4.1 Top surface temperature of microwave cured specimens

The temperature at the middle of the top surface of each slab was measured at the beginning and end of the microwave curing process. Fig. 12(a-b) show thermal images capturing the slab's surface temperatures at these two stages. Table 3 summarises the temperature data, showing the starting and ending values for all slabs, along with the total temperature increase during the microwave curing process. The results show that the temperature of the top surface increased significantly within 50 minutes of curing. The total temperature increase ranged from 12.6°C to 49.2°C, depending on the slab thickness. Slab S3 shows the highest temperature increase, reaching 49.2°C, attributed to its minimal thickness of 34 mm compared to the other slabs. The excessive peak temperature (76.5 °C at the end of microwave heating) observed in S3 raises durability concerns, including the potential for delayed ettringite formation and thermal cracking. This result underscores the importance of implementing appropriate control systems,

such as optimizing feedback sampling intervals and adaptive power ramping, to prevent similar temperature overshoots. The peak temperature of 76.5 °C exceeds the recommended limit of 40-45 °C (Mangat et al. 2016a).

4.2 Internal temperature development during microwave curing

Internal temperature refers to the reading from the thermocouple applied at the base of the mould on the inside face. Fig. 13 shows a typical internal temperature development graph of microwave cured slab S9. Results show that the internal temperature was approximately 28.7 °C at the start (38 minutes after the start of mixing the raw materials with water) and increased to 36.5 °C at 105 minutes (67 minutes after microwave curing) to reach the first peak. The temperature then decreased gradually before rising again at approximately 160 minutes and gradually reaching a peak heat of 51.7 °C at 517 minutes. Similar internal temperatures were recorded for all slabs (Fig. 14 to Fig. 16). The increase in temperature for the second peak is due to the heat of hydration. This secondary temperature rise is consistent with the expected hydration kinetics as has been reported previously by the authors (Mangat et al 2021). It underscores important durability considerations and emphasizes the need to maintain a conservative target temperature during microwave curing.

The temperatures at the end of microwave heating recorded at the internal point were within 37 to 45 °C (Fig. 13 to 16). This indicates a temperature variation of ± 4 °C of the corresponding surface average temperatures in all tests. This confirms that the interior concrete received adequate thermal exposure with a reliable correspondence between the two internal and surface measuring points. However, as each test is represented by one slab specimen, this limits statistical confidence and prevents assessment of variability and repeatability. This feasibility investigation was intended to demonstrate proof of concept performance rather than statistically validated trends.

4.2.1 Effect of repeated cycles of microwave heating

Concrete slabs S5 and S6 were both exposed to microwave heating at 1700 W for a total of 2.5 minutes per strip, equivalent to 50 minutes for the entire slab. In slab S5 (Fig. 17), heating was applied in a single continuous cycle (2.5 minutes per strip). In slab S6 (Fig. 14), the same total energy input was delivered in two cycles, each applying 1.25 minutes per strip, with the second pass occurring after completion of the first. Despite identical total power and duration, slab S6 exhibited a greater temperature rise of 16.6 °C compared to 12.6 °C for S5 (Table 2) and a higher internal peak temperature (52.5 °C vs. 47.0 °C). This represents approximately a 32% higher surface temperature for S5 (based on a single slab). The difference is attributed to the multi-cycle approach which reduced heat loss, rather than any difference in the control module as power delivery remained constant in both tests.

4.2.2 Temperature development of slab cast over concrete substrate

Repair is normally applied on top of a substrate surface. This is simulated in slab S4 where a repair material slab has been cast over a hardened concrete slab (substrate) to determine the heat penetration into the substrate during microwave curing of the repair patch. Thermocouples were used to monitor the temperature at two locations, the base of the repair patch (top of the hardened concrete slab) and the bottom of the substrate (hardened slab). These measurements were recorded over a 24-hour period following the microwave curing process.

Fig. 18 shows the internal temperatures recorded at the base of the repair slab and the bottom of the substrate slab during and after microwave curing. The data reveals that the temperature at the base of the freshly applied 58 mm thick repair slab started increasing immediately with the start of microwave curing and reached its maximum by the end of the curing cycle. However, the temperature at the base of the 58 mm deep substrate (thermocouple located at the base of the substrate) started increasing gradually only after the microwave curing process had

ended. This temperature rise in the substrate was primarily driven by heat convection from its top surface rather than direct penetration of microwave heating to the bottom of the lower slab. At the interface, the substrate temperature started increasing as soon as microwave heating was applied, which reduced the temperature differential with the repair patch at the interface. It indicates that microwave curing of repair patches in cold weather will facilitate warming of the substrate at the interface, hence reducing the risk of interfacial bond failure (cold joint). Additionally, pre-wetting and saturation of the substrate interface, along with moisture from the repair mix, will also enable microwave heat penetration at the interface. These factors collectively help minimise the risk of interface cracking (cold joint) and bond failure (Delatte et al. 2000; Grigoriadis 2016).

4.3 Validation of results

Relationships of microwave curing temperature with power, time and volume of material have been derived based on laboratory test results and reported elsewhere (Mangat et al 2016a). A general relationship between these parameters and the temperature rise ΔT under microwave curing is shown in Eq. (13).

$$\Delta T = k\frac{Pt}{\sqrt{V}} \qquad (13)$$

where ΔT is the temperature rise due to microwave curing (°C); P is the microwave power (W); t is the duration of microwave curing (s); V is the volume of the repair material (dm^3); k is an empirical constant for the different proprietary cementitious repair material formulations or standard concrete mixes ($°C \cdot dm^{2/3}/W \cdot s$), except for the fast setting or rapid hardening repair materials. Although these mixes differ in polymer and fibre content, previous microwave

curing conducted at 2.45 GHz showed similar microwave absorption characteristics (Mangat et al. 2016a).

In the case of field trials, the microwave prototype does not cure the whole surface of the slab under a single fixed position of the antenna. Therefore, the surface of the slab is divided into 20 strip areas (Fig. 10) as explained in Section 3.5. Each strip is exposed to a fixed microwave power and time. For example, for slab S10, each strip was exposed to microwave power of 1700 Watts for 2.5 minutes. Therefore, the total time taken to cover the whole surface of the slab was 50 minutes (2.5 minutes × 20 strips). However, the effective curing time for each strip was 2.5 minutes plus the heating time due to overlap of the antenna from its position in adjacent strips as shown in Fig. 10. As a result of the overlap, the effective curing time for each strip was greater than 2.5 minutes. It is calculated from Eq. (13) by substituting the values of ΔT, P and $\sqrt{V}$ for each trial slab S1 to S10 and presented in Table 4. A value of 0.000126 (based on previous laboratory data (Mangat et al. 2016a) is used for k.

Slabs S5 to S10, in Table 4 were microwave cured at a power of 1700 W for 2.5 minutes over each strip. The depth of these slabs was similar at between 58 mm and 64 mm. Slab S5 was exposed to two 2.5-minute cycles and the others to one cycle. Slabs S5 and S6 comprise the concrete Material I (Table 4) while the other slabs comprise proprietary repair materials. Slabs S5 to S9 have an effective curing time per strip of 9.7, 6.5, 11.7, 10 and 8.9 minutes, which leads to an average value of 9.4 minutes. The values for S5 and S6 are somewhat lower due to their concrete matrix while the others are the proprietary repair materials with admixtures and different k values. Also, S7 was exposed to one curing cycle against two cycles for S5. These calculated values of effective curing time show a consistent effect of antenna overlap and therefore validate the application of Eq. (13) to the field data. In the case of slab S10, the higher temperature rise is due to a combination of microwave energy and the rapid setting chemistry of the repair material which achieved 48.0 °C at the end of microwave curing compared with

40.4-44.5 °C for the other materials (Table 4). This increases the effective curing time of slab S10 to 15.2 minutes.

Slabs S1 to S4, in Table 4, were microwave cured at power 1500 W for 5 minutes over each strip. Slab S2 (strip 20) was microwave cured for an additional 5 minutes at power 1900 W. The depth of the slabs ranged between 46-80 mm for S1, S2, and S4. Slab S3 shows the highest temperature increase, reaching 49.2°C, attributed to its minimal thickness of 34 mm compared to the other slabs. The highest value for slab 2 is affected by the additional 5 minutes of exposure of strip 20 to 1900 W. It should also be noted that Eq. (13) was derived from specimens subjected to microwave heating 30 minutes after mixing. In contrast, during this feasibility study, microwave heating was initiated between 35 and 56 minutes after mixing.

5. Economic and environmental evaluation:

While comprehensive data on CO_2 emissions and lifecycle costs are still developing, microwave curing shows promise for sustainable and efficient concrete production. Microwave curing is an emerging technique in concrete processing that offers rapid early-age strength development and frost protection within one hour, compared to 6-18 hours required for traditional steam curing (Mangat et al. 2016b; Wang et al. 2023). The prototype system developed here demonstrated energy consumption of approximately 2 kWh to cure a 0.08 m^3 concrete slab (1 m × 1 m × 80 mm), which scales to approximately 25 kWh/m^3. This is significantly lower than the reported energy demand for steam curing. For example, Monkman and Shao (Monkman and Shao 2010) reported energy demand of 165 kWh/m^3 for low pressure steam, with actual values varying by cycle and equipment. In addition, the portability of microwave equipment enables mobile/in-situ use for pavement patching and structural repairs in cold climates, where downtime and accessibility are critical. While comprehensive CO_2/LCA and techno-economic data for Portland cement-based microwave curing are still

limited, related assessments exist for microwave-cured geopolymer precast concrete, underscoring the need for standardised system-level studies for Portland cement (Kastiukas et al. 2020). In comparison, electric curing systems which use resistive heating via blankets, embedded electrodes or conductive fillers, provide uniform temperature control and accelerated strength gain, making them ideal for precast environments and cold weather concreting (Abubakri et al. 2022; Sunga et al. 2024). Though less mobile than microwave systems, electric curing offers automated monitoring and has been demonstrated for cold weather concreting, pavement systems, precast and fixed installations. Cold weather admixtures, including accelerators and air-entraining agents, provide a chemical alternative by enhancing hydration and preventing early-age freezing without the need for external equipment (Abubakri et al. 2023; Abubakri et al. 2024b). These admixtures are widely used in field applications due to their simplicity and cost-effectiveness. Collectively, these methods offer complementary strategies for improving concrete performance in challenging environments, with microwave curing distinguished by its speed, energy efficiency, and mobility.

6. Conclusions

This paper presents a microwave curing prototype system and its control module, which were used for field trials on concrete repair slab elements of 1 × 1 m^2 surface area and thickness up to 0.08 m. Test results on the scaled-up slabs of volume (V) cured with the microwave system prototype validated the general relationship between the microwave curing parameters power (P), time (t) and temperature rise (ΔT), which was used to design the microwave system (Equation 13). This agreement is indicative rather than a statistical validation since it is based on single slab element tests for each repair mix/slab thickness. Further replicate testing will establish error bounds.

The temperature at the repair patch-substrate interface increases during microwave curing which is applied at the surface. This is likely to reduce the risk of interfacial bond failure (cold joint) in repair patches particularly when applied in cold weather. This likely mechanism remains to be confirmed in future work.

The Fixed Time Power Regulating (FTPR) algorithm has been developed as a proposed control approach for achieving a prescribed curing temperature-time profile and reaching the target temperature within the target time. At present, FTPR algorithm remains a conceptual control strategy intended to provide more accurate temperature control than the conventional PID algorithm in the control module of the prototype. The observed overshoot of temperature in slab S3 demonstrated that further refinement of the control method is required. Curing applied by two cycles of the microwave antenna of the prototype over a repair patch (slab) produces a significantly higher temperature than one cycle under a constant power and curing time.

CRediT authorship contribution statement

P.S. Mangat: writing - review & editing, validation, supervision, investigation, funding acquisition, conceptualisation, resources, project administration. **S. Abubakri:** writing - original draft, review & editing, validation, methodology, investigation, data curation, conceptualisation. **K. Grigoriadis:** writing - review & editing, validation, investigation, conceptualisation, **A. Javaid:** investigation, validation, microwave system development, project administration.

Data availability statement

All data, models, and code generated or used during the study appear in the submitted article.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Figure Captions

Fig. 1. Microwave prototype system.

Fig. 2. Microwave system safety feature.

Fig. 2a. Microwave shielding frame

Fig. 2b. Microwave leakage sensor.

Fig. 3. Pointed positions of non-contact infrared temperature sensors.

Fig. 4. Non-linear temperature versus time relationship of repair under microwave curing, divided into 3 linear periods.

Fig. 5. Temperature versus time relationship of repair under microwave curing with increasing power input.

Fig. 6. Slope α of the temperature-time relationship versus microwave power.

Fig. 7. Temperature versus time relationship of curing patch in the first curing period of t_1 minutes.

Fig. 8. Temperature-time curing profile of the repair over 45 minutes.

Fig. 9. Slab placed inside microwave prototype for microwave curing.

Fig. 10. Schematic diagram of microwave curing sequence of strip areas.

Fig. 11. Location of type T thermocouple.

Fig. 11a. On the base of the slab.

Fig. 11b. On top of the substrate surface of slab S4.

Fig. 12. Temperature distribution of Slab S10.

Fig. 12a. At the beginning of microwave curing.

Fig. 12b. At the end of microwave curing.

Fig. 13. Thermocouple readings of Slab S9 for a period of 1100 minutes from the start of mixing the raw materials with water.

Fig. 14. Thermocouple readings of Slab S6 for a period of 1114 minutes from the start of mixing the raw materials with water.

Fig. 15. Thermocouple readings of Slab S7 for a period of 1400 minutes from the start of mixing the raw materials with water.

Fig. 16. Thermocouple readings of Slab S8 for a period of 1284 minutes from the start of mixing the raw material with water.

Fig. 17. Thermocouple readings of Slab S5 for a period of 1266 minutes from the start of mixing the raw materials with water.

Fig. 18. Thermocouple readings for slab S4 for a period of 284 minutes after the start of mixing the raw materials with water.

Table 1 Details of repair materials.

Repair Material	water/powder ratio	Density of Fresh Mix (kg/m^3)	28-day Compressive Strength (MPa)	Bond Strength (MPa)	Description of Repair Material
I	0.50 (w/c)	2200	45	>2.0	Control (CEMII mortar)
II	0.14	2050	53	-	Fiber-reinforced concrete with polymer additives.
III	0.13	2100	50	2.0-2.5	Polymer-modified and fibre-reinforced cement mortar.
IV	0.12	2200	55	>2.0	Polymer-modified concrete.
V	0.11	1900	20	>0.8	Polymer-modified cement mortar with anti-corrosion admixture.

Table 2 Details of slabs S1 to S10.

Slab	Depth (mm)	Repair Material	water/powder	Moisture content (%)*	Pre-curing Time (min)	Substrate Material
S1	62	I	0.50	10.0	45	Timber
S2	80	I	0.50	10.0	52	Timber
S3	34	I	0.50	10.0	35	Timber
S4	46	I	0.50	10.0	56	Concrete
S5	58	I	0.50	10.0	51	Timber
S6	58	I	0.50	10.0	43	Timber
S7	62	II	0.14	14.0	40	Timber
S8	59	III	0.13	13.0	46	Timber
S9	61	IV	0.12	12.0	38	Timber
S10	64	V	0.11	11.0	41	Timber

*Moisture content is based on the mass of water added to the mix.

Table 3 Temperature increase due to microwave heating for 50 minutes.

Slab Number	Slab Thickness (mm)	Power (W)	Temperature at the Start of Microwave Curing (°C)	Temperature at the End of Microwave Curing (°C)	Temperature Increase (ΔT)
S1	62	1500	26.3	42.7	16.4
S2	80	1500*	22.0	42.2	20.2
S3	34	1500	27.3	76.5	49.2
S4	46	1500	19.6	44.5	24.9
S5	58	1700	25.2	41.8	16.6
S6	58	1700	27.8	40.4	12.6
S7	62	1700	22.8	41.9	19.1
S8	59	1700	26.7	43.3	16.6
S9	61	1700	27.9	42.5	14.6
S10	64	1700	24.1	48.5	24.4

*Strip 20 was also exposed to 1900 W for 5 minutes.

Table 4 Calculation of effective curing time of a strip of slab.

Slab Number	Repair Material	Number of Curing Cycles	Actual Time of Curing (mins)	Effective Curing Time for total slab (mins)	ΔT (°C)	Power (Watts)	Slab Depth (mm)	Volume (dm^3)
S1	I	1	5	11.6	16.4	1500	62	62
S2*	I	1	5	15.5	20.2	1500	80	80
S3	I	I	5	25.3	49.2	1500	34	34
S4**	I	1	5	14.9	24.9	1500	46	46
S5	I	2	2.5	9.7	16.6	1700	58	58
S6	I	1	2.5	6.5	12.6	1700	58	58
S7	II	1	2.5	11.7	19.1	1700	62	62
S8	III	1	2.5	10	16.6	1700	59	59
S9	IV	1	2,5	8.9	14.6	1700	61	61
S10	V	1	2.5	15.2	24.4	1700	64	64

Notes: *Slab S2, strip 20 was heated for extra 5 minutes at 1900 W. **Slab S4 cast on top of concrete slab S3.