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Published version

MANGAT, Pal, GRIGORIADIS, Konstantinos and ABUBAKRI, Shahriar (2016). Microwave curing parameters of in-situ concrete repairs. Construction and Building Materials, 112, 856-866.

Microwave Curing Parameters of In-situ Concrete Repairs

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Abstract

Different proprietary repair materials and a CEM II mortar were used to characterise the relationship between the main parameters of microwave curing (power, curing time, temperature rise and volume). The time-temperature-power relationships are linear for normal, non-rapid setting repair materials cured within the recommended temperature range taking account of temperature variation and heat of hydration. A general relationship between the microwave curing parameters of power, temperature rise, curing time and repair volume has been derived. It has been used to design and operate a prototype system. Steel reinforcement in the repair remains free from arcing under microwave exposure.

Keywords

Concrete, Microwave curing, Patch repair.

1. Introduction

Reinforced and pre-stressed concrete has been used at a massive scale for the construction of infrastructure in the last century with the secure assumption of its lasting durability. While the large majority of concrete construction is durable, repair is increasingly needed due to various concrete degradation mechanisms, abnormal loading or poor workmanship. According to CONREPNET [1] more than 50% of Europe's annual construction budget is spent on rehabilitation and refurbishment projects including the repair of deteriorated concrete structures. In the United States the annual cost of repair, strengthening and protection of concrete structures is between $18 and $21 billion [2].

Concrete repair can be applied either to provide structural strengthening or to protect the durability of a structure. Patch repair is perhaps the most common type of concrete repair. It can be defined as the repair of relatively small areas in large surfaces such as bridge and car park decks, bridge piers and shear walls in buildings. Emmons [3] provides detailed information on the various stages of a typical patch repair scheme.

Selection of suitable repair materials and their proper curing is of great importance in minimising restrained shrinkage and ensuring the long-term durability of patch repairs. Differential shrinkage of the repair patch relative to the substrate is the most common cause of cracking and failure of patch repairs. Under normal curing conditions, it may take 24 hours or more for OPC based repair materials to set and it may take several days before sufficient compressive strength is developed to carry the applied loads [4]. Under more extreme conditions such as repair application in cold weather, strength development may be compromised. Accelerating the curing process by applying heat or using admixtures can be beneficial in these situations. Rapid compressive strength development is also desirable when repairing localised damage in bridge decks or runways, such as potholes, areas damaged by heavily corroded reinforcement or severely delaminated areas. A compressive strength of approximately 14 MPa should be achieved for a road to be re-opened [5]. A correspondingly strong bond between the substrate and the repair patch is also critically important to provide durable repairs.

The rate of compressive strength development in OPC concrete can be increased by the application of thermal energy [6]. Thermal curing of concrete repair patches is often used in cold weather to prevent damage caused by freezing temperatures and to accelerate the repair process. Thermal curing can also be used in more general conditions to accelerate the hardening of repair patches for rapid opening of roads to traffic. The heating methods commonly adopted use open flame heaters or provide heating enclosures around the repaired area. These methods are inefficient and waste energy relative to microwave curing. They provide non-uniform heat through convection to the patch repair with high temperature at the surface and significant temperature gradients into the repair patch. The effect of such curing is damaging to the homogeneity and quality of hydration products. Rapid hydration caused by high temperature produces very fine C-S-H gel surrounded by unhydrates which hinder further hydration and can cause a reduction in long term strength development [7]. Non uniform heating also produces differential thermal strains causing microcracking which reduces the durability of the patch repair. Thermal blankets based on a conductive polymer technology have been developed [8], which transfer heat from the surface into a repair patch with the associated disadvantage of non-uniform heat transfer by convection. The technology is expensive and cumbersome to use on site.

The application of microwave curing on site will introduce new technology in the construction industry to replace inefficient current practices with more effective and economical methods. It will contribute to the introduction of automation in the repair sector through robotic controlled microwave curing systems. The industrial prototype developed in the MCure project of the European Commission FP7 programme (see acknowledgements) incorporates such technology which will be further enhanced in the next stage of industrial system production. Health and safety issues on site have been rigorously addressed in the project and the industrial systems will have European regulatory certification.

The development of a microwave heating system to provide early age curing to concrete repair patches has the potential to revolutionise the concrete repair industry by transforming the efficiency and economics of thermal curing. Its effectiveness for cold weather curing will prevent disruption to construction activity in winter, which will have a major economic impact by allowing continued construction activity during winter. Microwave heating is more economical than the thermal curing methods currently used on site such as open flame heaters with or without an enclosure around a repaired area. The energy use and CO_2 emission will also be lower. It has also the potential of reducing the use of expensive and environmentally undesirable chemical admixtures in proprietary repair formulations to accelerate curing.

Thermal curing, including microwave curing, leads to higher strength at early age which allows rapid progress of repair work. There is a reduction in long term strength, values of up to 20% and 6.75% have been reported for conventional thermal curing [6, 9] and microwave curing [10], respectively. However, the early age strength and the repair-substrate interfacial bond strength are the important properties required for a durable repair that can be applied rapidly. Long term strength is of secondary importance as long as it satisfies the specified requirement. Microwave curing delivers on the requirements of early age compressive strength and long term bond strength [10].

Microwave heating, which is based on dissipation of internal energy due to the excitation of molecular dipoles when exposed to an electromagnetic field, is an economical method of providing a higher rate of temperature increase [4] and more uniform heating than the traditional heating methods [11]. Hence, a much shorter exposure time (typically less than 60 minutes) is required for microwave curing to achieve high early age compressive strength [9]. Various studies [4, 9, 12-17] on microwave curing of OPC mortars made with different w/c ratios have confirmed the ability of microwave curing to significantly increase early age strength.

This paper provides a scientific framework on microwave curing of in-situ concrete repairs for the FP7 MCure project on the development of an energy efficient system for accelerated curing during repair of concrete structures. It is the first of a series of papers defining the relationship between microwave curing and the primary characteristics of concrete repairs. It derives relationships between the key parameters of concrete repair and microwave energy input. These results were used in developing and operating the prototype of a mobile microwave curing system for onsite use, which is compatible with EC standards.

2. Experimental Procedure

2.1. Materials and equipment

Microwave curing investigation was carried out on the following commercial repair materials:

Repair Material 1: A polymer-modified cement mortar, fibre-reinforced and shrinkage-compensated. Density of the fresh mix was 1730 kg/m^3.

Repair Material 2: A polymer-modified rapid-setting cement mortar and fibre-reinforced. Density of the fresh mix was 2140 kg/m^3.

Repair Material 3: A polymer-modified cement mortar, fibre-reinforced and shrinkage-compensated. Density of the fresh mix was 2280 kg/m^3.

Repair Material 4: A rapid hardening cement concrete with pulverised fuel ash and shrinkage-compensated. Density of the fresh mix was 2260 kg/m^3.

Repair Material 5: A polymer-modified cement mortar and fibre-reinforced. Density of fresh mix was 1500 kg/m^3.

Repair Material 6: A polymer-modified cement, rapid setting concrete. Density of fresh mix was 2200 kg/m^3.

Repair Material 7: A mortar with CEM II/A-L 32.5 N cement [18], coarse sharp sand (50% passing a 600 μm sieve) and w/c ratio of 0.5. Density of fresh mix was 2200 kg/m^3.

Two commercial microwave ovens were used, a Logik Model L25MDM13 with a maximum nominal output power of 900 Watts (manufacturer's specification) and a Sharp Model R-2370 with a maximum nominal output power of 1300 Watts (manufacturer's specification). Both microwave ovens could be set to generate power at incremental levels of 10% up to 100% of their maximum output. The microwave frequency for both ovens is 2.45 GHz. The microwave ovens were calibrated [11] according to ASTM F1317-98 [19] and BS EN 60705: 2012 [20] to determine their actual power outputs which in the case of the Logik Model L25MDM13 differed significantly from the manufacturer's specification. Unless otherwise mentioned, all values of microwave power given subsequently in the paper are the actual power values.

2.2. Details of specimens, mixing and microwave curing

2.2.1. Repair material specimens for surface temperature monitoring

Three volumes of specimens, 1, 3.38 and 4.38 litres were used for microwave curing [11]. Specimens were cast in polystyrene cube moulds of 100 mm and 150 mm internal dimensions. The 1 litre volume was provided by a 100 mm mould, the 3.38 litre volume by a 150 mm mould and the 4.38 litre volume comprised of the combined 100 mm and 150 mm cube moulds.

Details of all repair material mixes are given in Table 1. The mix proportions recommended by the manufacturers of each repair material were used. The quantity of each repair material and water, given in Table 1, was mixed together in a Hobart mixer to produce the required volume of mix for the cube mould. Each mix was cast in the cube mould and compacted on a vibrating table. The compacted specimens were kept in the laboratory environment (approximately 20 ^{o}C, 60% RH) for 30 minutes from the time of commencing mixing. After 30 minutes of pre-curing in the laboratory, the cube moulds were placed in the microwave oven and cured for 45 minutes at levels of power 60, 120, 132, 180 or 264 Watts. Temperature was measured at the centre of the top surface of each cube at 0, 10, 20, 30, 40 and 45 minutes from the start of microwave curing using a Flir i7 thermal camera.

Table 1
Details of repair material mixes.

Test series	Repair material	Mix number	Microwave oven	Power (W)	Weight of water (kg)	Weight of powder (kg)	w/p ratio*	Volume of mix (L)	Cube size (mm)	28 day strength** (MPa)
1	1	1	Logik	60	0.21	1.52	0.14	1	100	42
		2	L25MDM13	120						
		3		180						
	2	1		120	0.26	1.88	0.14			60
	3	1		60	0.23	2.05	0.11			65-70
		2		120						
		3		180						
	4	1		60	0.26	2.00	0.13			65
		2		120						
		3		180						
	5	1		60	0.17	1.33	0.13			≥ 25
		2		120						
		3		180						
	6	1		60	0.20	2.00	0.10			60
		2		120						
2	1	1	Sharp	132	0.72	5.12	0.14	3.38	150	42
		2	R-2370	264						
	3	1		132	0.78	6.93	0.11			65-70
		2		264						
	4	1		132	0.87	6.76	0.13			65
		2		264						
	5	1		132	0.59	4.51	0.13			≥25
		2		264						
3	1	1	Sharp	132	0.93	6.64	0.14	4.38	100	42
		2	R-2370	264					+	
	3	1		132	1.01	8.98	0.11		150	65-70
		2		264						
	4	1		132	1.12	8.76	0.13			65
		2		264						
	5	1		132	0.76	5.84	0.13			≥25
		2		264						

*w/p-water/powder ratio; **Manufacturer's compressive strength data.

2.2.2. Repair material specimens for internal temperature monitoring

Internal temperatures during 1169 minutes after microwave curing were recorded using thermocouples. Four T type thermocouples were located inside the 150 mm cube moulds as shown in Fig. 1 and the repair material was cast around them. The thermocouples were located at 37.5, 75, 112.5 and 150 mm from the top surface of the specimens along the vertical centroidal axis. Temperature measurements were taken every 30 seconds using a Data Taker DT85G digital logger. Details of the two repair material mixes used for this investigation are given in Table 2.

Table 2
Details of repair material mixes for internal temperature monitoring.

Repair material	Mix number	Microwave oven	Power (W)	w/p*	w/c**	Volume of mix (L)	Cube size (mm)
4	1	Sharp R-2370	132	0.13	–	3.38	150
7	2			–	0.5		

* w/p-water/powder ratio; ** w/c-water/cement ratio.

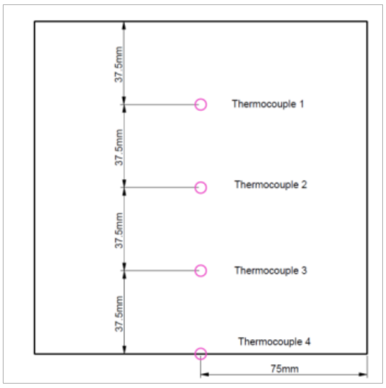

Fig. 1. Schematic diagram of thermocouples located inside a 150 mm cube specimen.

2.2.3. Repair material specimens for investigating the effect of ambient (initial) temperature on microwave curing temperature

The effect of different ambient temperatures of the fresh mix of a repair material on the microwave curing temperatures developed with time was investigated [11]. The investigation simulated the application of repairs in different in-situ conditions including cold weather. The constituent materials of each mix were conditioned and mixed at three different ambient temperature ranges: very low (1.7-6.5 ^{o}C), low (8.9-10.0 ^{o}C) and medium range (15.8-18.3 ^{o}C). The constituent materials were kept overnight in an environmental chamber to condition them to the selected ambient temperature. The ambient temperature was maintained during mixing and for 30 minutes after casting a 150 mm cube specimen (3.38 litres volume) for each mix. Materials 1, 3, 4 and 5 were tested using the Sharp R-2370 microwave oven at an actual output power of 132 Watts. Temperature measurements at the centre of the top surface of the cubes were taken at 0, 10, 20, 30, 40 and 45 minutes from the start of microwave curing using a Flir i7 thermal camera.

2.2.4. Steel reinforced mortar specimens for investigating safety of microwave curing

Long and pointed metallic objects or very thin metal strips when placed in a microwave oven act as an antenna and reflect the microwave energy. At high levels of microwave power this can create electric arcs (sparks) which can increase the temperature of its magnetron. This can reduce the life of the magnetron. An investigation of the safety of microwave curing was carried out on specimens cast with 1, 2 or 3 steel bars placed horizontally along the entire length of the 100 mm cube as shown in Fig. 2a. Details of all steel reinforced mortar mixes are given in Table 3. The total length of each steel bar was 140 mm to cover the cube length (100 mm) plus 20 mm thickness of two mould walls. Steel bars of diameters 10, 8 or 6 mm were located through holes drilled in the side faces of the mould. In addition, one specimen was made with 6 mm diameter bars protruding 30 mm from each side face of the mould as shown in Fig. 2b. The total length of each steel bar was 200 mm. Both galvanised and normal mild steel bars were used. The top cover to steel bars was 25, 15 or 5 mm as shown in Fig. 3.

A quantity of CEM II cement [18], sharp coarse sand and water (w/c ratio of 0.5) were mixed together to produce a 1 litre mix for the cube mould. Each cube was cast and compacted on a vibrating table and kept in the laboratory environment (approximately 20 ^{o}C, 60% RH) for 30 minutes after commencing mixing. After 30 minutes of pre-curing in the laboratory, the cube moulds were placed in the microwave oven and cured for either 45 or 15 minutes at powers ranging from 60 to 420 Watts (Table 3). The temperature at the mid-point of the top surface of the cube was measured at the end of microwave curing (maximum temperature) using a Flir i7 thermal camera.

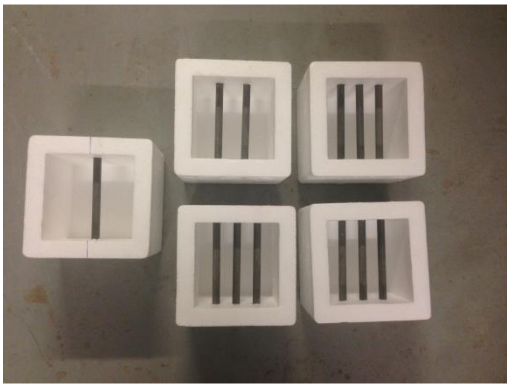

Fig. 2a. Moulds with 1, 2 or 3 steel bars placed inside them and top cover 25 mm.

Fig. 2b. Mould with steel bars protruding (exposed) and top cover 5 mm.

Fig. 3. Plain (control) and steel reinforced specimens with different top covers after microwave curing.

Table 3
Details of steel reinforced mortar mixes.

Cube size (mm)	Microwave power (W)	Microwave duration (min)	Number and type of bars	Bar diameter (mm)	Top cover (mm)	Orientation and length of steel bars
100	60	45	1 galvanised MS*	10	25	Horizontal (140 mm)
	60	45	2 galvanised MS*	10	25	Horizontal (140 mm)
	60	45	3 galvanised MS*	10	25	Horizontal (140 mm)
	120	45	3 galvanised MS*	10	25	Horizontal (140 mm)
	180	45	3 galvanised MS*	10	25	Horizontal (140 mm)
	180	45	3 galvanised MS*	10	15	Horizontal (140 mm)
	180	45	3 galvanised MS*	10	5	Horizontal (140 mm)
	300	15	3 galvanised MS*	10	5	Horizontal (140 mm)
	300	15	3 normal MS*	8	5	Horizontal (140 mm)
	300	15	3 normal MS*	6	5	Horizontal (140 mm)
	420	15	3 normal MS*	6	5	Horizontal (140 mm)
	420	15	3 normal MS*	6	5	Horizontal (200 mm). Protrusion (30 mm)

*MS-mild steel.

3. Results and Discussion

3.1. Temperature distribution

Significant variations of top surface temperature were observed during microwave curing of all specimens of Series 1, 2 and 3, Table 1 (1, 3.38 and 4.38 L volume). In all cases hot zones appeared at the edges and corners of the polystyrene moulds shortly after starting microwave curing. Typical temperature distributions across the top surface of a 100 mm cube at 0, 10, 20, 30, 40 and 45 minutes of microwave curing at 180 Watts power are shown in Fig. 4 (a-f). The dark edges represent the walls of the polystyrene moulds. At 40 minutes of curing, for example, the middle surface temperature is 81.7 ^{o}C whereas it increases towards 99 ^{o}C on the outer surfaces of the cube specimen. The temperature profiles show a significant variation of temperature developed in the cured material. This indicates the unreliability of firm relationships between temperature, time and strength development drawn by other researchers [4, 9, 12-17] based on localised temperature monitoring (e.g. by a single thermocouple).

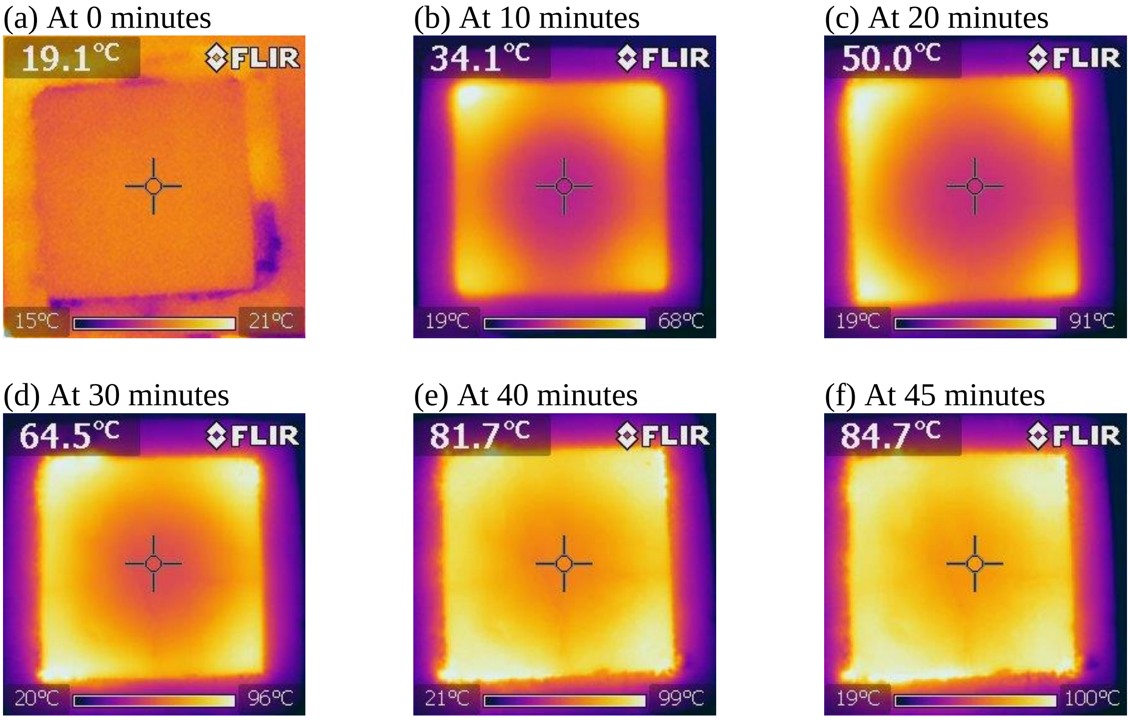

Fig. 4 (a-f). Top surface temperature distribution of Material 1 100 mm cube subjected to 180 W of microwave power.

Significant variations of top surface temperature at the end of microwave curing were observed between different repair materials of the same volume exposed to the same power. Typical temperature distributions of the six repair material specimens after 45 minutes of microwave curing at 120 Watts are shown in Fig. 5 (a-f).

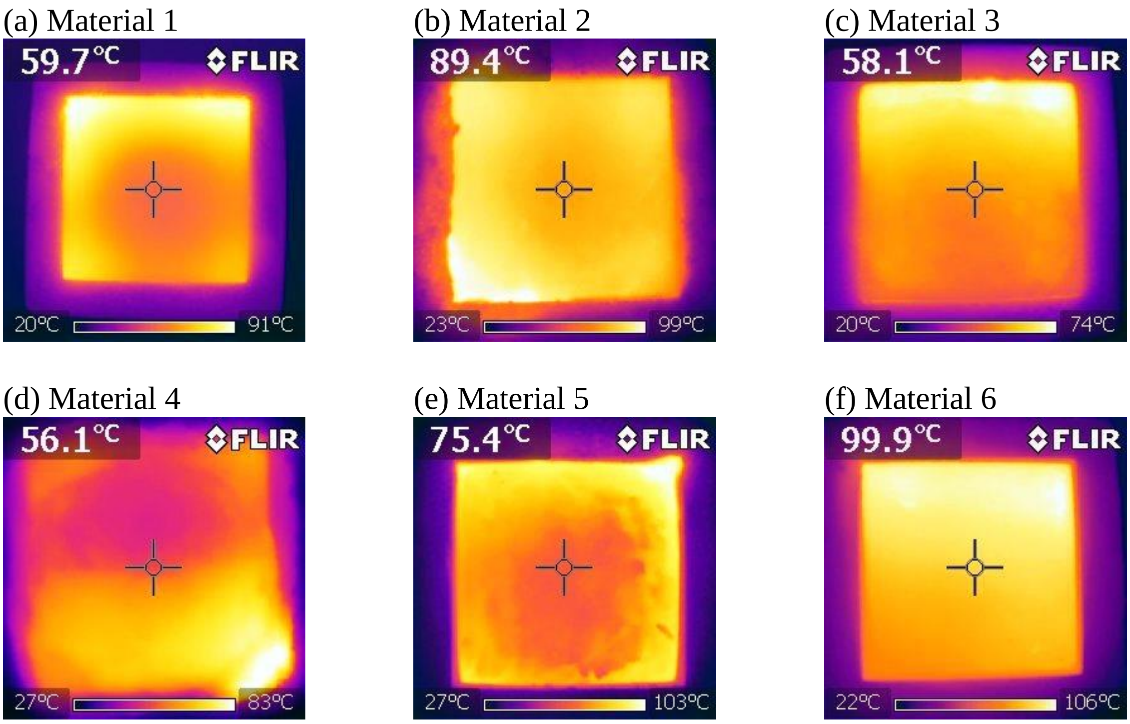

Fig. 5 (a-f). Top surface temperature of the six repair materials (1 litre volume subjected to 120 W power) at 45 minutes of microwave curing.

Materials 2 and 6 developed particularly high temperatures (89.4 ^{o}C and 99.6 ^{o}C respectively) at the end of microwave curing compared with the normal Materials 1 and 3 which developed 59.7 ^{o}C, and 58.1 ^{o}C, respectively. This is because both 2 and 6 are rapid setting repair materials. Material 4, which is a rapid hardening material did not develop higher temperatures than Materials 1 and 3. The admixtures, additives and the fineness of cement used in the repair mortars 2, 5 and 6 appear to affect the temperature. However, since the details of the constituents of these commercial materials are not available, precise conclusions cannot be drawn. There is no clear relationship between water/powder (w/p) or density of the mixes and the temperature developed by microwave curing. For example both normal Materials 1 and 3 have w/p ratios 0.14 and 0.11 respectively (Table 1) but the temperatures developed after 45 minutes of microwave curing are similar (57.9 ^{o}C and 58.1 ^{o}C, respectively). Materials 1 and 5 on the other hand have similar w/p ratios (0.14 and 0.13, respectively) and densities (1730 and 1500 kg/m^{3}, respectively) but they developed significantly different temperatures after 45 minutes of microwave curing (59.7 and 75.4 ^{o}C, respectively). It is clear, therefore, that the constituents of repair materials, rather than their w/p ratio or density, are the main factors which control the microwave curing temperature.

3.2. Time-temperature relationship

A linear increase of top surface temperature with microwave curing time was observed for the repair materials, material volumes and power levels used. A typical time-temperature graph is given in Fig. 6, for 1 litre volume of Material 4 subjected to microwave power levels of 60, 120 and 180 Watts. However, the fast setting repair Material 2 showed a discontinuous linear time-temperature relationship as shown in Fig. 7 (volume 1 litre, power 120 Watts). The rapid hardening material underwent a phase change from semi-fluid to hardened material at high temperature during microwave curing. This is represented by the two different linear relationships shown in Fig. 7. The maximum curing temperature attained is excessive (reaching 90 ^{o}C) which would not be desirable in practice. Materials with this kind of time-temperature relationship would not be suitable for microwave curing unless the ambient temperature is very low (cold weather application), when low power curing may be appropriate.

The linear relationships of the type shown in Fig. 6 would be applicable to most practical in-situ microwave curing situations where the maximum temperature remains below the recommended limit [11]. The industrial microwave curing system developed in this project will be based on this type of relationship.

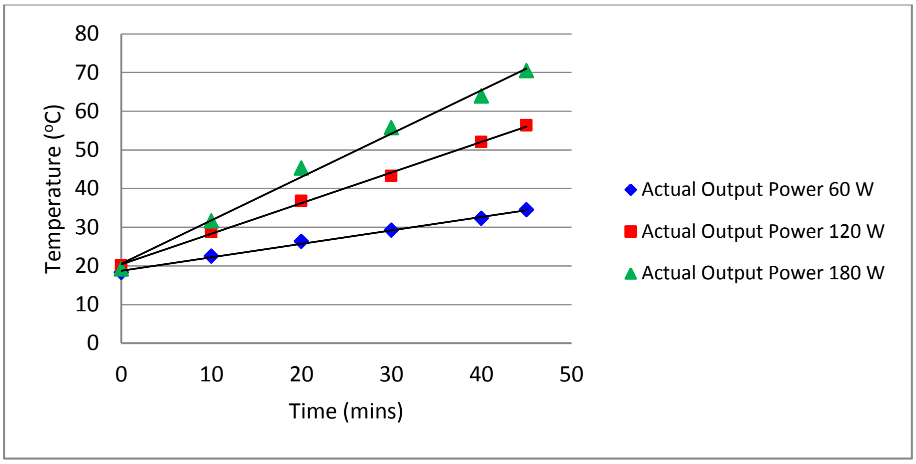

Fig. 6. Top surface middle point time-temperature relationship for Material 4 (1 litre volume).

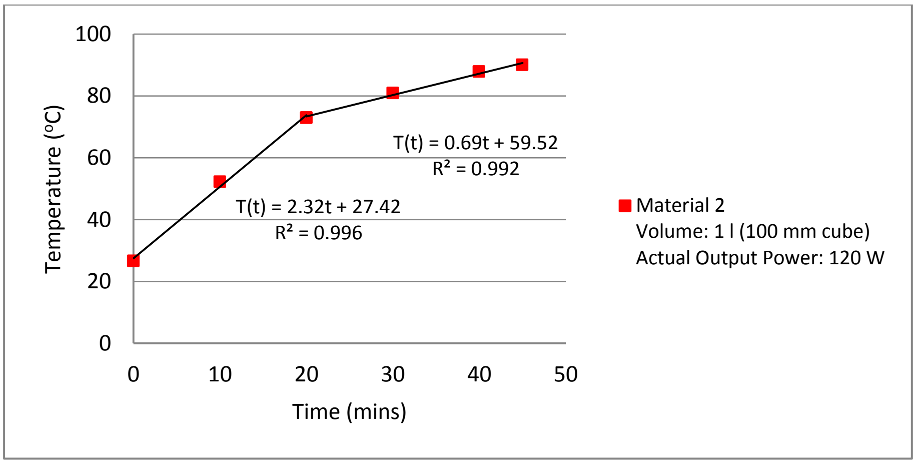

Fig. 7. Top surface middle point time-temperature relationship for Material 2 (1 litre volume) at 120 W.

3.3 Volume-temperature relationship

The thermodynamic formula for absorbed microwave power P_{abs} relates the volume V and temperature rise as follows [21]

$$\frac{P_{abs}}{V} = \frac{c\rho(T_f - T_a)}{t} \qquad (1)$$

where, P_{abs} is the microwave power (W); V is the volume (L); c is the heat capacity (J/kg/^{o}C); ρ is the density (kg/m^3); T_f is the temperature at the end of microwave curing (^{o}C); T_a is the ambient temperature (^{o}C); t is the microwave curing time (min).

This expression is applied to the experimental data of this investigation in Fig. 8, at a constant applied microwave power of (120-132 W) for a constant time of 45 mins for Materials 1, 3, 4 and 5. The ambient temperature of all tests ranged between 15.8 and 20.3 ^{o}C. Eq. 1 is re-written in the form

$$\Delta T = \frac{P_{abs}t}{c\rho}V^{-1} \tag{2}$$

$$\text{where, } \Delta T = T_f - T_a \tag{3}$$

Fig. 8 shows a linear relationship between ΔT and V for the constant power and microwave curing time for the experimental data of Materials 1, 3, 4 and 5. The slope of the graphs in Fig. 8 is a function of P_{abs}, t, c and ρ. The density ρ of Materials 1, 3, 4 and 5 is 1730, 2280, 2260 and 1500 kg/m^3, respectively. The coefficient c accounts for the different constituents of the repair materials and their mix proportions.

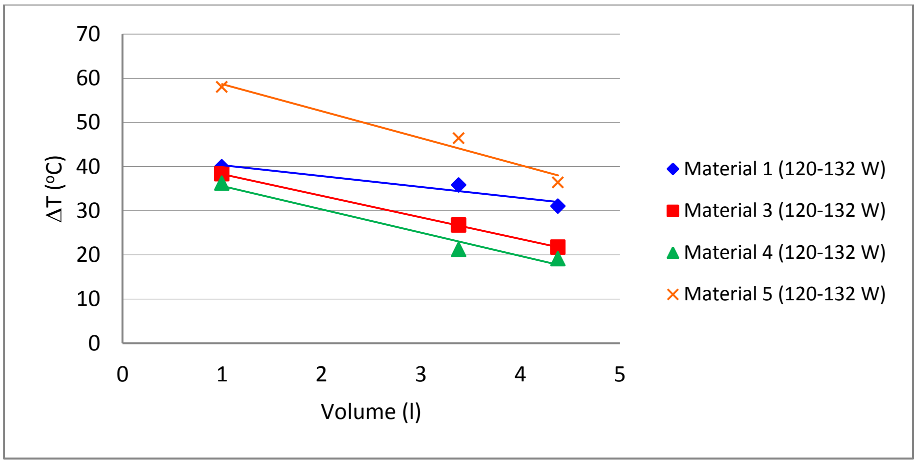

Fig. 8 Volume-temperature rise relationships of repair materials 1, 3, 4 and 5 at 132 W.

3.4. Rate of temperature increase with microwave power

Time-temperature relationships of the repair materials and volumes at different power levels described in Section 3.2 were analysed to determine the rate of temperature increase, *dT/dt* (slope α), with time. The rapid setting Materials 2 and 6 were excluded since they developed very high temperatures which would not be used in practice and had set before the end of microwave curing (Fig. 7). A linear relationship was observed between α and microwave power in all cases. A typical graph showing the relationships between microwave power and slope α for four repair materials (1 litre volume) is shown in Fig. 9. This relationship will provide an important input to the automatic control algorithm developed for the operation of the microwave curing prototype of the MCure project.

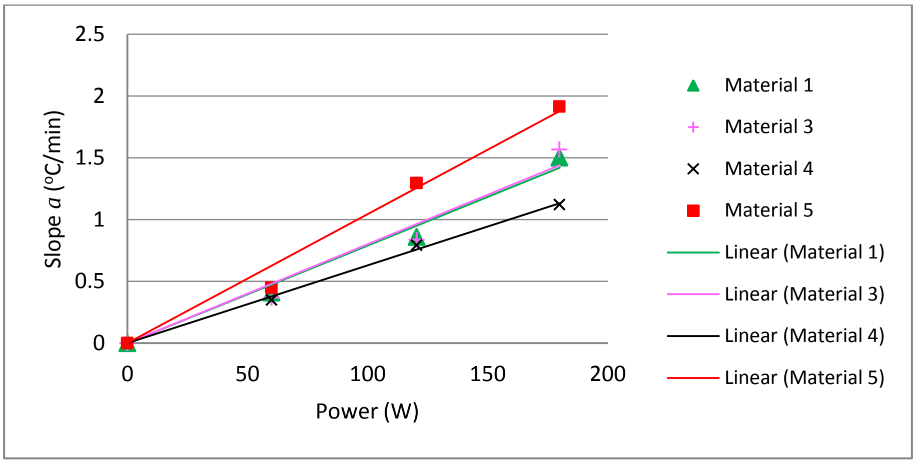

Fig. 9. Power versus slope α relationship for five repair materials (1 litre volume).

3.5 General relationship between microwave curing parameters of repair materials

The basic parameters of microwave curing which are Power, Time and Volume are related to the temperature rise provided by microwave curing as shown in Fig. 10. The data in Fig. 10 represent all tests listed in Table 1 for repair materials 1, 3 and 4 and volumes of cubes 1, 3.38 and 4.38 L. The best fit relationship in Fig. 10 is given by the equation:

$$\Delta T = \frac{Pt}{\sqrt{V}} \tag{4}$$

where, ΔT is the temperature rise due to microwave curing (^{o}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).

Eq. 4 has been used to design the microwave curing prototype rig for the MCure project. It was used to calculate the maximum power rating required of the prototype to deliver the specified range of parameters ΔT, t and V required for in-situ curing of scaled up repair elements [22]. The parameters ΔT and t were also specified on the basis of the results reported in the paper. Scaled up field trials on the MCure prototype proved that its design delivered the specified parameters [22].

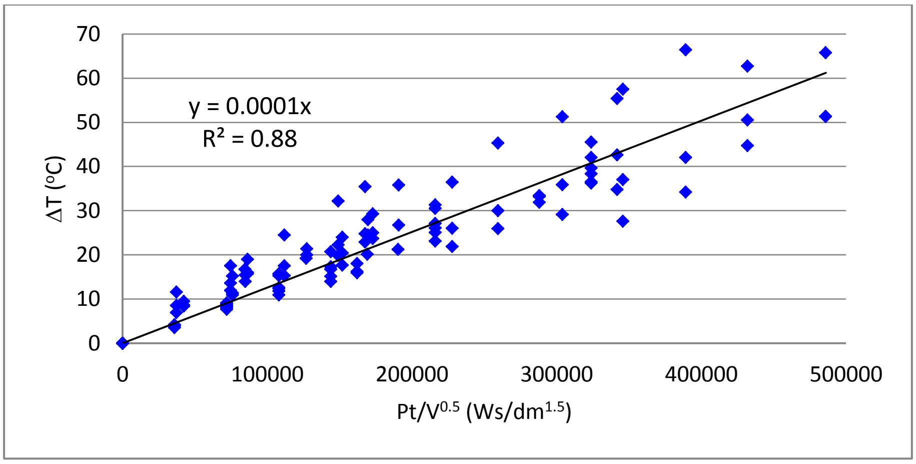

Fig. 10. General relationship between microwave curing parameters of repair materials 1, 3 and 4

3.6. Internal temperature development

Typical time-internal temperature graphs accompanied by time-top surface temperature graphs for both normally cured (at 20 °C) and microwave cured specimens of Material 4 are shown in Fig. 11 and Fig. 12, respectively. The internal temperatures were monitored from thermocouples located within the 150 mm cube specimens (3.38 litre volume) which were microwave cured for 45 minutes at 132 Watts. The relationship under normal curing (20 °C) given in Fig. 11 shows one hump at about 775 minutes (775 + 30 pre-curing after mixing = 805 minutes from the start of hydration), representing the peak heat of hydration temperature of about 45 °C. This represents a temperature rise of 25 °C due to heat of hydration. The corresponding microwave cured sample shows the first hump at 45 minutes (Fig. 12) when the peak microwave curing temperature is reached followed by a second hump at about 245 minutes (275 minutes from the start of hydration, 200 minutes after the end of microwave curing) indicating the peak heat of hydration point. It is clear that the heat of hydration reaction is significantly accelerated by microwave curing reducing the peak time from 805 to 275 minutes while increasing the peak temperature to 79 ^{o}C. This shows a temperature rise of 34 ^{o}C from the end of microwave curing (45 ^{o}C) to the peak of hydration (79 ^{o}C). Fig. 12 shows that heat of hydration develops after the microwave curing period and has an insignificant effect on the temperatures developed during microwave curing as shown in Fig. 6. Other results reported by the authors [23] for 100 mm cube specimens microwave cured to about 40 ^{o}C show that, for non-rapid setting repair materials, the maximum temperature of between 53.8 and 71.1 ^{o}C is reached at 10-60 minutes after the end of microwave curing.

The acceleration of heat hydration with microwave curing observed in Fig. 11 and Fig. 12 agrees with the results of Theo et al. [24] for microwave cured precast ferrocement roofing slabs of approximately 11 litres volume. The slabs were cured for 10-20 minutes at 3000 Watts microwave power. Maximum heat of hydration occurred during microwave curing, leading to high temperatures (approximately 70 ^{o}C) at the end of curing.

The results discussed above show that both the microwave curing temperature and the heat of hydration contribute to the maximum temperature developed in the concrete volume within a short period after the end of microwave curing. In practice, the maximum temperature during this period should remain below the limit which affects durability [6] and the maximum temperature used for microwave curing should reflect this.

Fig. 12 shows that the top surface mid-point temperatures measured by the thermal camera closely follow the internal temperatures (thermocouple readings) developed during the 45 minutes of microwave curing. Thereafter the internal temperatures are higher due to the accelerated heat of hydration. The hot spots developed at the edges of the cube specimens get significantly hotter (Fig. 12, thermal camera, top surface hot spot) but their temperature drops immediately at the end of microwave curing to the level of mid-point surface temperature.

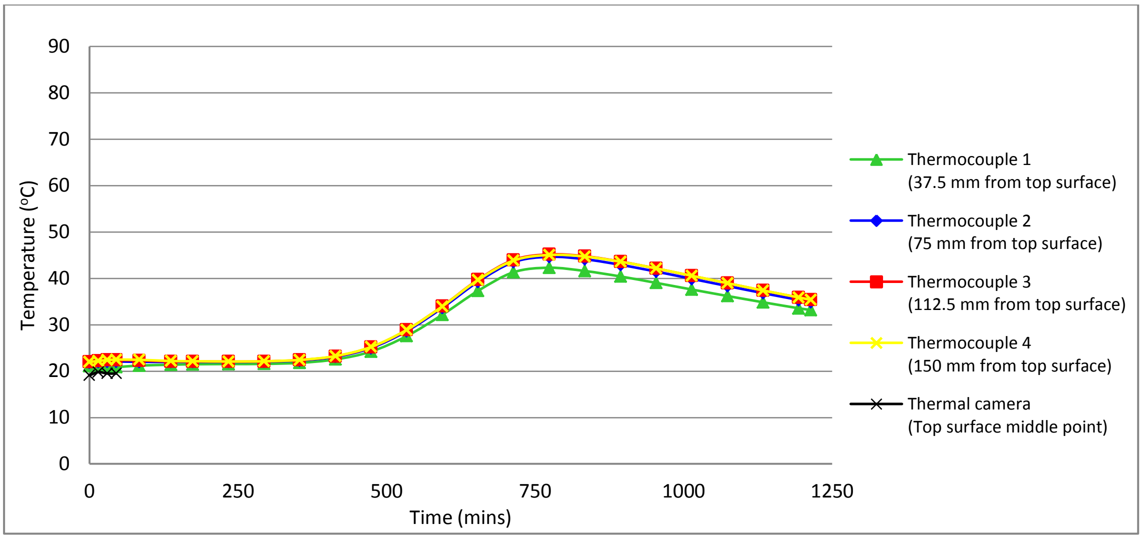

Fig. 11. Typical internal temperature-time relationship for Material 4 (3.38 litres volume) cured at 20 ^{o}C.

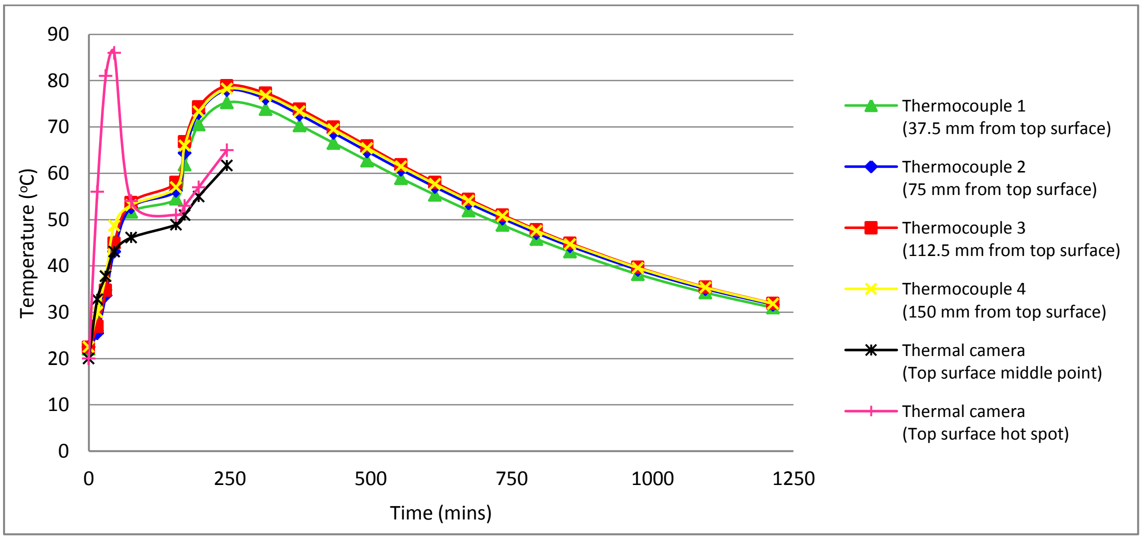

Fig. 12. Typical internal temperature-time relationship for Material 4 (3.38 litres volume) microwave cured at 132 W for 45 minutes, followed by curing at 20 ^{o}C.

3.7 Permissible Microwave Curing Temperature

The maximum temperature of 79 ^{o}C reached at the peak of hydration (Fig. 12) is excessive from the considerations of long-term durability [6]. Curing of concrete at temperatures exceeding about 70 ^{o}C can lead to durability problems such as delayed ettringite formation and loss of long-term strength [6]. Therefore, limits need to be set to the maximum microwave curing temperature for in-situ curing, taking account of the heat of hydration and temperature variations (hot spots) which occur during microwave curing. This can be done by adopting the following equations to determine the permissible temperature:

$$\boldsymbol{T_m + \Delta T_h \leq \frac{70}{\gamma_T}} \quad (5)$$

$$\boldsymbol{\Delta T_h = T_h - T_m} \quad (6)$$

where, T_m is the permissible temperature at the end of microwave curing (^{o}C); T_h is the peak heat of hydration temperature of unhardened concrete (^{o}C); γ_T is the factor of safety accounting for microwave curing temperature variations (hot spots).

The temperatures at the hot spots reported in this paper are likely to have been exaggerated by the edge effects of the polystyrene moulds. More accurate information will be obtained from the larger scale trials to be carried out with the microwave curing prototype. In addition, the prototype will adopt a magnetron of higher specifications, which will provide more uniform heating. Consequently, the value of γ_T is likely to be small. Most concrete repairs are relatively small (thin) and, therefore, their volume will not cause excessive heat of hydration. The acceleration of hydration by microwave curing, however, can lead to high temperature before the repair hardens thereby raising durability concerns. The upper limit set by durability considerations regulates the maximum microwave curing temperature $T_{m.}$ The temperature increase relative to the ambient (T_a), $\Delta T = T_m - T_a$ available for microwave curing at low ambient temperatures is high and, therefore, exceeding the durability upper limit temperature is less likely to cause a problem than in repairs applied at high ambient temperatures. The authors have used a microwave curing temperature T_m of 40 ^{o}C in subsequent tests which recorded a maximum temperature ($T_m + T_h$) of 71.1 ^{o}C for seven repair materials [23].

3.8. Effect of ambient temperature on the microwave curing temperature

A summary of results which include the temperature rise *ΔT*, the rate of temperature increase (*dT/dt*) and maximum temperature after microwave curing for 45 minutes at 132 Watts, is given in Table 4 for all repair materials prepared at different ambient temperatures. Fig. 13 shows the time-temperature relationships under microwave curing of Repair Material 5 prepared at different ambient temperatures of 1.7 ^{o}C, 8.9 ^{o}C and 15.8 ^{o}C (Material 5 mixes 1, 2 and 3 respectively, Table 4). The graphs are typical of repair materials 1, 3, 4 and 5 (Table 4) which show a linear increase in temperature with time.

The results in Table 4 for Materials 1, 3 and 4 show that the temperature rise *ΔT* achieved after 45 minutes of microwave curing is greater at lower temperature, resulting in a higher rate of temperature rise *dT/dt* at lower ambient temperatures. For example, the temperature rise of Material 1 at ambient temperature of 3 ^{o}C is 0.88 ^{o}C/min compared with 0.8 ^{o}C/min at 17.1 ^{o}C ambient temperature. The corresponding rates for Material 3 are 0.74 ^{o}C/min and 0.59 ^{o}C/min for ambient temperatures of 6.5 and 18.3 ^{o}C, while the corresponding rates for Material 4 are 0.61 ^{o}C/min and 0.47 ^{o}C/min for ambient temperatures of 3.2 and 17.8 ^{o}C. However, this trend is reversed for repair Material 5 which heats more rapidly at higher ambient temperatures (see Fig. 5).

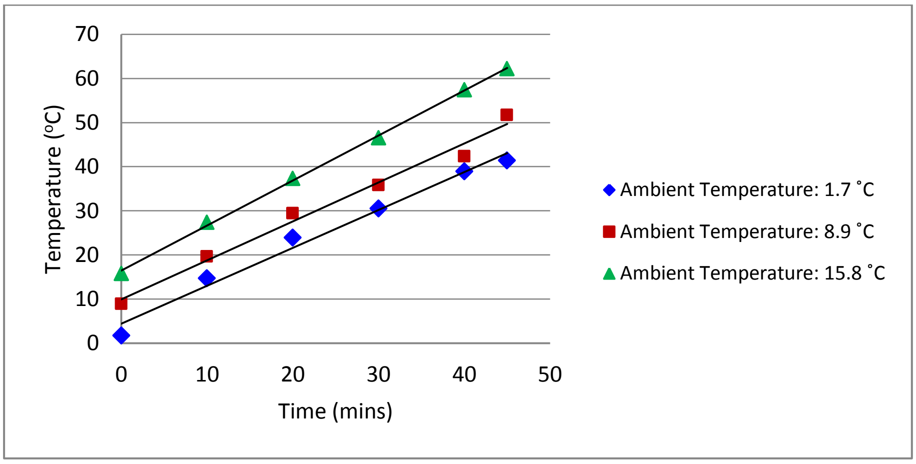

Fig. 13. Time-temperature profile of Material 5 prepared at 1.7 ^{o}C, 8.9 ^{o}C and 15.8 ^{o}C and microwave cured for 45 minutes at 132 W.

Table 4
Summary of microwave curing temperatures developed at different ambient temperatures.

Repair material	Mix	Power (W)	Volume (L)	Ambient temperature (^{o}C)	Maximum temperature* (^{o}C)	ΔT (^{o}C)	dT/dt (^{o}C/min)
1	1	132	3.38	3.0	42.5	39.5	0.88
	2			10.0	47.2	37.2	0.83
	3			17.1	52.9	35.8	0.80
3	1			6.5	39.9	33.4	0.74
	2			9.1	43.8	34.7	0.77
	3			18.3	45.0	26.7	0.59
4	1			3.2	30.5	27.3	0.61
	2			9.9	35.0	25.1	0.56
	3			17.8	39.0	21.2	0.47
5	1			1.7	41.4	39.7	0.88
	2			8.9	51.7	42.8	0.95
	3			15.8	62.2	46.4	1.03

*Temperature measured at the centre of the top surface of cube by using a Flir i7 thermal camera.

3.9. Effect of steel reinforcement

No sparks or arcing was observed during microwave curing of all steel reinforced cube specimens. Typical temperature distributions of a plain (control at 120 Watts), a mild steel reinforced (3 steel bars, 10 mm diameter, 25 mm cover at 120 Watts) and a mild steel reinforced (3 protruding steel bars, 6 mm diameter, 5mm cover at 420 Watts) specimen are shown in Fig. 14a-c, respectively. No significant changes in top surface temperature distribution and mid-point surface temperatures were observed by varying the type of mild steel (galvanised or normal), number of steel bars (1, 2 or 3), bar diameter (10, 8 or 6 mm) or top cover (25, 15 or 5 mm).

Fig. 14c shows the extreme case of steel bars protruding from the cube moulds. The temperatures in the protruding parts of the steel bars are on the lower end of the recorded temperature scale and are much lower than the mortar specimen. There was no arcing observed in these tests.

The above results are provided to allay health and equipment safety concerns. The effects of microwave curing on the bond strength of the steel reinforcement were also investigated, which will be reported in another paper.

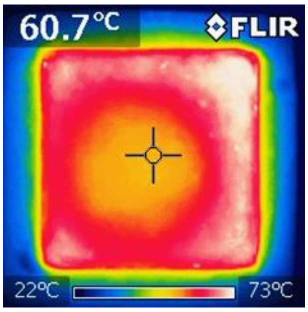

Fig. 14a. Temperature distribution of plain (control) mortar specimen after 45 minutes of microwave curing at 120 W.

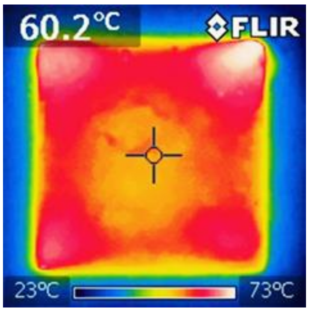

Fig. 14b. Temperature distribution of steel reinforced mortar specimen (3 steel bars, 10 mm diameter, 25 mm top cover) after 45 minutes of microwave curing at 120 W.

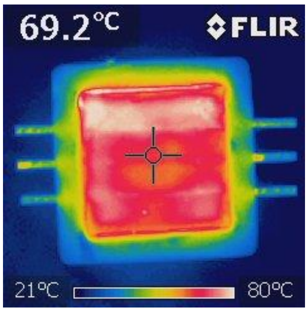

Fig. 14c. Temperature distribution of steel reinforced mortar specimen (3 protruding steel bars, 6 mm diameter, 5 mm top cover) after 15 minutes of microwave curing at 420 W.

Conclusions

The following conclusions can be drawn from the results presented in the paper:

- Microwave curing is suitable for normal, non-rapid setting repair materials which are not cured to excessively high temperatures. The cumulative total of the microwave curing and the heat of hydration temperatures of the fresh material should be kept below the limit set by durability considerations.
- Considerable variation of temperature occurs on the surface of microwave cured cubes. This should be taken into account in the cumulative total temperature of the microwave cured material.
- The temperature during microwave curing increases linearly with time and power input under the recommended moderate limits of microwave curing temperatures.

- Microwave curing accelerates hydration and reduces the time taken to reach peak heat of hydration temperature.
- The maximum microwave curing temperature is affected by the initial (ambient) temperature of the fresh mix.
- The rate of temperature increase with microwave curing time (slope $\alpha = dT/dt$) increases linearly with the applied power. The rapid setting materials are an exception unless the curing temperature T_m is relatively low.
- The presence of steel reinforcement in repair mortar does not cause any arcing during microwave curing. This also applies to steel located at very low cover (5 mm) and to exposed steel bars protruding from the mortar surface.

Acknowledgements

The authors gratefully acknowledge the funding provided by the European Commission 7th Framework Programme for the MCure project (Grant No: 605664) which produced this research and developed a prototype for microwave curing of concrete repair.

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