

## **Microwave curing parameters of in-situ concrete repairs**

MANGAT, Pal <<http://orcid.org/0000-0003-1736-8891>>, GRIGORIADIS, Konstantinos and ABUBAKRI, Shahriar <<http://orcid.org/0000-0001-6046-311X>>

Available from Sheffield Hallam University Research Archive (SHURA) at:

<http://shura.shu.ac.uk/12154/>

---

This document is the author deposited version. You are advised to consult the publisher's version if you wish to cite from it.

### **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.

---

### **Copyright and re-use policy**

See <http://shura.shu.ac.uk/information.html>

# 1 Microwave Curing Parameters of In-situ Concrete Repairs

2 P. S. Mangat\*, K. Grigoriadis, S. Abubakri

3 Centre for Infrastructure Management, Materials & Engineering Research Institute, Sheffield  
4 Hallam University, Howard Street, Sheffield, S1 1WB, UK (\*Corresponding author. Fax:  
5 +44 114 225 3501; Tel: +44 114 225 3339)

6 Emails: [p.s.mangat@shu.ac.uk](mailto:p.s.mangat@shu.ac.uk) (P. S. Mangat), [k.grigoriadis@shu.ac.uk](mailto:k.grigoriadis@shu.ac.uk) (K. Grigoriadis),  
7 [sabubakr@my.shu.ac.uk](mailto:sabubakr@my.shu.ac.uk) (S. Abubakri)

8

## 9 Abstract

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

18

## 19 Keywords

20 Concrete, Microwave curing, Patch repair.

21

## 22 1. Introduction

23 Reinforced and pre-stressed concrete has been used at a massive scale for the construction  
24 of infrastructure in the last century with the secure assumption of its lasting durability. While  
25 the large majority of concrete construction is durable, repair is increasingly needed due to

26 various concrete degradation mechanisms, abnormal loading or poor workmanship.  
27 According to CONREPNET [1] more than 50% of Europe's annual construction budget is  
28 spent on rehabilitation and refurbishment projects including the repair of deteriorated  
29 concrete structures. In the United States the annual cost of repair, strengthening and  
30 protection of concrete structures is between \$18 and \$21 billion [2].

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

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

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

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

75 The development of a microwave heating system to provide early age curing to concrete  
76 repair patches has the potential to revolutionise the concrete repair industry by transforming  
77 the efficiency and economics of thermal curing. Its effectiveness for cold weather curing will  
78 prevent disruption to construction activity in winter, which will have a major economic  
79 impact by allowing continued construction activity during winter. Microwave heating is more  
80 economical than the thermal curing methods currently used on site such as open flame heaters  
81 with or without an enclosure around a repaired area. The energy use and CO<sub>2</sub> emission will  
82 also be lower. It has also the potential of reducing the use of expensive and environmentally  
83 undesirable chemical admixtures in proprietary repair formulations to accelerate curing.

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

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

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

107

## 108 **2. Experimental Procedure**

### 109 2.1. Materials and equipment

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

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

114 *Repair Material 2:* A polymer-modified rapid-setting cement mortar and fibre-reinforced.  
115 Density of the fresh mix was 2140 kg/m<sup>3</sup>.

116 *Repair Material 3:* A polymer-modified cement mortar, fibre-reinforced and shrinkage-  
117 compensated. Density of the fresh mix was 2280 kg/m<sup>3</sup>.

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

120 *Repair Material 5:* A polymer-modified cement mortar and fibre-reinforced. Density of fresh  
121 mix was 1500 kg/m<sup>3</sup>.

122 *Repair Material 6:* A polymer-modified cement, rapid setting concrete. Density of fresh mix  
123 was 2200 kg/m<sup>3</sup>.

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

126

127 Two commercial microwave ovens were used, a Logik Model L25MDM13 with a  
128 maximum nominal output power of 900 Watts (manufacturer's specification) and a Sharp  
129 Model R-2370 with a maximum nominal output power of 1300 Watts (manufacturer's  
130 specification). Both microwave ovens could be set to generate power at incremental levels of  
131 10% up to 100% of their maximum output. The microwave frequency for both ovens is 2.45  
132 GHz. The microwave ovens were calibrated [11] according to ASTM F1317-98 [19] and BS  
133 EN 60705: 2012 [20] to determine their actual power outputs which in the case of the Logik  
134 Model L25MDM13 differed significantly from the manufacturer's specification. Unless  
135 otherwise mentioned, all values of microwave power given subsequently in the paper are the  
136 actual power values.

137

138 2.2. Details of specimens, mixing and microwave curing

139 2.2.1. *Repair material specimens for surface temperature monitoring*

140 Three volumes of specimens, 1, 3.38 and 4.38 litres were used for microwave curing [11].  
141 Specimens were cast in polystyrene cube moulds of 100 mm and 150 mm internal  
142 dimensions. The 1 litre volume was provided by a 100 mm mould, the 3.38 litre volume by a  
143 150 mm mould and the 4.38 litre volume comprised of the combined 100 mm and 150 mm  
144 cube moulds.

145 Details of all repair material mixes are given in Table 1. The mix proportions recommended  
146 by the manufacturers of each repair material were used. The quantity of each repair material  
147 and water, given in Table 1, was mixed together in a Hobart mixer to produce the required  
148 volume of mix for the cube mould. Each mix was cast in the cube mould and compacted on a

149 vibrating table. The compacted specimens were kept in the laboratory environment  
 150 (approximately 20 °C, 60% RH) for 30 minutes from the time of commencing mixing. After  
 151 30 minutes of pre-curing in the laboratory, the cube moulds were placed in the microwave  
 152 oven and cured for 45 minutes at levels of power 60, 120, 132, 180 or 264 Watts.  
 153 Temperature was measured at the centre of the top surface of each cube at 0, 10, 20, 30, 40  
 154 and 45 minutes from the start of microwave curing using a Flir i7 thermal camera.

155

156 **Table 1**  
 157 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 L25MDM13	60	0.21	1.52	0.14	1	100	42
		2		120						
		3		180						
	2	1		120	0.26	1.88	0.14			60
		3		60						
		2		120						
	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 R-2370	132	0.72	5.12	0.14	3.38	150	42
		2		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 R-2370	132	0.93	6.64	0.14	4.38	100	42
		2		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							

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

159

### 160 2.2.2. Repair material specimens for internal temperature monitoring

161 Internal temperatures during 1169 minutes after microwave curing were recorded using  
 162 thermocouples. Four T type thermocouples were located inside the 150 mm cube moulds as  
 163 shown in Fig. 1 and the repair material was cast around them. The thermocouples were



164 located at 37.5, 75, 112.5 and 150 mm from the top surface of the specimens along the  
 165 vertical centroidal axis. Temperature measurements were taken every 30 seconds using a  
 166 Data Taker DT85G digital logger. Details of the two repair material mixes used for this  
 167 investigation are given in [Table 2](#).

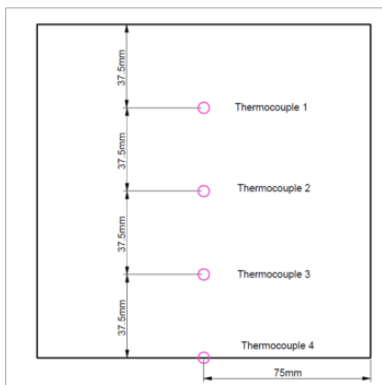
168

169 **Table 2**  
 170 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		

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

172



173

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

175

176 *2.2.3. Repair material specimens for investigating the effect of ambient (initial) temperature*  
 177 *on microwave curing temperature*

178 The effect of different ambient temperatures of the fresh mix of a repair material on the  
 179 microwave curing temperatures developed with time was investigated [11]. The investigation  
 180 simulated the application of repairs in different in-situ conditions including cold weather. The  
 181 constituent materials of each mix were conditioned and mixed at three different ambient  
 182 temperature ranges: very low (1.7-6.5 °C), low (8.9-10.0 °C) and medium range (15.8-18.3  
 183 °C). The constituent materials were kept overnight in an environmental chamber to condition

184 them to the selected ambient temperature. The ambient temperature was maintained during  
185 mixing and for 30 minutes after casting a 150 mm cube specimen (3.38 litres volume) for  
186 each mix. Materials 1, 3, 4 and 5 were tested using the Sharp R-2370 microwave oven at an  
187 actual output power of 132 Watts. Temperature measurements at the centre of the top surface  
188 of the cubes were taken at 0, 10, 20, 30, 40 and 45 minutes from the start of microwave  
189 curing using a Flir i7 thermal camera.

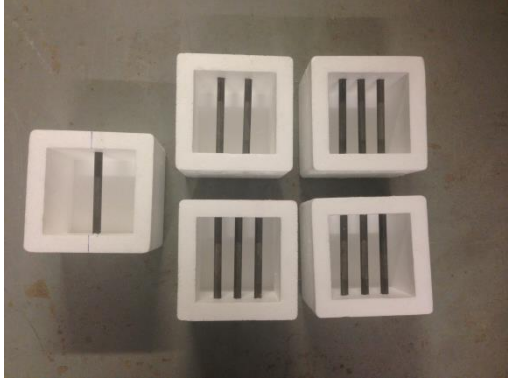
190

#### 191 *2.2.4. Steel reinforced mortar specimens for investigating safety of microwave curing*

192 Long and pointed metallic objects or very thin metal strips when placed in a microwave  
193 oven act as an antenna and reflect the microwave energy. At high levels of microwave power  
194 this can create electric arcs (sparks) which can increase the temperature of its magnetron.  
195 This can reduce the life of the magnetron. An investigation of the safety of microwave curing  
196 was carried out on specimens cast with 1, 2 or 3 steel bars placed horizontally along the entire  
197 length of the 100 mm cube as shown in [Fig. 2a](#). Details of all steel reinforced mortar mixes  
198 are given in [Table 3](#). The total length of each steel bar was 140 mm to cover the cube length  
199 (100 mm) plus 20 mm thickness of two mould walls. Steel bars of diameters 10, 8 or 6 mm  
200 were located through holes drilled in the side faces of the mould. In addition, one specimen  
201 was made with 6 mm diameter bars protruding 30 mm from each side face of the mould as  
202 shown in [Fig. 2b](#). The total length of each steel bar was 200 mm. Both galvanised and normal  
203 mild steel bars were used. The top cover to steel bars was 25, 15 or 5 mm as shown in [Fig. 3](#).

204 A quantity of CEM II cement [\[18\]](#), sharp coarse sand and water (w/c ratio of 0.5) were  
205 mixed together to produce a 1 litre mix for the cube mould. Each cube was cast and  
206 compacted on a vibrating table and kept in the laboratory environment (approximately 20 °C,  
207 60% RH) for 30 minutes after commencing mixing. After 30 minutes of pre-curing in the  
208 laboratory, the cube moulds were placed in the microwave oven and cured for either 45 or 15

209 minutes at powers ranging from 60 to 420 Watts (Table 3). The temperature at the mid-point  
210 of the top surface of the cube was measured at the end of microwave curing (maximum  
211 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.



212

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

215

216

217

218

219

220

221

222

223

224

225

226

227

228

229 **Table 3**  
 230 Details of steel reinforced mortar mixes.

Cube size	Microwave power	Microwave duration	Number and type of bars	Bar diameter	Top cover	Orientation and length of steel bars
(mm)	(W)	(min)		(mm)	(mm)	
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)

231 \*MS-mild steel.  
 232

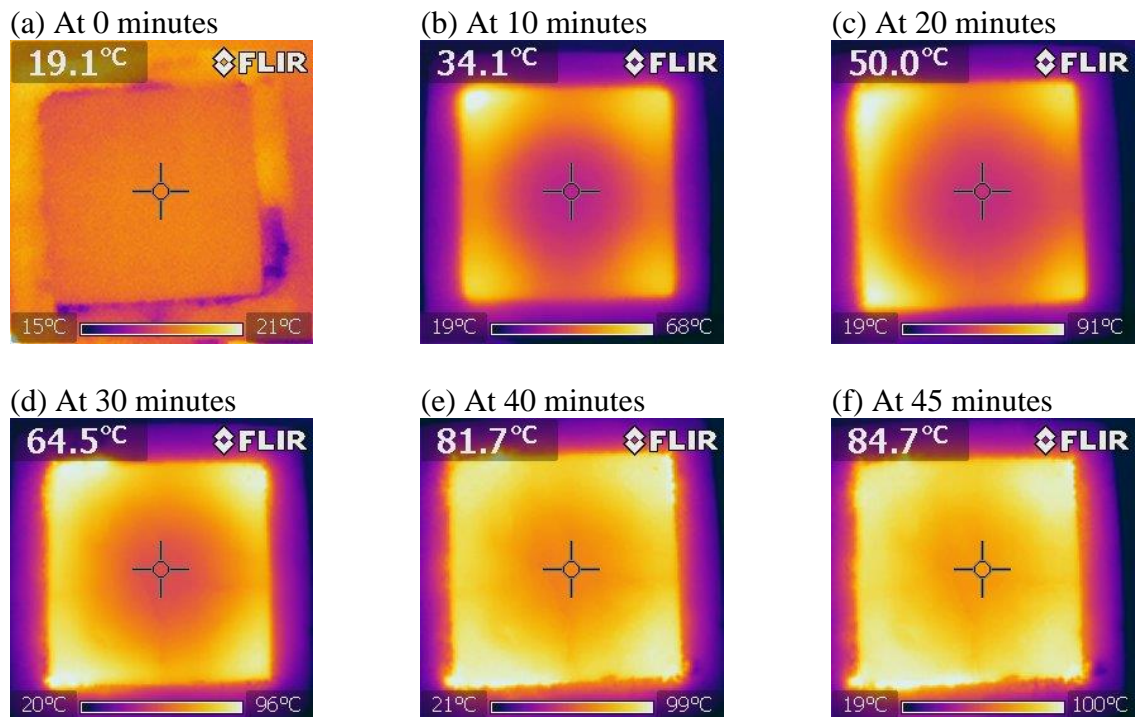
### 233 3. Results and Discussion

#### 234 3.1. Temperature distribution

235 Significant variations of top surface temperature were observed during microwave curing of  
 236 all specimens of Series 1, 2 and 3, [Table 1](#) (1, 3.38 and 4.38 L volume). In all cases hot zones  
 237 appeared at the edges and corners of the polystyrene moulds shortly after starting microwave  
 238 curing. Typical temperature distributions across the top surface of a 100 mm cube at 0, 10,  
 239 20, 30, 40 and 45 minutes of microwave curing at 180 Watts power are shown in [Fig. 4 \(a-f\)](#).  
 240 The dark edges represent the walls of the polystyrene moulds. At 40 minutes of curing, for  
 241 example, the middle surface temperature is 81.7 °C whereas it increases towards 99 °C on the  
 242 outer surfaces of the cube specimen. The temperature profiles show a significant variation of  
 243 temperature developed in the cured material. This indicates the unreliability of firm  
 244 relationships between temperature, time and strength development drawn by other  
 245 researchers [[4](#), [9](#), [12-17](#)] based on localised temperature monitoring (e.g. by a single  
 246 thermocouple).

247

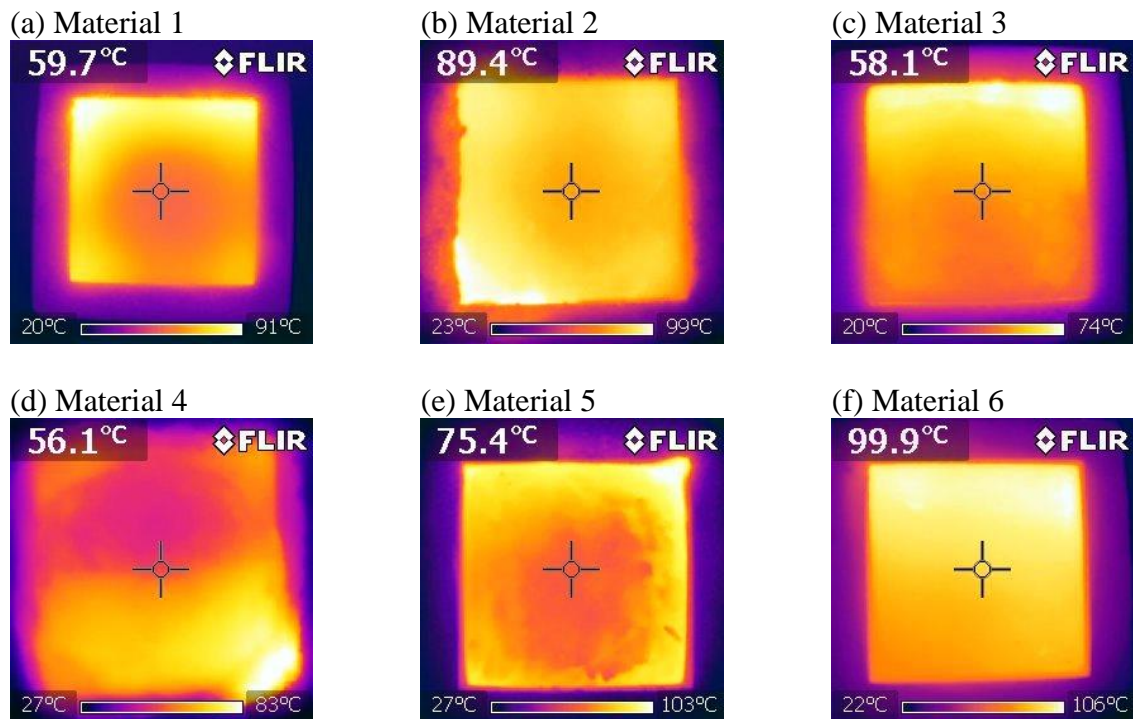
248



249  
 250  
 251  
 252  
 253  
 254  
 255  
 256  
 257  
 258  
 259  
 260  
 261  
 262  
 263  
 264  
 265

**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).



266  
 267 **Fig. 5 (a-f).** Top surface temperature of the six repair materials (1 litre volume subjected to  
 268 120 W power) at 45 minutes of microwave curing.  
 269

270 Materials 2 and 6 developed particularly high temperatures (89.4 °C and 99.6 °C  
 271 respectively) at the end of microwave curing compared with the normal Materials 1 and 3  
 272 which developed 59.7 °C, and 58.1 °C, respectively. This is because both 2 and 6 are rapid  
 273 setting repair materials. Material 4, which is a rapid hardening material did not develop  
 274 higher temperatures than Materials 1 and 3. The admixtures, additives and the fineness of  
 275 cement used in the repair mortars 2, 5 and 6 appear to affect the temperature. However, since  
 276 the details of the constituents of these commercial materials are not available, precise  
 277 conclusions cannot be drawn. There is no clear relationship between water/powder (w/p) or  
 278 density of the mixes and the temperature developed by microwave curing. For example both  
 279 normal Materials 1 and 3 have w/p ratios 0.14 and 0.11 respectively (Table 1) but the  
 280 temperatures developed after 45 minutes of microwave curing are similar (57.9 °C and 58.1  
 281 °C, respectively). Materials 1 and 5 on the other hand have similar w/p ratios (0.14 and 0.13,  
 282 respectively) and densities (1730 and 1500 kg/m<sup>3</sup>, respectively) but they developed

283 significantly different temperatures after 45 minutes of microwave curing (59.7 and 75.4 °C,  
284 respectively). It is clear, therefore, that the constituents of repair materials, rather than their  
285 w/p ratio or density, are the main factors which control the microwave curing temperature.

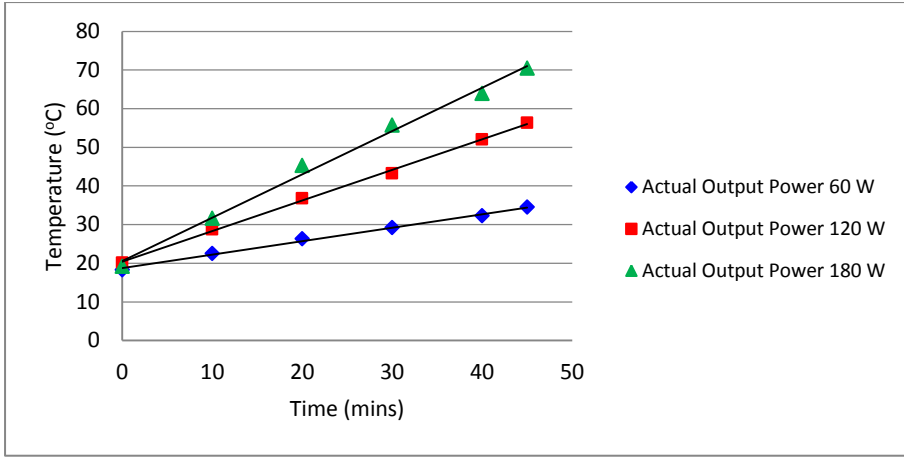
286

### 287 3.2. Time-temperature relationship

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

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

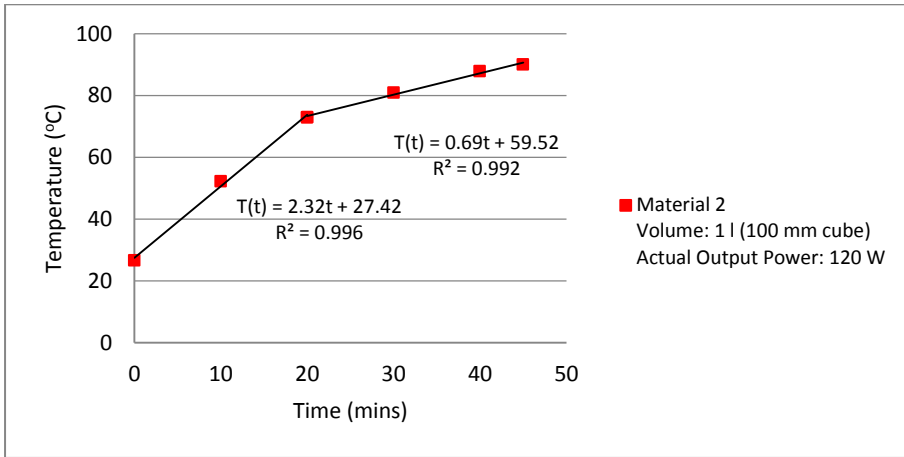




304

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

306



307

308

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

311

312 3.3 Volume-temperature relationship

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

315 
$$\frac{P_{abs}}{V} = \frac{c\rho(T_f - T_a)}{t} \tag{1}$$

316

317 where,  $P_{abs}$  is the microwave power (W);  $V$  is the volume (L);  $c$  is the heat capacity (J/kg/°C);  
 318  $\rho$  is the density (kg/m<sup>3</sup>);  $T_f$  is the temperature at the end of microwave curing (°C);  $T_a$  is the  
 319 ambient temperature (°C);  $t$  is the microwave curing time (min).



320

321 This expression is applied to the experimental data of this investigation in Fig. 8, at a  
322 constant applied microwave power of (120-132 W) for a constant time of 45 mins for  
323 Materials 1, 3, 4 and 5. The ambient temperature of all tests ranged between 15.8 and 20.3 °C.

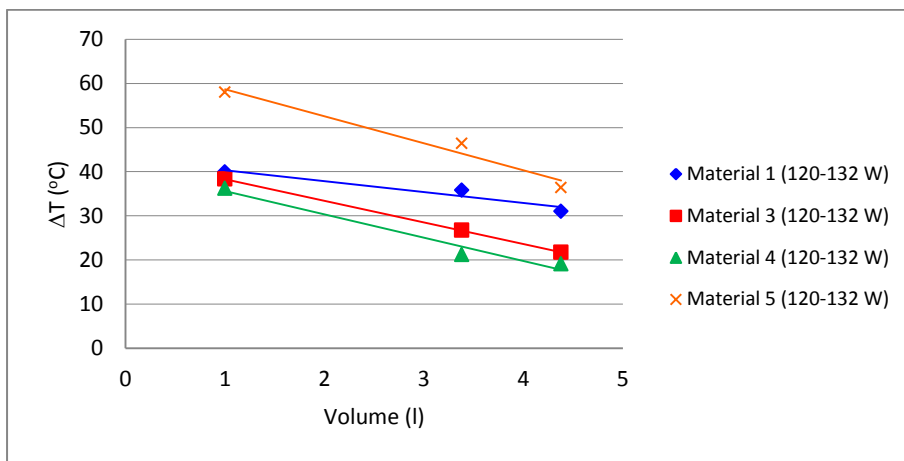
324 Eq. 1 is re-written in the form

$$325 \Delta T = \frac{P_{abs}t}{c\rho} V^{-1} \quad (2)$$

$$326 \text{ where, } \Delta T = T_f - T_a \quad (3)$$

327

328 Fig. 8 shows a linear relationship between  $\Delta T$  and  $V$  for the constant power and microwave  
329 curing time for the experimental data of Materials 1, 3, 4 and 5. The slope of the graphs in  
330 Fig. 8 is a function of  $P_{abs}$ ,  $t$ ,  $c$  and  $\rho$ . The density  $\rho$  of Materials 1, 3, 4 and 5 is 1730, 2280,  
331 2260 and 1500 kg/m<sup>3</sup>, respectively. The coefficient  $c$  accounts for the different constituents  
332 of the repair materials and their mix proportions.



333

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

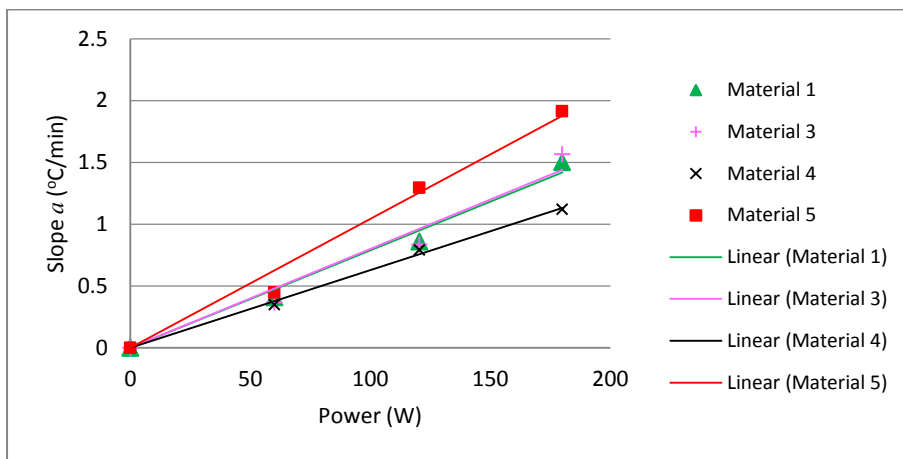
335

336

### 337 3.4. Rate of temperature increase with microwave power

338 Time-temperature relationships of the repair materials and volumes at different power levels  
339 described in Section 3.2 were analysed to determine the rate of temperature increase,  $dT/dt$   
340 (slope  $\alpha$ ), with time. The rapid setting Materials 2 and 6 were excluded since they developed

341 very high temperatures which would not be used in practice and had set before the end of  
 342 microwave curing (Fig. 7). A linear relationship was observed between  $\alpha$  and microwave  
 343 power in all cases. A typical graph showing the relationships between microwave power and  
 344 slope  $\alpha$  for four repair materials (1 litre volume) is shown in Fig. 9. This relationship will  
 345 provide an important input to the automatic control algorithm developed for the operation of  
 346 the microwave curing prototype of the MCure project.



347  
 348 **Fig. 9.** Power versus slope  $\alpha$  relationship for five repair materials (1 litre volume).  
 349

### 350 3.5 General relationship between microwave curing parameters of repair materials

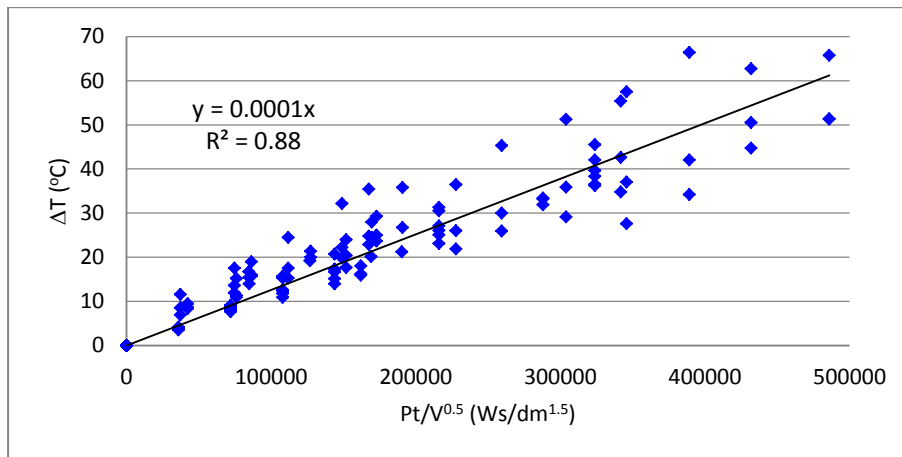
351 The basic parameters of microwave curing which are Power, Time and Volume are related  
 352 to the temperature rise provided by microwave curing as shown in Fig. 10. The data in Fig.  
 353 10 represent all tests listed in Table 1 for repair materials 1, 3 and 4 and volumes of cubes 1,  
 354 3.38 and 4.38 L. The best fit relationship in Fig. 10 is given by the equation:

$$355 \quad \Delta T = \frac{Pt}{\sqrt{V}} \quad (4)$$

356 where,  $\Delta T$  is the temperature rise due to microwave curing ( $^{\circ}\text{C}$ );  $P$  is the microwave power  
 357 (W);  $t$  is the duration of microwave curing (s);  $V$  is the volume of the repair material ( $\text{dm}^3$ ).

358  
 359 Eq. 4 has been used to design the microwave curing prototype rig for the MCure project. It  
 360 was used to calculate the maximum power rating required of the prototype to deliver the

361 specified range of parameters  $\Delta T$ ,  $t$  and  $V$  required for in-situ curing of scaled up repair  
362 elements [22]. The parameters  $\Delta T$  and  $t$  were also specified on the basis of the results  
363 reported in the paper. Scaled up field trials on the MCure prototype proved that its design  
364 delivered the specified parameters [22].



365  
366 **Fig. 10.** General relationship between microwave curing parameters of repair materials 1, 3  
367 and 4

368  
369 3.6. Internal temperature development

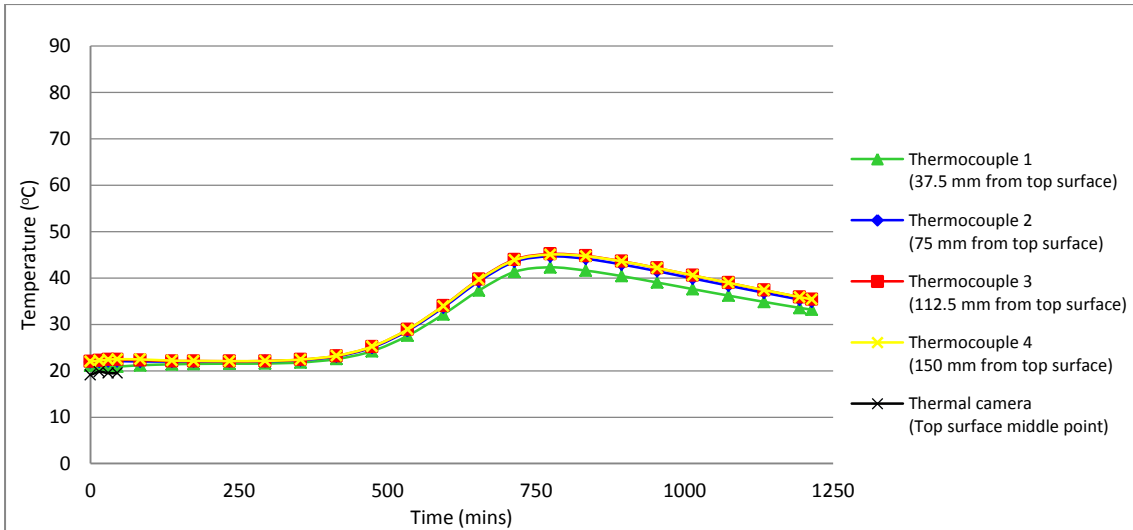
370 Typical time-internal temperature graphs accompanied by time-top surface temperature  
371 graphs for both normally cured (at 20 °C) and microwave cured specimens of Material 4 are  
372 shown in Fig. 11 and Fig. 12, respectively. The internal temperatures were monitored from  
373 thermocouples located within the 150 mm cube specimens (3.38 litre volume) which were  
374 microwave cured for 45 minutes at 132 Watts. The relationship under normal curing (20 °C)  
375 given in Fig. 11 shows one hump at about 775 minutes (775 + 30 pre-curing after mixing =  
376 805 minutes from the start of hydration), representing the peak heat of hydration temperature  
377 of about 45 °C. This represents a temperature rise of 25 °C due to heat of hydration. The  
378 corresponding microwave cured sample shows the first hump at 45 minutes (Fig. 12) when  
379 the peak microwave curing temperature is reached followed by a second hump at about 245  
380 minutes (275 minutes from the start of hydration, 200 minutes after the end of microwave  
381 curing) indicating the peak heat of hydration point. It is clear that the heat of hydration

382 reaction is significantly accelerated by microwave curing reducing the peak time from 805 to  
383 275 minutes while increasing the peak temperature to 79 °C. This shows a temperature rise of  
384 34 °C from the end of microwave curing (45 °C) to the peak of hydration (79 °C). Fig. 12  
385 shows that heat of hydration develops after the microwave curing period and has an  
386 insignificant effect on the temperatures developed during microwave curing as shown in Fig.  
387 6. Other results reported by the authors [23] for 100 mm cube specimens microwave cured to  
388 about 40 °C show that, for non-rapid setting repair materials, the maximum temperature of  
389 between 53.8 and 71.1 °C is reached at 10-60 minutes after the end of microwave curing.

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

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

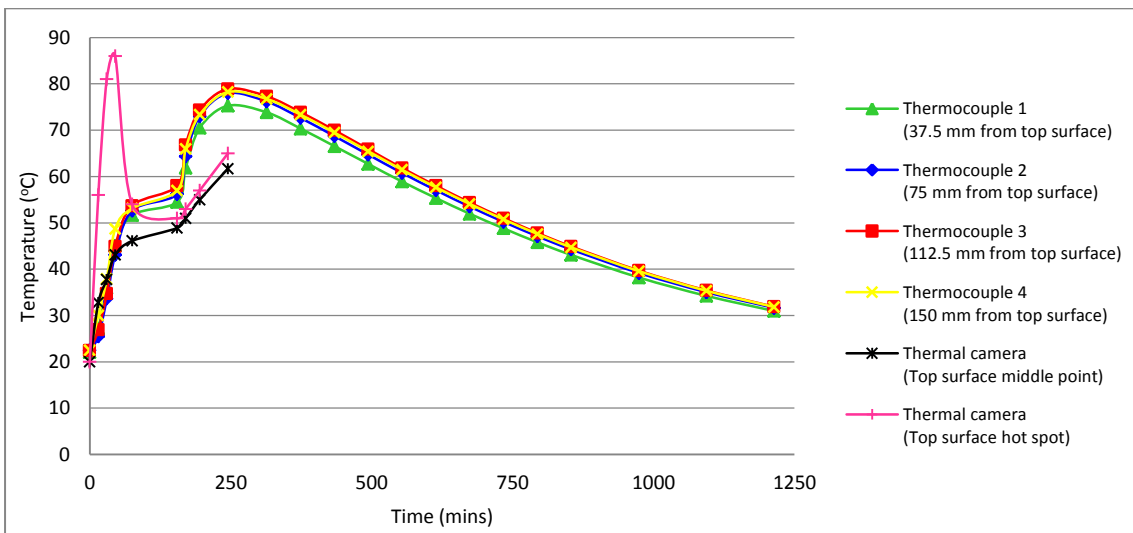
400 Fig. 12 shows that the top surface mid-point temperatures measured by the thermal camera  
401 closely follow the internal temperatures (thermocouple readings) developed during the 45  
402 minutes of microwave curing. Thereafter the internal temperatures are higher due to the  
403 accelerated heat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



406

407 **Fig. 11.** Typical internal temperature-time relationship for Material 4 (3.38 litres volume)  
 408 cured at 20 °C.

409



410

411 **Fig. 12.** Typical internal temperature-time relationship for Material 4 (3.38 litres volume)  
 412 microwave cured at 132 W for 45 minutes, followed by curing at 20 °C.

413

414 3.7 Permissible Microwave Curing Temperature

415 The maximum temperature of 79 °C reached at the peak of hydration (Fig. 12) is excessive  
 416 from the considerations of long-term durability [6]. Curing of concrete at temperatures  
 417 exceeding about 70 °C can lead to durability problems such as delayed ettringite formation  
 418 and loss of long-term strength [6]. Therefore, limits need to be set to the maximum  
 419 microwave curing temperature for in-situ curing, taking account of the heat of hydration and

420 temperature variations (hot spots) which occur during microwave curing. This can be done by  
421 adopting the following equations to determine the permissible temperature:

$$422 \quad T_m + \Delta T_h \leq \frac{70}{\gamma_T} \quad (5)$$

$$423 \quad \Delta T_h = T_h - T_m \quad (6)$$

424

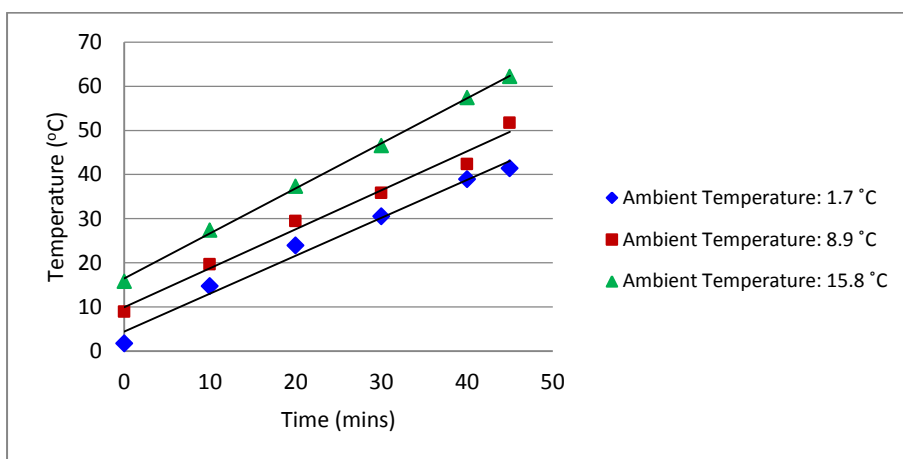
425 where,  $T_m$  is the permissible temperature at the end of microwave curing ( $^{\circ}\text{C}$ );  $T_h$  is the peak  
426 heat of hydration temperature of unhardened concrete ( $^{\circ}\text{C}$ );  $\gamma_T$  is the factor of safety  
427 accounting for microwave curing temperature variations (hot spots).

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

442 3.8. Effect of ambient temperature on the microwave curing temperature

443 A summary of results which include the temperature rise  $\Delta T$ , the rate of temperature  
 444 increase ( $dT/dt$ ) and maximum temperature after microwave curing for 45 minutes at 132  
 445 Watts, is given in Table 4 for all repair materials prepared at different ambient temperatures.  
 446 Fig. 13 shows the time-temperature relationships under microwave curing of Repair Material  
 447 5 prepared at different ambient temperatures of 1.7 °C, 8.9 °C and 15.8 °C (Material 5 mixes  
 448 1, 2 and 3 respectively, Table 4). The graphs are typical of repair materials 1, 3, 4 and 5  
 449 (Table 4) which show a linear increase in temperature with time.

450 The results in Table 4 for Materials 1, 3 and 4 show that the temperature rise  $\Delta T$  achieved  
 451 after 45 minutes of microwave curing is greater at lower temperature, resulting in a higher  
 452 rate of temperature rise  $dT/dt$  at lower ambient temperatures. For example, the temperature  
 453 rise of Material 1 at ambient temperature of 3 °C is 0.88 °C/min compared with 0.8 °C/min at  
 454 17.1 °C ambient temperature. The corresponding rates for Material 3 are 0.74 °C/min and  
 455 0.59 °C/min for ambient temperatures of 6.5 and 18.3 °C, while the corresponding rates for  
 456 Material 4 are 0.61 °C/min and 0.47 °C/min for ambient temperatures of 3.2 and 17.8 °C.  
 457 However, this trend is reversed for repair Material 5 which heats more rapidly at higher  
 458 ambient temperatures (see Fig. 5).



459  
 460 **Fig. 13.** Time-temperature profile of Material 5 prepared at 1.7 °C, 8.9 °C and 15.8 °C and  
 461 microwave cured for 45 minutes at 132 W.  
 462  
 463

464 **Table 4**  
 465 Summary of microwave curing temperatures developed at different ambient temperatures.  
 466

Repair material	Mix	Power (W)	Volume (L)	Ambient temperature (°C)	Maximum temperature* (°C)	$\Delta T$ (°C)	$dT/dt$ (°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	132	3.38	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	132	3.38	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	132	3.38	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

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

468

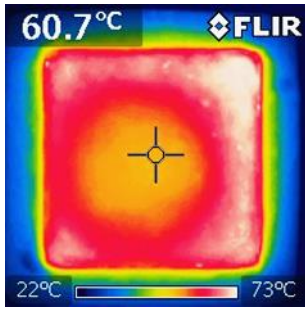
### 469 3.9. Effect of steel reinforcement

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

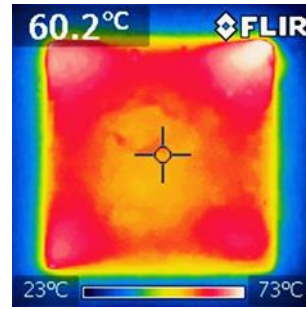
478 Fig. 14c shows the extreme case of steel bars protruding from the cube moulds. The  
 479 temperatures in the protruding parts of the steel bars are on the lower end of the recorded  
 480 temperature scale and are much lower than the mortar specimen. There was no arcing  
 481 observed in these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

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

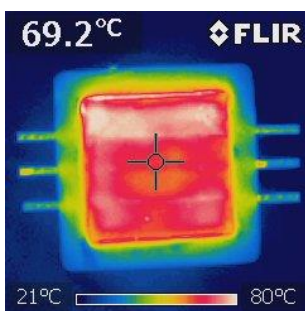




**Fig. 14a.** Temperature distribution of plain (control) mortar specimen after 45 minutes of microwave curing at 120 W.



**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.

485  
486  
487

## Conclusions

488

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

489

- 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.

493

- 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.

496

- The temperature during microwave curing increases linearly with time and power input under the recommended moderate limits of microwave curing temperatures.

497

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

508

#### 509 **Acknowledgements**

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

513

#### 514 **References**

- 515 [1] G. Tilly, J. Jacobs, Concrete Repairs: Observations on performance in service and  
516 current practice. CONREPNET Project Report. Watford, UK: IHS BRE Press; 2007.
- 517 [2] P.H. Emmons, D.J. Sordyl, The state of the concrete repair industry and a vision for its  
518 future. Concr Repair Bull 2006; 6: 7-14.
- 519 [3] P.H. Emmons, Concrete repair maintenance illustrated. 1<sup>st</sup> ed. John Willey and Sons;  
520 1992.

- 521 [4] C.K.Y. Leung, T. Pheeraphan, Microwave curing of Portland cement concrete:  
522 experimental results and feasibility for practical application. *Constr Build Mater* 1995;  
523 9: 67-73, [http://dx.doi.org/10.1016/0950-0618\(94\)00001-I](http://dx.doi.org/10.1016/0950-0618(94)00001-I).
- 524 [5] F. Parker, W.L. Shoemaker, Rapid-setting PCC pavement patching materials. *New*  
525 *pavement materials*. American Society of Civil Engineers 1988; 81-95.
- 526 [6] A.M. Neville, *Properties of concrete*. 5<sup>th</sup> ed. Harlow, Essex: Pearson Education  
527 Limited; 2011.
- 528 [7] K.C.G. Ong, A. Akbarnezhad, *Microwave-Assisted Concrete Technology: Production,*  
529 *Demolition and Recycling*. 1<sup>st</sup> ed. Boca Raton, Florida: CRC Press, Taylor and  
530 FrancisGroup; 2014.
- 531 [8] P.S. Mangat, D.J. Catley, A novel low-voltage heating system for curing and protection  
532 of early age concrete. *Concr Plant International* 2005; 4: 106-112.
- 533 [9] X. Wu, J. Dong, M. Tang, Microwave curing technique in concrete manufacture. *Cem*  
534 *Concr Res* 1987; 17: 205-210, [http://dx.doi.org/10.1016/0008-8846\(87\)90103-7](http://dx.doi.org/10.1016/0008-8846(87)90103-7).
- 535 [10] K. Grigoriadis, P.S. Mangat, Bond between microwave cured repair and concrete  
536 substrate (submitted to *Materials and Structures*)
- 537 [11] P. Mangat, K. Grigoriadis, S. Abubakri, Microwave curing of concrete bridge repairs.  
538 In: *Proceedings of the 16<sup>th</sup> European bridge conference*. Edinburgh, 2015.
- 539 [12] N. Makul, B. Chatveera, P. Ratanadecho, Use of microwave energy for accelerated  
540 curing of concrete: a review. *Songklanakarin J Sci Technol* 2009; 31: 1-13.
- 541 [13] J. Pera, J. Ambroise, M. Farha, Microwave processing of fibre reinforced cement  
542 composites. In: *Proceedings of the 4<sup>th</sup> RILEM international symposium on fibre*  
543 *reinforced cement and concrete*. Sheffield 1992. p. 61-9.

- 544 [14] C.K.Y. Leung, T. Pheeraphan, Determination of optimal process for microwave curing  
545 of concrete. *Cem Concr Res* 1997; 27: 463-472, [http://dx.doi.org/10.1016/S0008-](http://dx.doi.org/10.1016/S0008-8846(97)00015-X)  
546 8846(97)00015-X.
- 547 [15] M.G. Lee, Preliminary study for strength and freeze-thaw durability of microwave and  
548 steam-cured concrete. *J Mat Civ Eng* 2007; 11: 972-6,  
549 [http://dx.doi.org/10.1061/\(ASCE\)0899-1561\(2007\)19:11\(972\)](http://dx.doi.org/10.1061/(ASCE)0899-1561(2007)19:11(972)).
- 550 [16] N. Makul, D.K. Agrawal, Influence of microwave-accelerated curing procedures on the  
551 microstructure and strength characteristics of Type I-Portland cement pastes. *J Ceram*  
552 *Process Res* 2011; 12: 376-381.
- 553 [17] D. Sohn, D.L. Johnson, Microwave curing effects on the 28-day strength of  
554 cementitious materials. *Cem Concr Res* 1999; 29: 241-7,  
555 [http://dx.doi.org/10.1016/S0008-8846\(98\)00189-6](http://dx.doi.org/10.1016/S0008-8846(98)00189-6).
- 556 [18] BS EN 197-1, Cement-Part 1: Composition, specifications and conformity criteria for  
557 common cements. London (UK): British Standards Institution; 2011.
- 558 [19] ASTM F1317, Standard test method for calibration of microwave ovens. West  
559 Conshohocken, PA, (USA): ASTM International; 1998.
- 560 [20] BS EN 60705, Household microwave ovens. Methods for measuring performance.  
561 London (UK): British Standards Institution; 2012.
- 562 [21] Y. Shamis, A. Taube, N. Mitik-Dineva, R. Croft, R.J. Crawford, E.P. Ivanova, Specific  
563 electromagnetic effects of microwave radiation on escherichia coli. *Appl Environ*  
564 *Microbiol* 2011; 77(9): 3017-3023, <http://dx.doi.org/10.1128/AEM.01899-10>.
- 565 [22] P.S. Mangat, K. Grigoriadis, S. Abubakri, A. Javaid, C. Zhao. Microwave system for  
566 in-situ curing of concrete repair. In: Proceedings of the 6<sup>th</sup> international conference on  
567 concrete repair. Thessaloniki 2016.

- 568 [23] P.S. Mangat, K. Grigoriadis, S. Abubakri. Temperature development in microwave  
569 cured repair materials. In: Proceedings of the 6<sup>th</sup> international conference on concrete  
570 repair. Thessaloniki 2016.
- 571 [24] C.P. Theo, K.C.G. Ong, C.H. Shum, S.T. Tan, Accelerated heating of precast  
572 ferrocement secondary roofing slabs using microwave energy. In: Proceedings of the  
573 27<sup>th</sup> conference on our world in concrete & structures. Singapore: Singapore Concrete  
574 Institute 2002. p. 589-596.