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Temperature development in microwave cured repair materials

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ABSTRACT: This paper is part of the FP7 MCure project on the development and demonstration of an energy efficient system for accelerated curing during repair of concrete structures. It provides laboratory results on temperature development in microwave cured specimens of six commercial repair materials and a CEM II mortar. Specimens were cast in 100 mm polystyrene moulds and exposed to 60 Watts microwave power to reach approximately 40 °C recommended temperature for microwave curing. Temperature development of specimens was monitored for 24 hours after mixing. The results show that microwave curing triggers the peak heat of hydration and brings it forward for all repair materials. In addition, internal temperatures of specimens are higher than the top surface temperatures and the difference increases with increasing temperature. These laboratory based results are backed by the currently confidential data obtained from pre-industry prototype tests which are being used to upgrade the technology to industrial scale.

1 INTRODUCTION

A high rate of compressive strength development of cement based repair materials is often greatly desirable, and can be achieved by higher temperature curing. For instance, high early strength development, makes early removal of formwork possible and accelerates the construction process. Accelerated curing of concrete repair to runways or pavements is another advantage, which prevents traffic disturbance. The Specifications for the Reinstatement of Openings in Highways (RAUC(S) 2015), Manual of Contract Documents for Highway Works (Highways England 2006) and the Design Manual for Roads and Bridges (Highways England 2015) define a compressive strength of 25 N/mm² for roads to be reopened and traffic reinstated.

Concrete repair in cold weather is another case where accelerated curing is important to prevent frost attack. If concrete is exposed to the freezing temperature before developing sufficient strength, it suffers a significant loss of performance (Neville 2011). Yi et al. (2014) showed that concrete exposed to 6 hours freezing temperature during the first 12 hours, suffered over 20% reduction in its 28 day strength. The strength reduction exceeds 50%, if exposed to 12 hours freezing temperature. According to ACI306R-10 (ACI 2010) a minimum strength of 3.5 MPa is required for fresh concrete to prevent frost damage. However, according to Koh et al. (2013) even 5 MPa is not adequate to resist the

combination of chloride ion penetration and freeze thaw cycles.

In general, 24 hours or more are required for OPC based repair materials to develop sufficient compressive strength under normal ambient temperatures. In some cases, several days are required before safely handling the repair and removing formwork. However, sometimes in order to meet tight construction schedules in cold weather, it is necessary to place concrete in frosty conditions. Developing a technology that can accelerate curing of concrete repair in cold weather is highly desirable.

Curing is the process for promoting the hydration of cement that leads to the development of strength. The curing process affects the strength and durability of concrete in the short and long terms (Bentz & Stutzman 2006). Curing temperature is an important factor in the hydration, microstructure formation and bulk properties of Portland and blended cements. The chemical reaction of hydration is promoted by elevated temperatures and high early strength is achieved (Neville 2011). A high temperature of fresh concrete reduces the length of the dormant period of cement hydration. Conventional heating techniques, such as steam curing, apply heat from the exterior to the interior of concrete through conduction. The result is non-uniform heating and a long heating period - up to 24 hours to attain the required temperature and strength. In general, curing mortar and concrete at high temperature during placing and setting, increases the early strength but it

may adversely affect the long-term strength (Neville 2011). However, controlled rise in curing temperature can speed up hydration and result in high early strength of concrete without causing any ill effect on later strength. Microwave curing is one of the recent methods for accelerated development of early age strength of concrete. There are experimental investigations of microwave curing of cement-based mortars using different w/c ratios (Wu et al. 1987, Hutchison et al. 1991, Leung & Pheeraphan 1995, Leung & Pheeraphan 1997, Sohn & Johnson 1999, Lee 2007, Rattanadecho et al. 2008, Makul & Agrawal 2011, Mangat et al. 2015) which confirm the possibility of its practical application. Microwave curing applies heat to the concrete by dissipation of internal energy due to the excitation of water molecular dipoles when exposed to an electromagnetic field (Leung & Pheeraphan 1995).

2 EXPERIMENTAL STUDY

2.1 Materials and mix proportions

The following six commercial repair materials and a CEM II mortar were used for this investigation.

- Repair Material 1: A polymer-modified cement, fibre-reinforced, shrinkage-compensated mortar. Plastic density of mix is 1730 kg/m^3 (Monomix).
- Repair Material 2: A polymer-modified cement, fibre-reinforced, rapid-setting mortar. Plastic density of mix is 2140 kg/m^3 (Fast-fill).
- Repair Material 3: A polymer-modified cement, fibre-reinforced, shrinkage-compensated mortar. Plastic density of mix is 2280 kg/m^3 (Monopour PC6).
- Repair Material 4: A rapid hardening cement with pulverised fuel ash, shrinkage-compensated concrete. Plastic density of mix is 2260 kg/m^3 (Five Star).
- Repair Material 5: A polymer modified cement, fibre-reinforced mortar with plastic density of 1500 kg/m^3 (HB40).
- Repair Material 6: A polymer-modified, low resistivity, highway agency class M patching mortar and render for cathodic protection. Plastic density of mix is 2200 kg/m^3 (Weber Mortar).
- Repair Material 7: A mortar with CEM II/A-L 32.5 N cement conforming to BS EN 197-1 (BSI 2011), coarse sharp sand (50% passing a $600 \mu\text{m}$ sieve) with a cement/sand ratio of 1:2, w/c ratio of 0.5, and plastic density of 2200 kg/m^3 .

The repair materials were mixed according to the manufacturer's recommendations. The water/powder ratio, (w/p), for each repair material mix is given in

Table 1 along with the 28 day strength given in the manufacturer's data sheet.

A commercial microwave (Logik Model L25MDM13) with maximum nominal output power of 900 watts (manufacturer's specification) was used. The microwave oven generated power at incremental levels of 10% up to 100% of its maximum output power. The microwave frequency was 2.45 GHz. The microwave was calibrated according to BS EN 60705 (BSI 2012) to determine the actual output power. For this experimental investigation, 10% of the actual output power was used (60 W).

2.2 Casting and curing

Two specimens were cast in 100 mm polystyrene cube moulds for each repair material (mix). A T-type thermocouple (with a welded tip) was located at the centre of each polystyrene mould by securing it to a wooden coffee stirrer stick as shown in Figure 1 (a). The tip of the thermocouple was located approximately 5 mm away from the stirrer stick. The specimens were cast in a laboratory environment ($20 \text{ }^\circ\text{C}$ and 60% RH) and cured in the laboratory without any cover.

Thirty minutes after commencing mixing, one cube specimen per mix was placed uncovered in the laboratory environment to cure for 24 hours. This is referred to as the normally cured specimen. The internal temperature of the cube was monitored using a Data Taker DT85G digital logger for 24 hours. The second cube specimen of each mix was exposed to 60 Watts of microwave energy 30 minutes after mixing. Microwave curing was applied until the centre of the cube top surface reached approximately 40 to $45 \text{ }^\circ\text{C}$ (target temperature) recommended by Mangat et al. (2015). The temperature of the top surface was recorded with a Flir i7 Thermal camera before the start of microwave curing, then every 10 minutes. The internal temperature was also measured from the T type thermocouple by using the Data Taker DT85G digital logger. The microwave oven was stopped and the specimen removed from the oven to record the thermocouple data since the data logger could not be placed in the oven. Subsequently, the specimen was moved back for further microwave heating. When the centre of the top surface of the cube reached the target temperature, it was removed from the microwave oven and placed without cover in the laboratory environment ($20 \text{ }^\circ\text{C}$, 60% RH) to cure for 24 hours. This represented the worst possible case of moisture loss during and for 24 hours after microwave curing. The moisture loss was monitored and will be published later. Figure 1 (b) shows the specimen inside the oven during microwave curing.

After the end of microwave curing, the internal temperatures of the specimens were recorded every

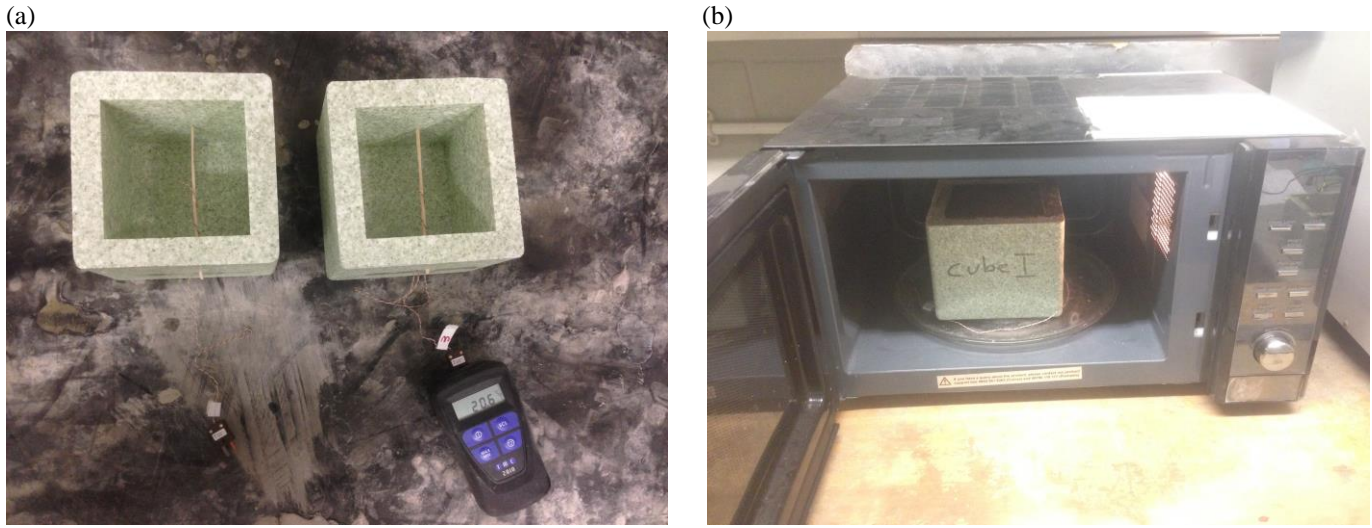


Figure 1 (a-b). (a) Polystyrene mould with support for T type thermocouple and (b) Specimen placed inside microwave oven.



Figure 2. Set up for monitoring internal temperature

Table 1. Details of repair materials.

Repair material	w/p ratio	28 Days strength (MPa)*
1	0.14	42
2	0.14	60
3	0.11	65-70
4	0.13	65
5	0.13	≥ 25
6	0.10	45
7	w/c=0.5	40

* 28 days strength according to the manufacturer's data sheet

30 seconds over 24 hours by using the data logger. These are referred to as microwave cured specimens. Figure 2 shows the experimental set up to monitor internal temperature of cubes during 24 hours after mixing.

Each repair material has a different capacity to absorb microwave energy (Mangat et al. 2015), therefore, different durations of microwave exposure were used to achieve the target temperature with a constant power of 60 W. The period of microwave

curing for each mix was estimated from previous research results (Mangat et al. 2015) and is given in Table 2 for each mix.

3 RESULTS

3.1 Temperature distribution at top surface

Figure 3 (a-g) shows the top surface temperature distribution for all repair materials at the end of microwave curing exposed to 60 Watts power for different time durations (Table 2). The temperature at the centre of top surface for repair materials reached 39.9 °C (Material 4) to 44.1 °C (Material 5) at the end of microwave curing. Temperature variation across the top surface observed in Figure 3 (a-g) is due to the non- uniformity of microwave heating. Figure 4 shows the temperature-time relationship for all tested repair materials. The temperature rises linearly with time for all repair materials (except Mate-

rial 2). Repair materials experience different rates of temperature rise which is related to their dielectric properties. Dielectric properties of repair materials depend on many parameters such as water/cement ratio (Kharkovsky et al. 2001), temperature, electric field inside microwave cavity and composition of

repair material such as admixtures, additives and the fineness of powders (Mangat et al. 2015).

Material 2 is a rapid hardening repair material which hardens after about 10 minutes of microwave curing and its time-temperature relationship becomes much steeper.

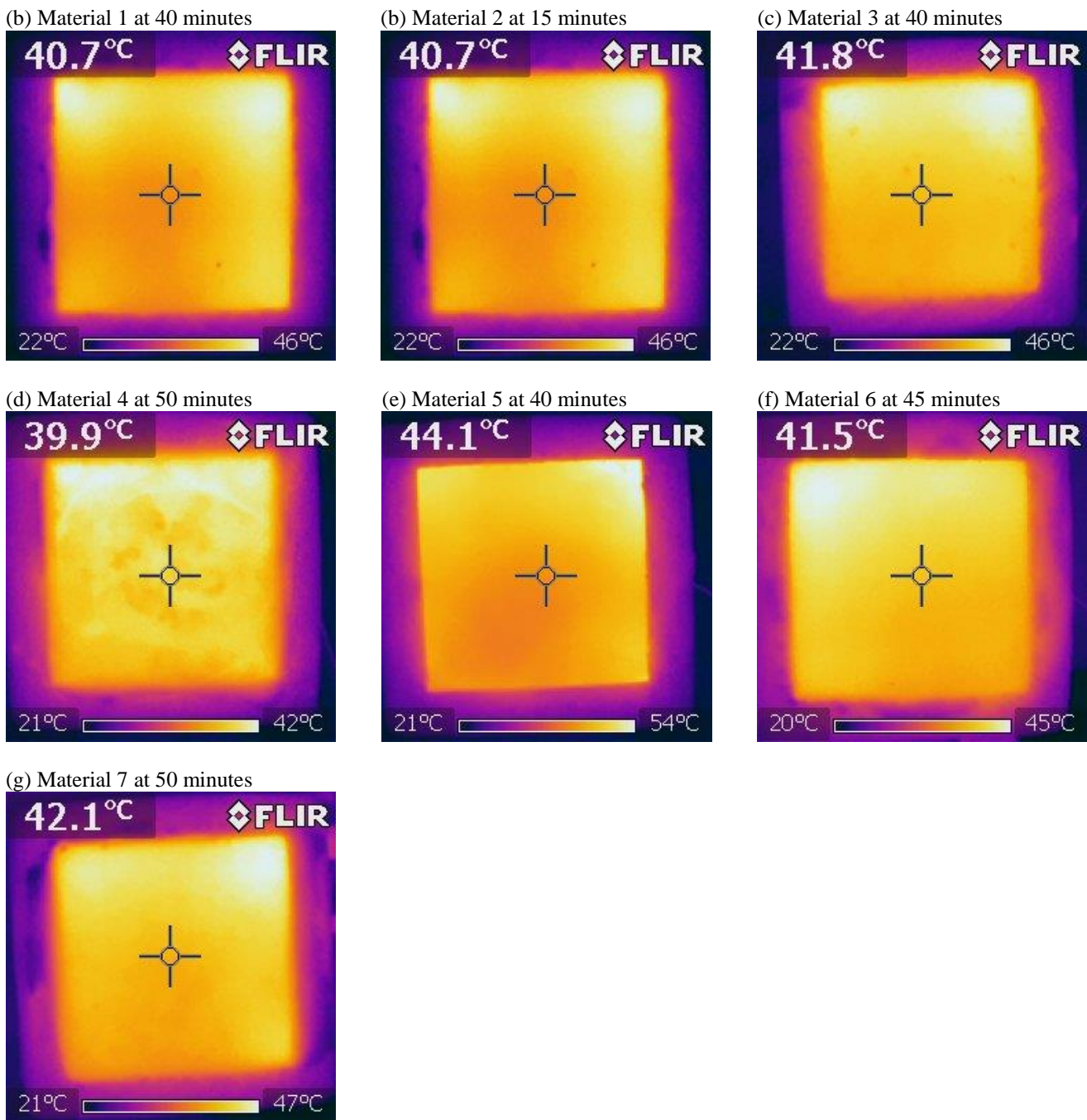


Figure 3 (a-g). Top surface temperature distribution of all repair materials exposed to 60 Watts of power at the end of microwave curing (Table 1)

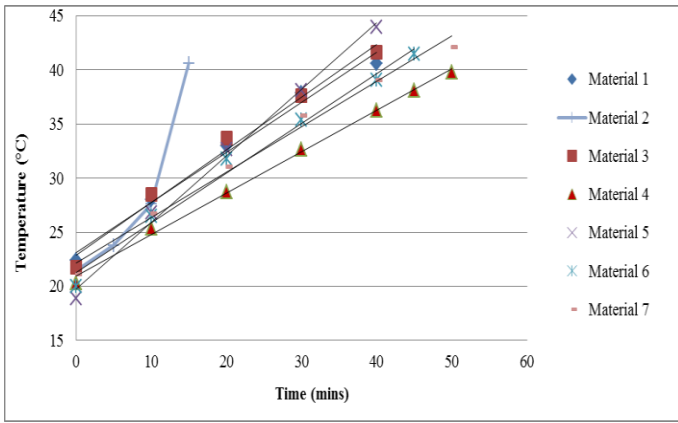


Figure 4. Temperature-time relationship of repair materials exposed to 60 Watts of microwave curing.

3.2 Development of internal temperature

Figure 5 presents the temperature-time relationship for Material 7 during 50 minutes of microwave curing. The thermal camera and thermocouple temperatures are plotted. The thermocouple temperature recorded in the normally cured cube, at 20 °C, 60% RH, is also plotted. The results show that internal temperatures (thermocouple) for all repair materials were higher than at the centre of the top surface (thermal camera). The differences between top surface and internal temperatures ranged from 5.7 °C (Material 2) to 23.7 °C (Material 5) for all repair materials at the end of microwave curing. These differences start getting bigger as the microwave curing temperature goes beyond about 35° C. The differences for all repair materials are given in Table 2. These differences can be due to the concentration of microwave energy at the centre of the microwave cavity (Kim et al. 2015) and also due to convective heat loss from the top surface of the specimen. In addition, evaporation of water from the exposed top surface may affect temperature.

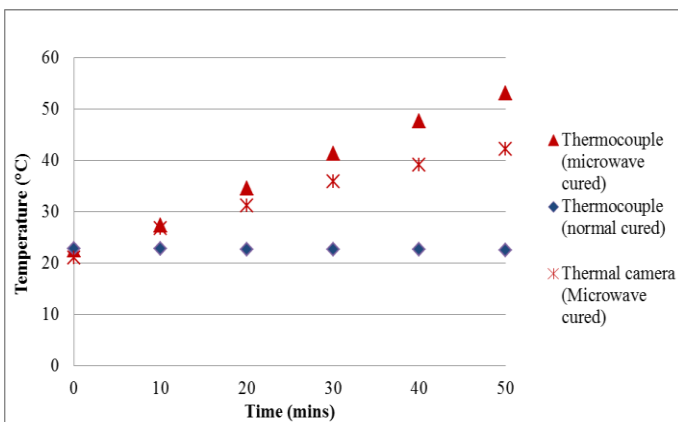


Figure 5. Temperature-time relationship for Material 7.

Table 2. Temperature at the end of microwave curing.

Repair Material	Microwave curing time (mins)	Temperature at the end of microwave curing (°C)		Temperature difference δT (°C)
		Thermal Camera	Thermo-couple	
1	40	40.7	59.8	19.1
2	15	40.7	46.4	5.7
3	40	41.8	51.8	10.0
4	50	39.9	57.5	17.6
5	40	44.1	67.8	23.7
6	45	41.5	51.5	10.0
7	50	42.1	53.0	10.9

3.3 Effect of microwave curing on peak heat of hydration

The temperature at the centre of microwave cured and control (normally cured) specimens was monitored for 24 hours after commencing mixing. Figures 6 to 12 show the temperature profiles at the centre of normally and microwave cured cube specimens for all repair materials. The maximum temperature occurred after the end of microwave heating within the limits of 4 minutes (Material 6) to 60 minutes (Material 1) for all materials (Table 3). Immediately after the end of microwave curing, the temperature continued to rise for a short period for all materials (Table 3) due to continuing hydration and redistribution of temperature. Variation in temperature distribution occurred during microwave curing, including hot spots, that concurred with previous findings from the food industry (Vadivambal & Jayas 2010) and also other research on cement based materials (Teo et al. 2002, Mangat et al. 2015, Mangat et al. 2016.). These variations became uniform soon after the end of microwave curing.

The temperature of microwave cured specimens started decreasing gradually after reaching the maximum values at the times given in Table 3. However, a peak of hydration temperature occurred on the falling temperature curve and can be clearly detected for Materials 3, 6 and 7 and less clearly for Material 4 (Figures 6 to 12). The peak of hydration temperature for Materials 1, 2 and 5, on the other hand, occurred before reaching the maximum temperature.

A comparison of the normally cured and microwave cured specimens for each repair material, in Figures 6 to 12, shows that the peak hydration temperature of microwave cured specimens was reached much sooner than the normally cured specimens. This is due to the acceleration of hydration with high temperature (Neville 2011). In some materials such as Material 2 and 5, the peak heat of hydration almost merged with the microwave curing period. For instance, the hydration temperature of the rapid setting Material 2 peaked at about 15 minutes after the end of microwave curing (30 minutes after microwave curing started) whereas for the normally cured

specimen of Material 2, the peak heat of hydration occurred at 35 minutes (Figure 7). Other materials, such as 3, 4, 6 and 7, reached their peak heat of hydration during the cooling down period after microwave curing. In each case, the normally cured specimens reached their peak hydration temperature later than the microwave cured specimens.

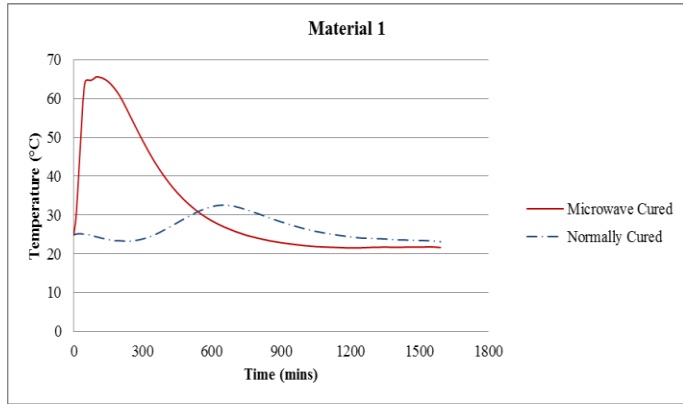


Figure 6. Internal temperature of microwave and normally cured samples for Material 1.

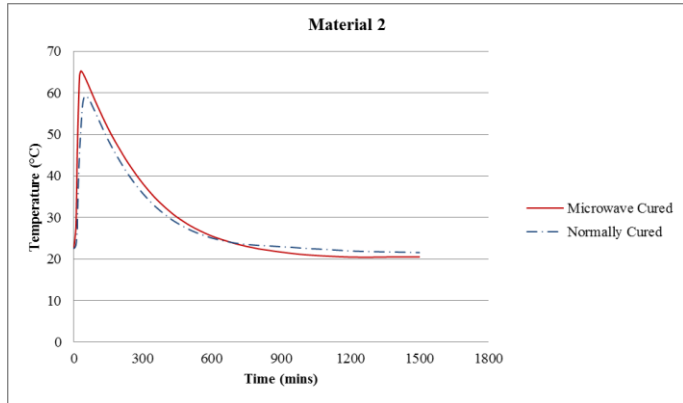


Figure 7. Internal temperature of microwave and normally cured samples for Material 2.

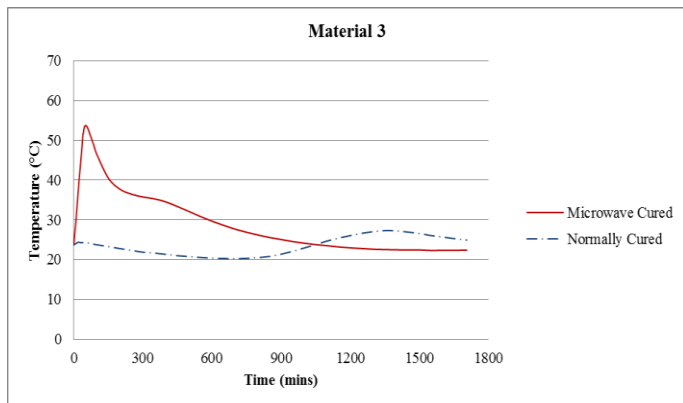


Figure 8. Internal temperature of microwave and normally cured samples for Material 3.

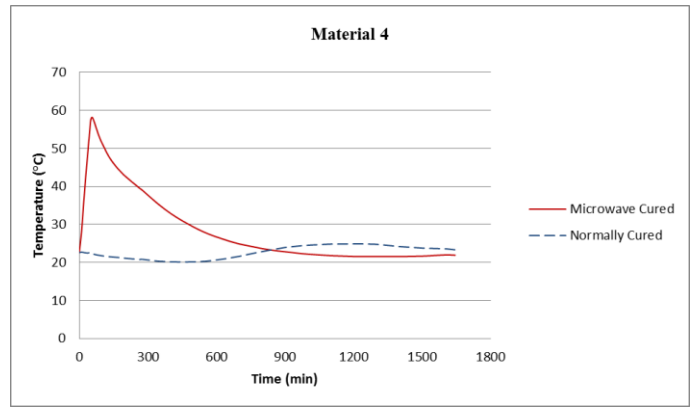


Figure 9. Internal temperature of microwave and normally cured samples for Material 4.

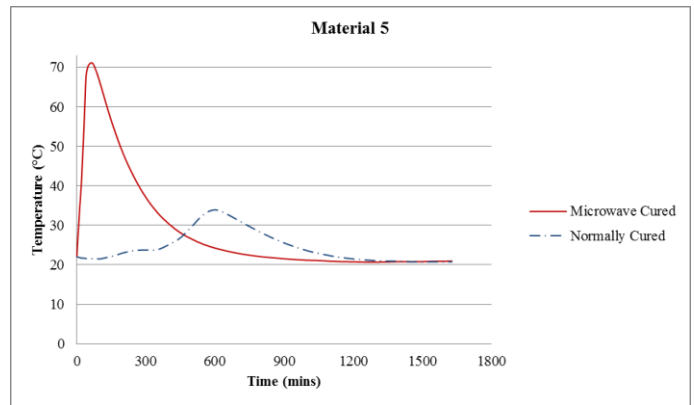


Figure 10. Internal temperature of microwave and normally cured samples for Material 5.

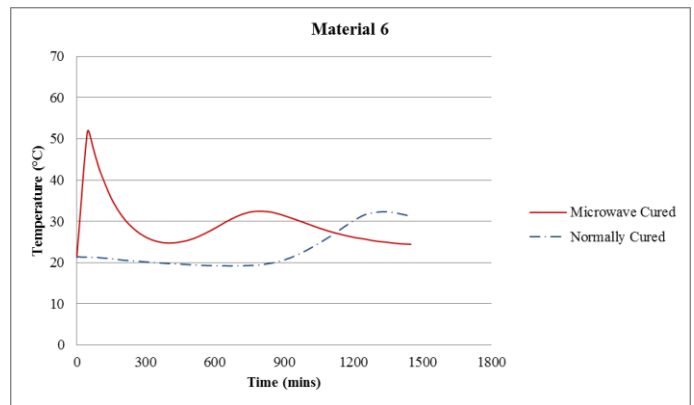


Figure 11. Internal temperature of microwave and normally cured samples for Material 6.

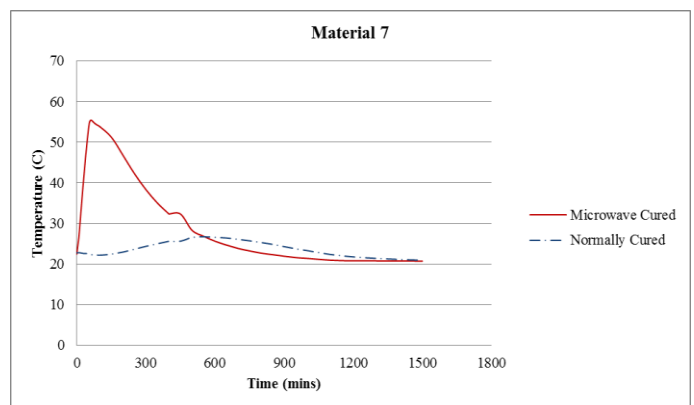


Figure 12. Internal temperature of microwave and normally cured samples for Material 7.

Table 3. Time and maximum temperature after microwave curing.

Repair material	Microwave curing time (mins)	Maximum temperature (°C)	Time* (mins)
1	40	65.5	60
2	15	65.3	15
3	40	53.8	10
4	50	58.2	5
5	40	71.1	20
6	45	52.1	4
7	50	55.4	10

*Time from the end of microwave curing.

4 CONCLUSIONS

The following conclusions are drawn from the results presented in the paper:

- The internal temperatures measured with the thermocouple and the surface temperatures monitored by the thermal camera during microwave curing are similar up to about 35°C. Subsequently, the difference between internal and surface temperature increases with increasing temperature.
- The surface temperature of the cube is not uniform. The non-uniformity increases with temperature.
- Different durations of microwave curing at constant power (60 W) are required for different repair materials to reach a common target temperature of curing.
- Microwave curing accelerates the heat of hydration reactions and brings forward the time to reach the peak hydration temperature.

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