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MICROWAVE CURING OF CONCRETE BRIDGE REPAIRS

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KEYWORDS

Concrete, Microwave curing, Patch repair

ABSTRACT

The paper introduces the FP7 MCure project on the "Development and demonstration of an energy efficient system for accelerated curing during repair and refurbishment of concrete structures". It provides test results on microwave curing of six commercial repair materials. The results provide the basic relationships between microwave energy input and curing characteristics of the repair materials by presenting data on the following aspects:

- Surface temperature profiles and hot spots.
- Interrelationships between temperature profiles, power input, volume and microwave curing time for different repair materials.
- Response of different repair materials to microwave power.
- Recommendations on optimum curing temperatures and curing time.

INTRODUCTION

Large numbers of reinforced and pre-stressed concrete structures such as buildings, bridges, tunnels, dams, harbours, and nuclear power stations are approaching or have approached a state where repair is necessary due to various concrete disintegration mechanisms, abnormal loading or poor workmanship. According to CONREPNET (CONREPNET, 2005) more than 50% of Europe's annual construction budget is spent on rehabilitation and refurbishment projects including the repair of deteriorated concrete structures. In United States the annual cost of repair, strengthening and protection of concrete structures is estimated to be between $18 and $21 billion (Emmons & Sordyl, 2006).

Patch repair is perhaps the most common type of concrete repair. It can be defined as the repair of relatively small areas in mainly large surface structural elements such as bridge and car park decks, bridge piers and shear walls in buildings. Detailed information on the various stages of a typical patch repair scheme is provided by (Emmons, 1992).

Proper curing of the installed repair material is of great importance in minimising restrained shrinkage (most common cause of patch repair failures) and ensuring the long-term durability of patch repairs. However, under typical curing conditions, it may take 24 hours or more for OPC based repair materials to fully set and it may take several days before sufficient compressive strength is developed to safely carry the applied loads in the case of a structural repair (Leung & Pheeraphan, 1995).

In many cases a higher rate of compressive strength development in OPC based repair materials is of great importance such as for frost attack prevention during cold weather concreting. A high rate of compressive strength development is also desirable when repairing localised damage in concrete bridges or runways, such as potholes, contaminated concrete, areas damaged by heavily corroded reinforcement or severely delaminated areas. Traffic should be severely restricted until the installed repair material has achieved sufficient compressive strength. A compressive strength of approximately 14 MPa should be achieved for a road to be re-opened (Parker & Shoemaker, 1988).

The rate of compressive strength development in OPC concrete can be increased by the application of thermal energy (Neville, 2011). Steam curing and autoclaving (steam at high pressure) are commonly used by precast concrete manufacturers. However, these methods require the use of expensive equipment and a relatively long exposure time and cannot be used on site. In addition, the increase in early age compressive strength is accompanied in most cases by a loss in later age compressive strength relative to conventionally cured concrete. This loss can be explained by the formation of non-uniform hydration products when the rate of hydration is high (Verbeck & Helmuth, 1969).

Microwave heating, which is based on dissipation of internal energy due to the excitation of molecular dipoles when exposed to an electromagnetic field, offers a significantly higher rate of temperature increase and more uniform heating when compared to the traditional heating methods (Leung & Pheeraphan, 1995). Hence, a much shorter exposure time (typically less than 60 minutes) is required to achieve high early age compressive strength (Wu et al, 1987).

Various studies (Wu et al, 1987); (Pera et al, 1992); (Leung & Pheeraphan, 1995); (Leung & Pheeraphan, 1997); (Sohn & Johnson, 1999); (Lee, 2007); (Makul et al, 2009); (Makul & Agrawal, 2011) of the effect of microwave curing on the early and later age strength of OPC mortars made with different w/c ratios have confirmed the ability of microwave curing to significantly increase early age strength.

The MCure project of the European Commission 7th Framework Programme, which is the basis of this paper, aims to provide a scientific framework for the microwave accelerated curing process of concrete repairs. It will define the primary characteristics of concrete repairs and deteriorated concrete substrates which influence microwave curing and derive relationships between the key parameters of concrete repairs and of microwave energy input. It will develop a prototype mobile microwave curing system for onsite use which is compatible with EC standards.

EXPERIMENTAL PROCEDURE

Materials and Equipment

Microwave curing experiments were carried out on the following commercial repair materials:

- A polymer-modified cement, fibre-reinforced, shrinkage-compensated mortar (Monomix).
- A polymer-modified cement, fibre-reinforced, shrinkage-compensated mortar (Monopour PC6).
- A polymer-modified cement, fibre-reinforced, rapid-setting mortar (Fastfill).
- A rapid hardening cement with pulverised fuel ash, shrinkage-compensated concrete (Five Star).
- A polymer-modified cement, fibre-reinforced mortar (HB40).
- A polymer-modified cement, rapid setting concrete (Pyrapatch).

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 according to ASTM F1317 (ASTM F1317, 98) and BS EN 60705 (BS EN 60705, 2012) to determine their actual power outputs which in the case of Logik Model L25MDM13 were found to differ significantly from the manufacturer's specification values. Unless otherwise mentioned, all values of microwave power given subsequently in the paper are the actual power values.

Details of Specimens, Mixing and Microwave Curing

Repair Material Specimens for Surface Temperature Monitoring

Three different volumes of specimens, 1, 3.38 and 4.38 litres were used for microwave curing. Specimens were cast in polystyrene cube moulds. Two different size moulds were used, 100 mm and 150 mm. The 1 litre volume was obtained from a single 100 mm mould, the 3.38 litre volume was provided by a single 150 mm mould. The 4.38 litre volume comprised of the combined 100 mm and 150 mm cube mould. A quantity of each repair material and water 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 at 60% Relative Humidity) 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 pre-determined levels of power (60, 120, 132, 180 and 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. Details of all repair material mixes are given in Table 1. The mix proportions recommended by the manufacturers of each repair material were used.

Table 1 Details of repair material mixes.

Test series	Repair material	Mix number	Microwave oven	Power (Watts)	Weight of water (kg)	Weight of powder (kg)	W/P ratio[(a)]	Volume of mix (lt)	Cube size (mm)	28 day strength[(b)] (MPa)
1	Monomix	1	Logik L25MDM13	60	0.21	1.52	0.14	1	100	42
		2		120						
		3		180						
	Fastfill	1		120	0.26	1.88	0.14			60
	Monopour PC6	1		60	0.23	2.05	0.11			65-70
		2		120						
		3		180						
	Five Star	1		60	0.26	2.00	0.13			65
		2		120						
		3		180						
	HB40	1		60	0.17	1.33	0.13			≥ 25
		2		120						
		3		180						
	Pyrapatch	1		60	0.20	2.00	0.10			60
		2		120						
2	Monomix	1	Sharp R-2370	132	0.72	5.12	0.14	3.38	150	42
		2		264						
	Monopour PC6	1		132	0.78	6.93	0.11			65-70
		2		264						
	Five Star	1		132	0.87	6.76	0.13			65
		2		264						
	HB40	1		132	0.59	4.51	0.13			≥25
		2		264						
3	Monomix	1	Sharp R-2370	132	0.93	6.64	0.14	4.38	100 + 150	42
		2		264						
	Monopour PC6	1		132	1.01	8.98	0.11			65-70
		2		264						
	Five Star	1		132	1.12	8.76	0.13			65
		2		264						
	HB40	1		132	0.76	5.84	0.13			≥25
		2		264						

(a) W/P-Water/Powder ratio; (b) Manufacturer's compressive strength data.

Repair Material Specimens for Investigating the Effect of Ambient (Initial) Temperature on Microwave Curing Temperature

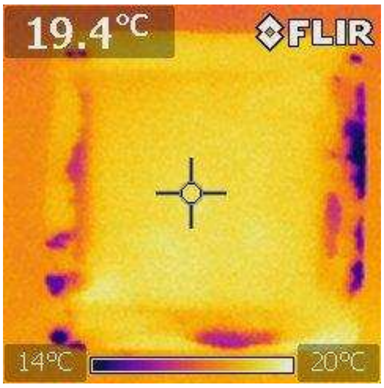
The effect of different ambient temperatures of the fresh mix of a repair material on the microwave curing temperatures developed with time was investigated. The investigation simulated the application of repairs in different in-situ conditions including cold weather. Repair materials Monopour PC6, HB40 and Monomix were tested using the Sharp R-2370 microwave oven at an actual output power of 132 Watts. The constituent materials of the three mixes from each repair material were conditioned and mixed at three different ambient temperature ranges: very low (1.7-6.5 ^{o}C), low (8.9-9.1 ^{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. Temperature measurements of 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.

RESULTS AND DISCUSSION

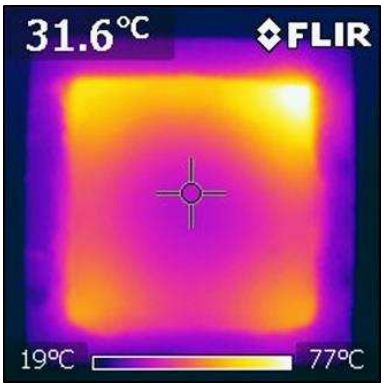
Temperature Distribution

Significant variations of top surface temperature during microwave curing across the top surface were observed on all specimens of Series 1, 2 and 3 experiments (1, 3.38 and 4.38 litres volume). In all cases hot zones appeared at the edges and corners of the polystyrene moulds shortly after commencement of microwave curing. Typical temperature distributions at 0, 10, 20, 30, 40 and 45 minutes across the top surface of a specimen (Five Star 100 mm cube subjected to 45 minutes of microwave curing at 180 Watts power) are shown in Fig. 1 (a-f). The dark square edges represent the walls of the polystyrene moulds. At

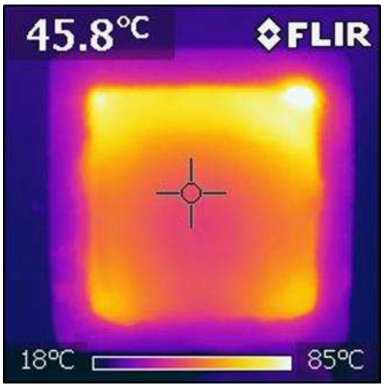
40 minutes of curing, for example, the middle surface temperature is 63.5 °C whereas it increases towards 100 °C on the outer surfaces of the cube specimen. The temperature profiles show a significant variation of temperature developed in the cured material. This indicates the unreliability of conclusions drawn by other researchers based on localised temperature monitoring (eg. by a single thermocouple embedded in a sample) and drawing firm relationships between temperature, time and strength development (Wu et al, 1987); (Pera et al, 1992); (Leung & Pheeraphan, 1995); (Leung & Pheeraphan, 1997); (Sohn & Johnson, 1999); (Lee, 2007); (Makul et al, 2009); (Makul & Agrawal, 2011).



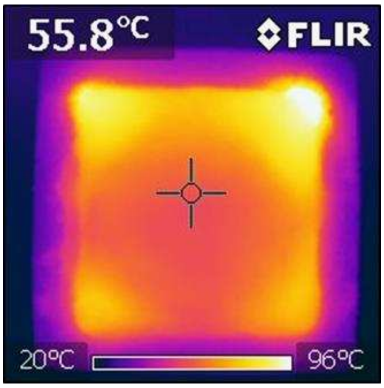
(a) At 0 minutes



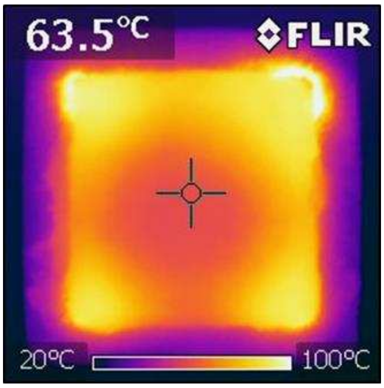
(b) At 10 minutes



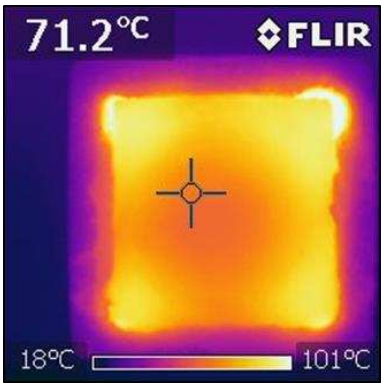
(c) At 20 minutes



(d) At 30 minutes



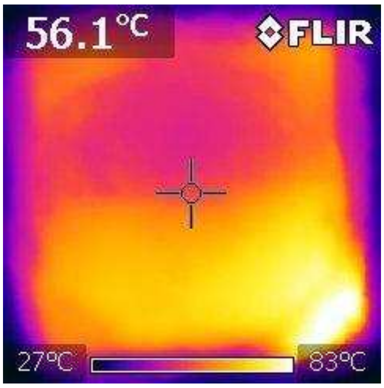
(e) At 40 minutes



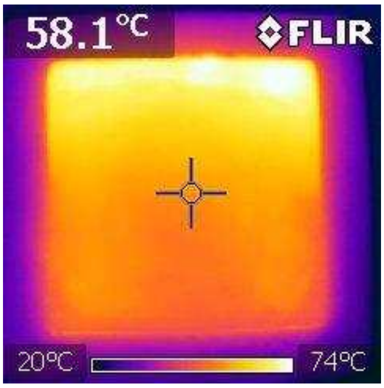
(f) At 45 minutes

Fig. 1 (a-f) Top surface temperature distribution of Five Star 100 mm cube subjected to 180 Watts power.

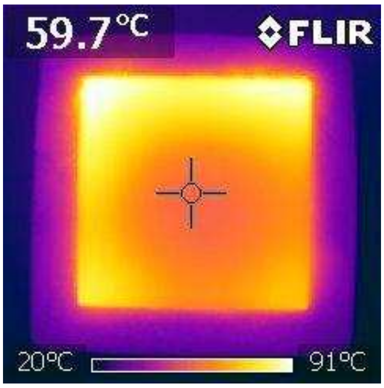
Significant variations of top surface temperature at the end of microwave curing were observed between different repair materials of the same volume exposed to the same power. Typical temperature distributions of all six repair material specimens at 45 minutes (1 litre volume subjected to 120 Watts power) are shown in Fig. 2 (a-f).



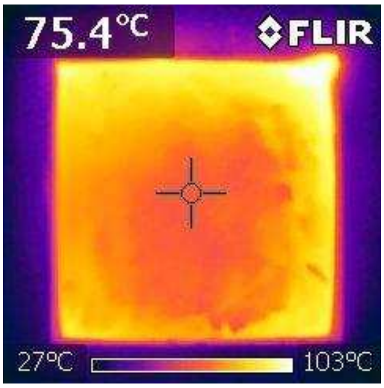
(a) Five Star



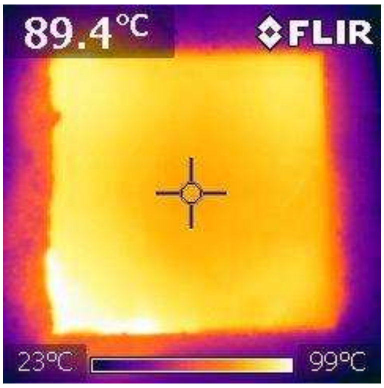
(b) Monopour PC6



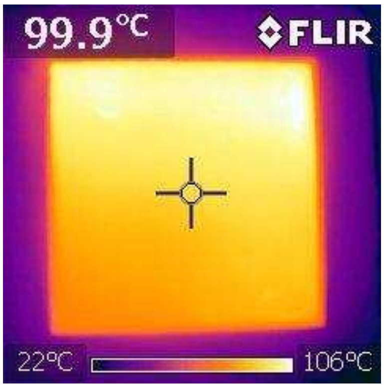
(c) Monomix



(d) HB40



(e) Fastfill



(f) Pyrapatch

Fig. 2 (a-f) Top surface temperature of the six repair materials (1 litre volume subjected to 120 Watts power) at 45 minutes of microwave curing.

Fastfill and Pyrapatch developed particularly high temperatures at the end of microwave curing. This is because both of them are rapid setting repair materials. The W/P ratio does not appear to be an important factor because there is no clear trend evident between temperature developed and W/P ratio of the mixes given in Table 1. For example Five Star and HB40, for the same W/P ratio (0.13), gave 56.1 and 75.4 ^{o}C temperature. On the other hand the types of admixtures and additives used in the repair mortars appear to affect the temperature. For example materials Five Star, Monopour PC6, Monomix and HB40 have very similar W/P ratios as shown in Table 1 but they contain different additives. As a result material HB40 developed a significantly higher temperature of 75.4 ^{o}C compared to the rest which range between 56.1 and 59.7 ^{o}C.

Temperature-Time Relationship

A strong linear increase of top surface temperature with microwave curing time (45 minutes duration) was observed for all tested repair materials, material volumes and power levels used. A typical temperature-time graph is represented by Fig. 3, for 1 litre volume Monomix repair material subjected to 3 microwave power levels (60, 120 and 180 Watts). A notable exception to the linear relationship was the fast setting repair material Fastfill. A non-linear (or discontinuous linear) temperature-time graph was obtained for this material as shown in Fig. 4 (volume 1 litre, power 120 Watts). Fastfill is a rapid hardening material and underwent a phase change from semi-fluid to hardened material during the microwave curing. This is represented by the two different linear relationships shown in Fig. 4. The curing temperatures attained are excessive (reaching 90 ^{o}C) which would not be desirable in practice. Materials with this kind of temperature-time microwave curing relationship would not be suitable for in-situ microwave curing. Microwave curing, therefore, will be suitable for normal, non-rapid hardening repair materials which are not cured to excessively high temperatures. The recommended limit is approximately 40-45 ^{o}C to take account of temperature variations produced in the material volume. The linear relationships of the type shown in Fig. 3 would be applicable to most practical in-situ microwave curing situations which will be within the recommended limit. The development and industrial application of microwave curing systems to be developed will be based on this type of relationship.

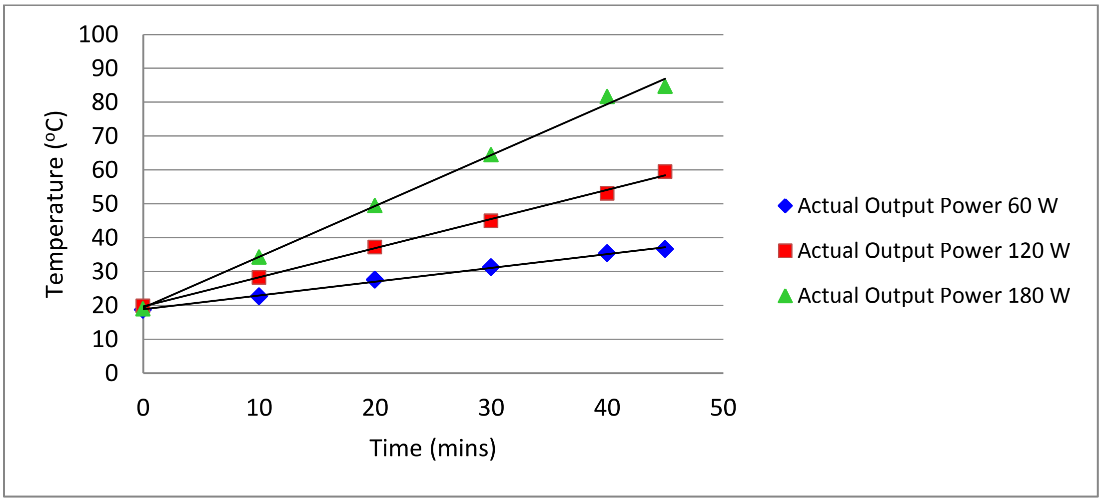


Fig. 3 Top surface middle point temperature-time relationship for Monomix (1 litre volume).

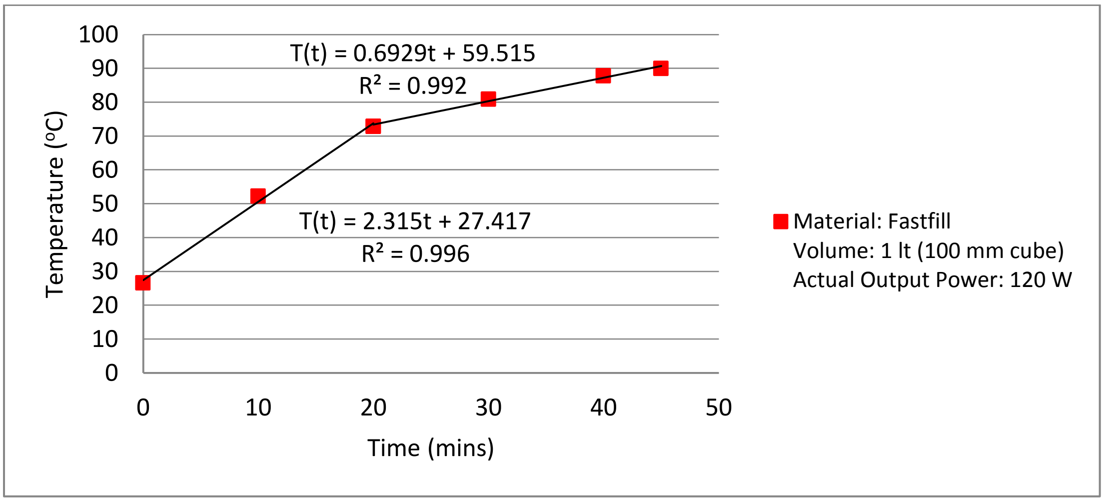


Fig. 4 Top surface middle point temperature-time relationship for Fastfill (1 litre volume) at 120 W.

Effect of Ambient Temperature on the Microwave Curing Temperature

A typical graph for repair material HB40 prepared at different ambient temperatures and subjected to 45 minutes of microwave curing is shown in Fig. 5. A summary of all results is given in Table 2.

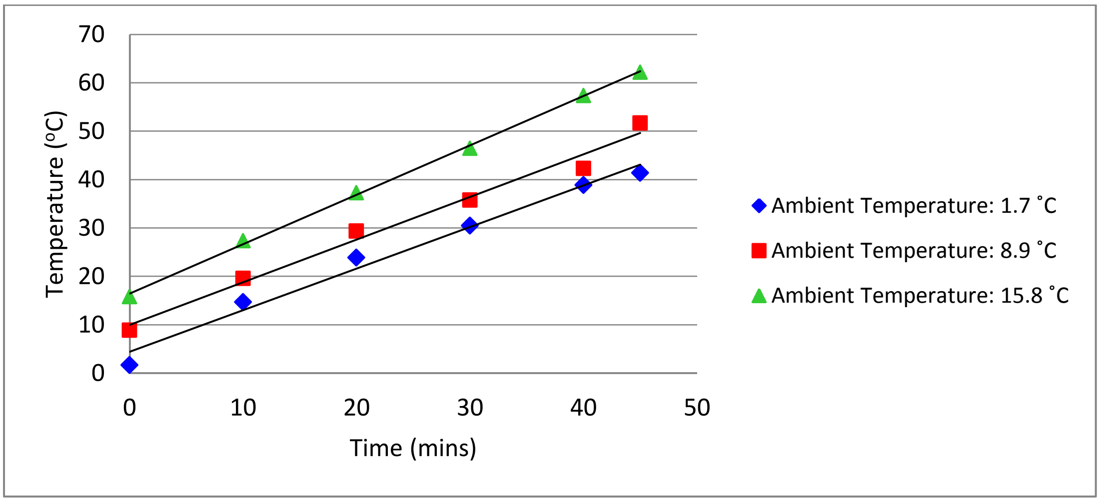


Fig. 5 Temperature-time profile of repair material HB40 prepared at 1.7 °C, 8.9 °C and 15.8 °C temperatures and microwave cured for 45 minutes.

Table 2 Summary of microwave curing temperatures developed at different ambient temperatures.

Repair material	Mix number	Power (Watts)	Volume of mix (lt)	Ambient temperature (°C)	Rate of temperature increase dT/dt (°C/min)	Maximum temperature[a] (°C)
Monopour PC6	1	132	3.38	6.5	0.694	39.9
	2			9.1	0.765	43.8
	3			18.3	0.581	45.0
HB40	1			1.7	0.860	41.4
	2			8.9	0.881	51.7
	3			15.8	1.020	62.2
Monomix	1			3.0	0.810	42.5
	2			10.0	0.773	47.2
	3			17.1	0.733	52.9

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

The above results clearly show that the top surface temperature of the cubes, at the end of 45 minutes microwave curing, is affected by the ambient (initial) temperature of the fresh mix. However, the rate of temperature increase with time appears to be similar.

CONCLUSIONS

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

- Microwave curing will be suitable for normal, non-rapid hardening repair materials which are not cured to excessively high temperatures. The recommended limit is approximately 40-45 °C to take account of temperature variations in the material volume. The temperature during microwave curing increases linearly with time and power input under these conditions.
- Considerable variation of temperature occurs on the surface of cubes. Some typical ranges are: 63.5 to 100 °C (power 180 Watts) for 1 litre, 46 to 76 °C (power 132 Watts) for 3.38 litres and 44.3 to 95 °C (power 264 Watts) for 4.38 litres volume of repair material. The hot areas are at the edges of the mould, sometimes showing melting of the polystyrene mould.
- The microwave curing temperature is affected by the initial temperature of the fresh mix.

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