Pore properties and moisture loss of repair mortars under low-impact microwave curing

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Abstract

Microwave curing (MC) can facilitate rapid concrete repair in cold climates without using conventional accelerated curing technologies which are environmentally unsustainable. Accelerated curing of concrete under MC can contribute to the decarbonization of the environment and provide economies in construction in several ways such as reducing construction time, energy efficiency, lower cement content, lower carbonation risk, and reducing emissions from equipment.

The paper investigates moisture loss and pore properties of six cement-based proprietary concrete repair materials subjected to MC. The impact of MC on these properties is critically important for its successful implementation in practice and current literature lacks this information.

Specimens were microwave cured for 40-45 minutes to surface temperatures between 39.9 and 44.1 °C. The fast-setting repair material was microwave cured for 15 minutes to 40.7 °C. MC causes a higher water loss which shows the importance of preventing drying during MC and the following 24 hours.

Portland cement-based normal density repair mortars, including materials incorporating fly ash and polymer latex, benefit from the thermal effect of MC on hydration, resulting in up to 24% reduction in porosity relative to normal curing. Low density and flowing repair materials suffer an increase in porosity up to 16% due to MC. The moisture loss at the end of microwave curing and after 24h is related to the mix water content and porosity respectively.

Keywords

Microwave curing, Concrete repair, Porosity, Water loss

Abbreviations

D	Diameter of pores (nm)
P	Applied pressure (Pa)
γ	Surface tension of mercury (N/m)
θ	Contact angle between mercury and concrete (°)
MC	Microwave curing
M_0	Mass of the cube at the start of microwave curing (g)
M_t	Mass of the cube at time t (g)
M_w	Mass of water present in the cube (g)
RH	Relative Humidity
Rh	Rapid hardening
Rs	Rapid setting
Pm	Polymer modified
Nd	Normal density
Ld	Low density

1. Introduction

The pore structure of cement-based repair materials is one of the most important parameters that affect their physical, mechanical and durability properties (Odlern and Rößler, 1985; Kumar and Bhattacharjee, 2003; Yudenfreund et al., 1972). Curing conditions, especially curing temperature and humidity, have an important effect on the pore size and pore distribution. Kjellsen et al. (Kjellsen et al., 1990) investigated the pore structure of plain cement pastes hydrated at three different temperatures of 5, 20 and 50 °C by carrying out mercury intrusion porosimetry (MIP) tests after 70% of hydration had taken place. MIP results showed an increase in porosity by increasing temperature. For example, whilst a cement paste cured at 5 °C showed porosity of 33.2% its porosity increased to 35.7% when cured at 50 °C. The pore size distribution curves of the two pastes were very similar except that the volume of pores of radius 20-100 nm increased with increasing temperature.

Goto and Roy (Goto and Roy, 1981) carried out an investigation to determine the porosity of pastes of Type I Cement with different w/c ratios by curing specimens in a $Ca(OH)_2$ saturated solution at 27 and 60 °C. Specimens cured at 60 °C showed a higher porosity by MIP. However, porosity measured by evaporated water (difference in weight of sample when saturated and dried) showed a reduction of porosity by curing at 60 °C (Goto and Roy, 1981). The reason for the difference with the two methods can be attributed to the MIP technique that did not measure pores larger than 7.5 μm in radius. Khatib and Mangat (Khatib and Mangat, 1999) reported increased porosity for specimens exposed to air at 45 °C for 14 days compared to specimens cured at 20 °C and 55% Relative Humidity (RH).

Ballester et al. (Ballester et al., 2009) investigated the effect of heat on microstructure and mechanical properties in fresh cement-based materials. Cement and mortar specimens were heat cured under Infrared Radiation (IR) to a temperature of 40, 60 and 80 °C within four hours. The results showed that porosity increased with curing temperature. Ballester et al. (Ballester et al., 2009) also showed that immersion of specimens in water for 5 minutes at 24, 48 and 72 hours after heat curing decreases their porosity compared to the air cured specimens. The properties of thermal cured cement-based materials also depend on the wet and dry curing conditions. It is essential that after application of thermal curing, water is supplied to the specimen to overcome the effects of early moisture loss (Mangat and Ojedokun, 2016).

Chemical composition of cementitious materials affects the mechanical properties of the concrete products cured at varying temperatures (Mansourkhaki et al., 2020; Mansourkhaki et al., 2019,). Cement replacement materials such as fly ash, slag, silica fume and admixtures are commonly used in concrete repair materials. Fall et al. (Fall et al., 2010) carried out an investigation on the pore structure of Portland cement with 7% slag cured for 160 days at 20 and 50 °C. Results showed a significant impact of curing temperature on the pore size distribution and porosity with higher temperature leading to a finer pore structure at w/c of 0.5.

Khatib and Mangat (Khatib and Mangat, 1999) also determined the effect of superplasticizers on reducing the porosity of blended concretes exposed to different temperatures.

Moisture loss and pore structure of cementitious materials affect the strength and durability of concrete. Most research on microwave curing (MC) of concrete has focused on the effect of MC temperatures on rapidly developing the high strength of concrete (Leung and Pheeraphan, 1997; Neelakantan et al., 2014; Mohd et al., 2016; Makul and Agrawal, 2011; Makul, 2019) without considering the interactions of MC temperature with the heat of hydration. The interactions between MC and early hydration temperatures can have significant consequences on the pore properties and long-term deterioration processes in concrete repair due to high temperatures reached in early age concrete (Mangat et al., 2021).

Research reported in this paper promises significant environmental impact. Microwave curing of cementitious materials is a technology that has the potential to reduce carbon emissions (Moreira et al., 2023) in the construction industry, which is a significant source of greenhouse gas emissions (Crawford, 2022). MC uses microwave energy to accelerate the early hydration and rapid curing of concrete, thereby reducing the time required by conventional curing methods (Leung and Pheeraphan, 1997). It is also environmentally more favourable than accelerated curing methods like steam or open flame heating used in current practice. Accelerated curing of concrete under MC can contribute to the decarbonization of the environment in several ways such as reducing construction time, energy efficiency, lower cement content, lower carbonation risk, and reducing emissions from construction equipment. For example, microwave curing requires less energy than traditional methods such as steam curing, which requires heating large quantities of water. It also can significantly reduce the time needed for concrete curing. This allows construction projects to be completed quicker and hence, reducing overall energy consumption and emissions associated with construction activities. Microwave curing also leads to improved early strength development in concrete which potentially allows the use of lower cement content. Cement production is a major source of carbon dioxide emissions in the construction industry (Rehan and Nehdi, 2005; Sousa et al., 2023), so a reduction in cement usage can help mitigate these emissions.

This paper is a part of a research project funded by the European Commission on microwave curing of patch repair and on the development of a prototype system for in-situ curing of concrete patch repairs (FP7 MCure project). The research is particularly relevant to concrete repair applications in cold conditions. Relationships between microwave curing parameters of power, temperature rise, curing time and repair volume have been derived (Mangat et al, 2016) together with bond of repair with the substrate and reinforcement (Grigoriadis et al., 2017; Mangat et al., 2017), in normal and cold weather conditions (Grigoriadis et al., 2017). These publications (Mangat et al., 2016; Grigoriadis et al., 2017; Mangat et al., 2017) also provide detailed results under microwave curing of the mechanical properties of the repair materials used in the current investigation. A prototype of a MC system has been developed and tested on small patch repairs and is being taken to the next stage of commercial development.

Despite considerable research on microwave curing of concrete which is referred to in this paper (e.g. Makul et al., 2014), there is little information available in literature on the effect of MC on water loss and pore properties of concrete. This knowledge is critical for successful application of MC in construction. The lack of knowledge is even greater with proprietary materials which are used in concrete repairs. These repair mortars are usually blended formulations of cementitious materials with additives and admixtures resulting in complex systems which require research into the effect of microwave curing.

2. Test programme

Experimental investigations were carried out to determine moisture loss and porosity of microwave cured repair materials. Different repair materials were cast in 100 mm polystyrene cube moulds and exposed to 60 W to reach 40-45 °C. The water loss during microwave heating and subsequently for up to 24 hours was determined. In addition, the porosity and pore structure of the specimens were investigated at 28 days of age for all repair materials by means of mercury intrusion porosimetry. Figure 1 shows the test program.

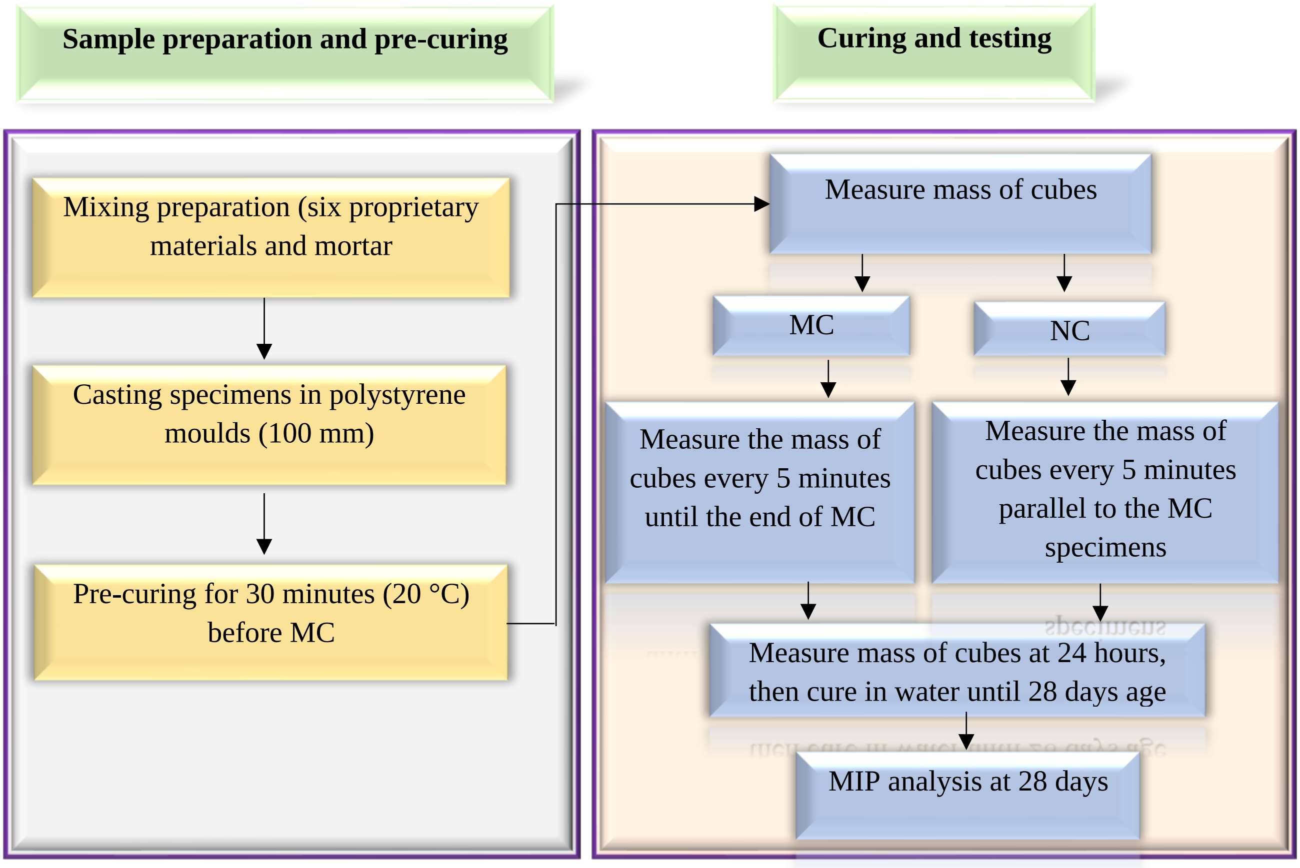


Figure 1: Test program

2.1 Repair materials

The following six proprietary (commercial) repair materials of different categories and a CEM II mortar were used for this investigation (Mangat et al., 2021):

Categories:

Material 1(Rh,Nd): A proprietary shrinkage-compensated, rapid hardening cement mortar with fly ash. Density of the fresh mix was 2200 kg/m^3

Material 2 (Pm, Ld): A proprietary polymer-modified cement mortar, fibre-reinforced and shrinkage-compensated. Density of the fresh mix was 1725 kg/m^3.

Material 3 (Pm, Nd): A polymer-modified cement based poured repair material, fibre-reinforced, shrinkage-compensated mortar. Density of fresh mix was 2250 kg/m^3.

Material 4 (Pm, Ld): A proprietary lightweight, low density, polymer modified cement mortar. Density of the fresh mix was 1500 kg/m^3.

Material 5 (Pm, Nd): A proprietary polymer-modified, low resistivity, National Highway's (formerly the Highway Agency, UK) Class M patching mortar and render for cathodic protection. Density of the fresh mix was 2200 kg/m^3.

Material 6 (Rs, Nd): A proprietary polymer-modified, fibre reinforced Portland cement based fast setting repair material. Density of fresh mix was 2150 kg/m^3.

Material 7 (CEM II Mortar, Nd): Portland limestone cement (CEM II/A-L32.5 N) (BS EN 197-1, 2011) and coarse sharp sand (50% passing a 600 μm sieve) were used in a ratio of 1:2. The mix was designed with a w/c ratio of 0.5 and a plastic density of 2200 kg/m^3.

The repair materials were mixed according to the manufacturer's recommendations. The chemical composition of the repair materials determined by XRF (PANalytical MegiX Pro X-Ray) and their properties can be found elsewhere (Mangat et al., 2021; Mangat et al., 2016).

2.2 Microwave curing regime.

A Logik Model L25MDM13 oven with a maximum output power of 600 W (900 W manufacturer's specification) was used for curing the 100 mm specimens. Microwave oven could be set to generate power at increments of 10% up to the maximum output power. The microwave frequency of the oven was 2.45 GHz. A 10% power level of 60W was used to microwave cure the cube specimens. The microwave oven was calibrated according to BS EN 60705 (BS EN 60705, 2012) and ASTM F1317 (ASTM F1317, 2012).

2.3 Preparation of cube specimens and curing

100 mm polystyrene cube moulds (20 mm wall thickness) were used to prepare two cube specimens for each repair material. The repair materials were mixed in proportions according to the manufacturers' recommendations. The cube specimens were cast, compacted by vibration, and then placed in the laboratory environment (approximately 20 °C and 60% RH) to cure within a period of 30 minutes from the start of mixing. One of the two cubes prepared for each repair material provided the control (normally cured) specimen which was cured in the ambient environment (20 °C, 60 % RH) for 24 hours from the start of mixing.

The second cube specimen of each repair material was exposed to microwave curing at a power of 60 Watts at 30 minutes from the start of mixing. Microwave energy was applied to the cube until the centre of its top surface reached a temperature of approximately 40-45 °C which was selected as the target temperature recommended by Mangat et al. (Mangat et al., 2015, Mangat et al., 2016). The top surface temperatures of the cubes were recorded with a Flir i7 thermal camera before the start of microwave curing and then every 10 minutes until the end of microwave curing. The cube was removed from the microwave oven upon reaching the target temperature and then placed in the laboratory environment along with the normally cured control specimen. The weight of each cube was also measured during the curing period at each increment of time when temperature was recorded. The cubes were also weighed at the end of 24 hours.

A different time period of microwave curing was required for each repair material to achieve the target temperature of 40-45 °C at a constant power of 60 W. This is due to the fact that each repair material has a different capacity to absorb microwave energy (Mangat et al., 2016). The absorption of microwave energy is related to the dielectric properties of each material, which depend on many parameters such as w/c ratio (Kharkovsky et al.,2014), temperature of the material, intensity of the electric field inside the microwave cavity and constituents of repair materials such as admixtures, additives and the fineness of powders (Abubakri, 2018).

2.4 Specimens for MIP investigation

The 100 mm cube specimens were demoulded at 24 hours and cured in water for 27 days. Specimens were removed from water at the age of 28 days and placed in an oven to dry at +105 °C for 3 days. Then they were removed from the oven and kept in the laboratory environment (20 °C) and wrapped airtight in a plastic sheet to cool off. The cubes were then crushed in a compression testing machine under a loading rate of 10 kN/s. Next, mortar samples with a mass of 1-2 g were collected near the centre of the crushed cubes, placed inside a plastic sample bag and kept airtight inside a desiccator until the MIP test was carried out.

A PASCAL 140/240 porosimeter was used to determine the effect of microwave curing on the porosity and pore size distribution. The instrument is controlled through hardware installed on it or it can be connected to a PC and controlled remotely. The diameter of pores was calculated according to the Washburn equation given below:

$$D = \frac{4\gamma cos\theta}{P} \qquad (1)$$

Where: γ is the surface tension of mercury (N.m^{-1}); θ is the contact angle between mercury and concrete; P is the applied pressure (Pa) and D is the diameter of pores (nm). The surface tension of mercury γ is 0.48 N.m^{-1} and the contact angle θ is assumed to be 140 °.

2.5 Determination of moisture loss

The water loss of the 100 mm cube specimens during 24 hours after the start of mixing was calculated by recording the mass loss of a specimen during the microwave curing period and after 24 hours. The mass of water added to the mix was recorded and the mass loss of specimens during microwave curing was assumed to be due to the evaporation of water. The water loss was calculated as follows:

$$\text{Water loss \%} = \frac{M_0 - M_t}{M_w} \times 100 \qquad (2)$$

Where: M_0 is the mass of the cube at the start of microwave curing (30 minutes after starting mixing); M_t is the mass of the cube at time t and M_w is the initial mass of water present in the cube (based on the w/c ratio).

3. Results and discussion

3.1 Effect of microwave curing on pore properties

3.1.1 Pore size distribution

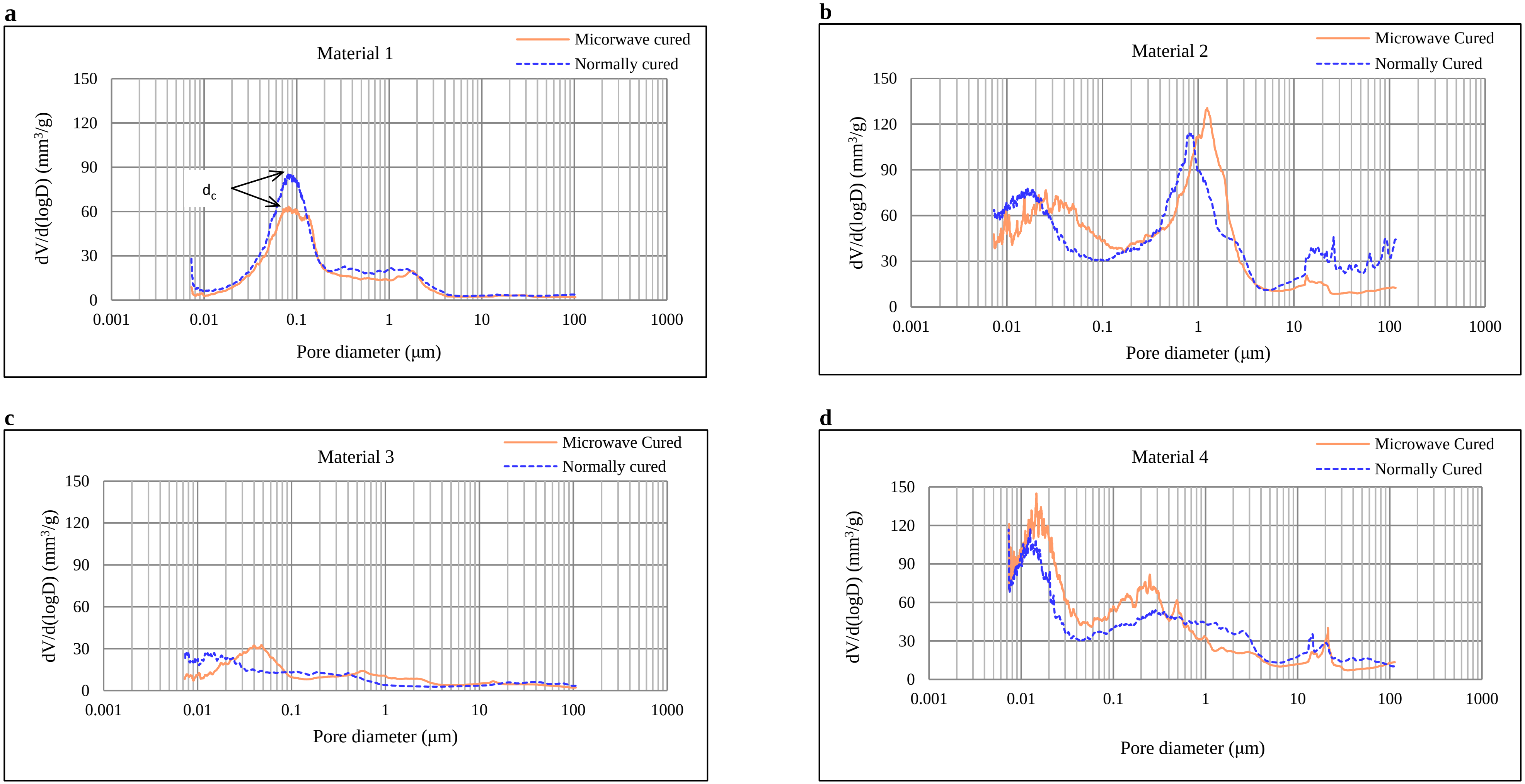
Figure 2(a-g) presents the differential pore volume distribution graphs for all repair materials, both under normal and microwave curing. These graphs are plotted to estimate the critical pore diameter d_c as shown in Figure 2a. Critical pore diameter corresponds to the peak of curves in the log differential intrusion volume vs. equivalent pore diameter (Cui and Cahyadi, 2001). It is generally accepted that the smaller the critical pore diameter, the finer the pore structure.

The shapes of the pore size distribution curves of both normal and microwave cured specimens of each repair material are similar with the obvious difference being a shift in the position of the critical pore diameter and the corresponding differential pore volume. For example, normally cured repair Material 1 (Rh, Nd) shows a critical pore diameter of 0.1 μm and the differential pore volume is 80.72 mm^3/g. The corresponding critical pore diameter under microwave curing is similar at 0.1 μm, however, the differential volume reduces to 61.6 mm^3/g indicating lower porosity. In the case of Material 3, both the critical pore diameter and differential volume have increased under microwave curing indicating greater porosity under MC. Material 3 is a normal density flowing repair material and it shows contrary behaviour to the other normal density materials.

Another significant observation is that the repair materials exhibit a multi-modal pore size distribution graph, except Material 7 (CEM II). Multi-modal graphs represent more than one peak of differential volume at different pore diameters (Abubakri et al., 2022). Both microwave and normal curing show a similar multi-modal pore size distribution graph, however, the peaks are at different pore diameters. Microwave curing shifts the peaks toward either smaller or larger pores. For example, normally cured Material 2 (Pm, Ld) shows two peaks at pore diameters 0.90 and 0.019 μm. The corresponding peaks under microwave curing are at 1.34 and 0.023 μm respectively.

Material 7 which is a CEM II mortar shows only one peak which is typical of Portland cement compositions. Kong et al. (Kong et al., 2016) reported the distribution of pore diameter for mortar with CEM I 42.5 under normal and microwave curing at 40 °C. Their results showed a single peak like Material 7 in Figure 2g. However, the peaks for both the normal and microwave cured specimens appeared at a smaller pore diameter than Material 7 presented in Figure 2g. This is because, they used CEM I with high compressive strength (42.5 MPa) compared to CEM II used in this study which has a lower compressive strength (32.5 MPa). The CEM II is a Portland limestone cement (6-20% high purity limestone content based on BS EN 197-1). The presence of limestone, up to 20%, increases porosity by 5-10% (Elgalhud et al., 2016).

The study of this section concludes that both normal and microwave curing result in a similar shape of pore size distribution curves for repair materials, with variations in the position and volume of critical pore diameters, indicating a shift in pore sizes. Additionally, multi-modal pore size distribution is observed in most proprietary repair materials (1, 2, 4, 5, and 6), with microwave curing affecting the peak pore diameters, and CEM II mortar (Material 7) showing a unique single-peak distribution characteristic of Portland cement compositions.


a
Material 1
Micorwave cured
Normally cured
dc
dV/d(logD) (mm3/g)
150
120
90
60
30
0
0.001
0.01
0.1
1
10
100
1000
Pore diameter (µm)
b
Material 2
Microwave Cured
Normally Cured
dV/d(logD) (mm3/g)
Pore diameter (µm)
c
Material 3
Microwave Cured
Normally cured
dV/d(logD) (mm3/g)
Pore diameter (µm)
d
Material 4
Microwave Cured
Normally Cured
dV/d(logD) (mm3/g)
Pore diameter (µm)

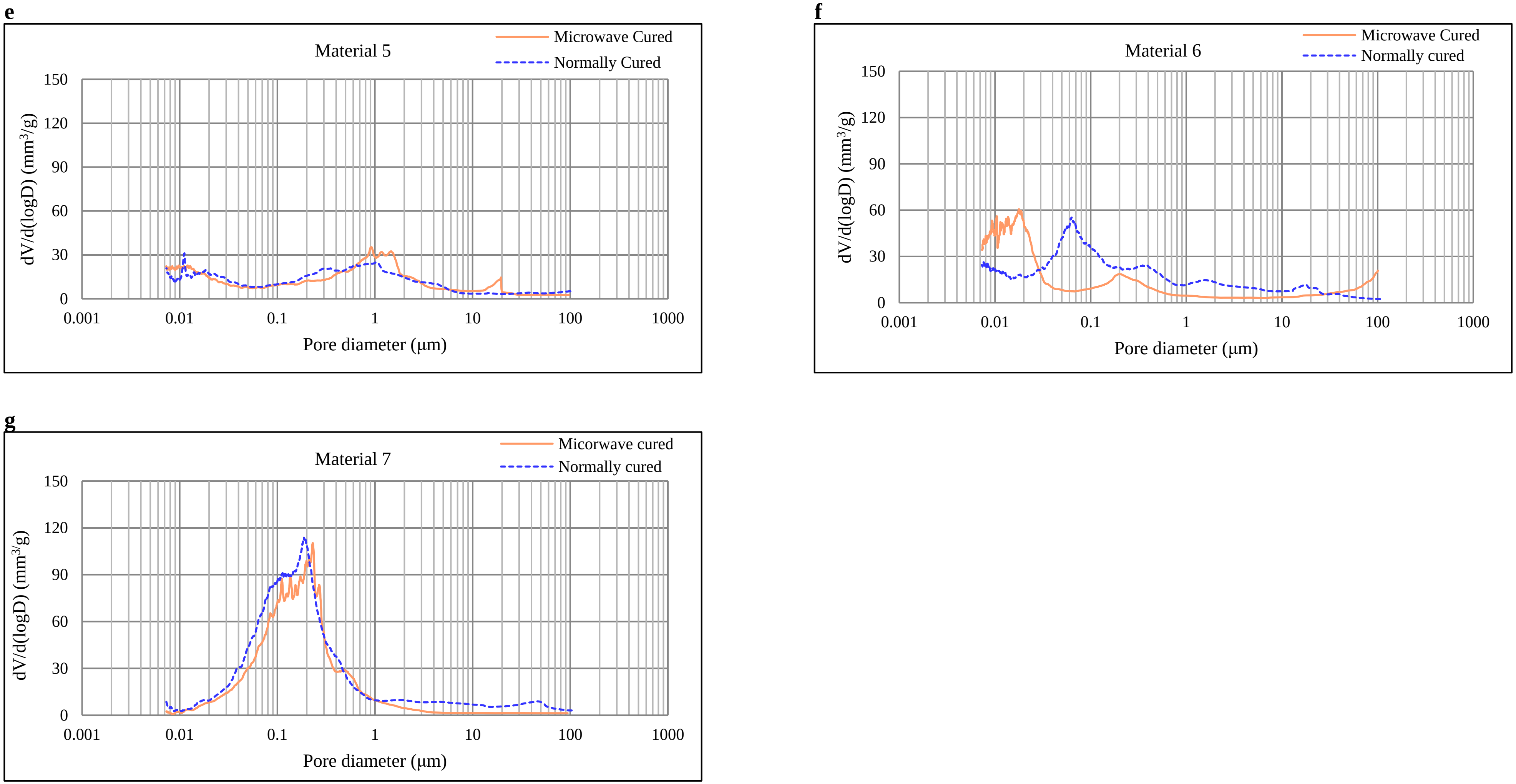


Figure 2. Pore distribution for normal and microwave cured materials

3.1.2 Effect of microwave curing on the volume of large and small pores:

Figure 3 presents the influence of microwave curing on the volume of large (capillary) and small (gel) pores for all repair materials. The data is obtained from the pore size distribution curves in Figure 2(a-g) or alternatively from the corresponding cumulative intrusion distribution curves, both of which are the output data of the MIP test. The total intruded pore volume for each repair material is provided in Figure 3 while differentiating the intruded volume of large pores (>50 nm) and small pores (<50 nm). In general, large pore sizes (>50 nm) which refer to the capillary pores are more influential in determining the strength and permeability of mortar and small pores (<50 nm) play an important role in the drying shrinkage and creep properties of concrete (Mehta and Monteiro, 2014).

The results show that microwave curing decreases the cumulative intruded pore volume of pore diameters larger than 50 nm for Materials 1, 4, 6 and 7. For example, normally cured Material 1 shows a differential pore volume of 65.4 mm^3/g of large pores (>50 nm) which decreases to 54.0 mm^3/g under microwave curing. In addition, microwave curing reduces the cumulative intruded volume of pore diameters smaller than 50 nm for Materials 1, 2, 3 and 7 and increases it for Materials 4, 5 (insignificantly) and 6.

Materials 2 and 4 are cementitious materials modified with polymer additive to provide low density which results in relatively high porosity (Table 1) and volume of both large and small pores compared to the other repair materials. Repair Materials 1, 6 and 7 are Portland cement based with normal density. However, both Materials 1 and 6 are rapid setting but contain fly ash and polymer latex respectively. Both additives provide lower porosity (Ramli and Tabassi, 2012; Ramli et al., 2013; Gingos and Sutan, 2011) to Materials 1 and 6 than Material 7 which is a standard Portland cement mortar without additives. Normal density Materials 3 and 5 which contain CEM I cement and polymer latex have the lowest porosity among all the repair materials due to the contribution of both CEM I cement and polymer (Ramli and Tabassi, 2012; Ramli et al., 2013) by filling micro-pores and voids.

The conclusion drawn from this study indicates that microwave curing tends to enhance the properties of certain repair materials by reducing the cumulative volume of large pores (>50 nm) pores in Materials 1, 4, 6 and 7, and altering the volume of small pores (<50 nm) in different materials. The effect is particularly notable in Portland cement-based materials with additives, such as Materials 1, and 6, which exhibit lower porosity and improved characteristics due to the impact of microwave curing on pore structure.

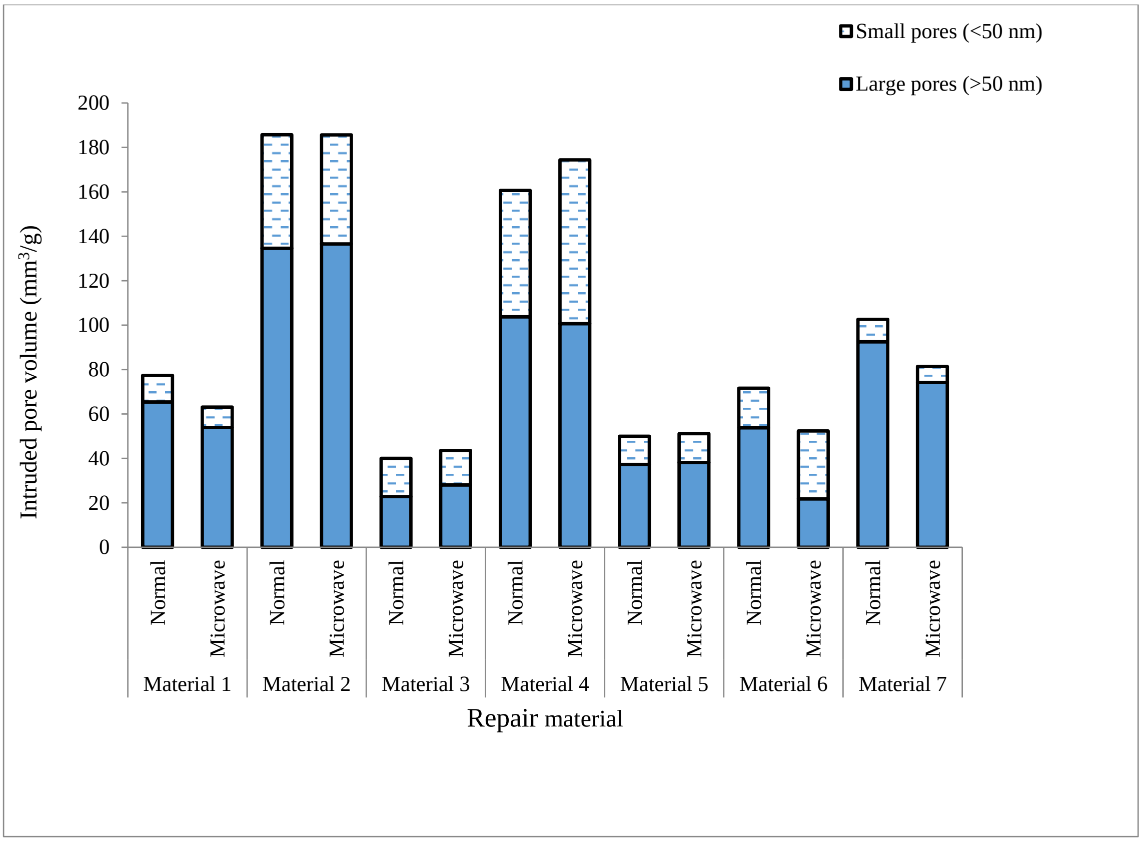


Figure 3. Influence of microwave curing on large (>50 nm) and small pores (<50 nm).

3.1.3 Effective Porosity

Table 1 shows the effective porosity (intruded mercury) for all repair materials (microwave and normally cured). The MIP test samples were collected close to the centroid of the cube specimens. Results show a significant difference in the porosity of the repair materials, which ranged from 8.3% (Normally cured Material 3) to 29.1% for the microwave cured repair Material 4. Repair Materials 2 and 4 represent the highest porosity, which corresponds to their low density (1725 and 1500 kg/m^3, respectively). They are polymer modified repair materials. Results presented by Calderón et al. (Calderón et al., 2013) showed that replacing sand by polymer waste particles in mortar by 0, 25, 50, 75 and 100% gives a fresh density of 2113, 1910, 1690, 1440 and 1200 kg/m^3, respectively, while increasing the porosity. Materials 3, 5 and 6 are also described as polymer modified but they have normal density of 2250, 2200 and 2150 kg/m^3, respectively, which is in the same range as Material 1 (2200 kg/m^3) and Material 7 (2200 kg/m^3).

The effect of microwave curing on porosity can be significant depending on the composition of each material. Based on the experimental results, the effect of microwave curing on effective porosity can be divided into three categories: Category I: repair materials in which microwave curing increases porosity. These include Materials 3 and 4 whose porosity increased by 16% and 9%, respectively, compared to their normally cured specimens. Category II: repair materials in which microwave curing resulted in a denser structure. Materials 1, 6 and 7 experienced a reduction in porosity by 18%, 24% and 19%, respectively, under microwave curing relative to normal curing. Category III: repair materials in which microwave curing has no significant effect on the effective porosity. It includes Materials 2 and 5, whose porosities are within 1% of the normally cured materials.

It is evident that microwave curing has different effects on the porosity of repair materials based on their binders. The reduction in porosity for repair materials in Category II (Material 1, 6 and 7) under microwave curing is possibly due to the well-documented phenomena of greater formation and growth of hydration products in the pore space due to thermal curing, resulting in reduced pore volume (Neville, 2011). The reduction of porosity in microwave cured Material 1, which contains pulverised fuel ash, is also in agreement with the results of other researchers (Khatib and Mangat, 2003; Alamri, 1988; Wu et al., 1987; Wang and Liu, 2011). For example, Alamri (Alamri, 1988) reported that specimens containing fly ash, cured at 20, 35 and 45 °C, showed a significantly lower effective porosity under 45 °C curing. Goto and Roy (Goto and Roy, 1981) also reported a decrease in porosity for pastes of Type I cement with water cement ratios of 0.35, 0.4 and 0.45 cured at 60 °C compared to 27 °C.

The similarity in porosity under normal and microwave curing for Materials 2 and 5 is due to the high temperature curing enhancing the hydration of their CEM I cement phase being balanced by the polymer admixtures used in these materials. Only Material 4 showed a significant increase in porosity under microwave curing due to its markedly low density (1500 kg/m^3) provided by its polymer constituent. The results in Figure 3 and Table 1 show that the very low-density Materials 2 and 4 have very high porosity relative to the other materials. All materials have a lower (or similar) porosity under microwave curing relative to normal curing, except the lowest density Material 4.

Table 1 Effect of microwave curing on effective porosity.

Repair material	Porosity (%)	
	Microwave Cured	Normally Cured
Material 1	13.6	16.6
Material 2 (low density)	29.0	28.6
Material 3	9.6	8.3
Material 4 (low density)	29.1	26.6
Material 5	11.4	11.4
Material 6 (rapid setting)	10.8	14.2
Material 7	17.0	20.9

3.2 Effect of microwave curing on water loss

3.2.1 Water loss during microwave curing

The temperature of repair material, environmental temperature, relative humidity and the velocity of air are primarily responsible for the loss of water in freshly applied concrete repairs. A higher loss of water is expected at a lower humidity, higher environmental and mix temperature (Al-Fadhala et al., 2001). In the case of microwave curing, the fresh repair material is subjected to microwave heating at an early stage when it is most vulnerable to moisture loss. An evaluation of moisture loss under unprotected conditions has been carried out in order to determine the need for preventative measures such as curing membranes or covers during microwave curing. The 100 mm cube specimens were kept in the polystyrene mould with the top surface uncovered during microwave curing and subsequently up to 24 hours of age at 20 °C, 60% RH to represent the worst case of water loss in practice. Water loss of each repair material was measured during microwave curing and at 24 hours after casting. The calculation of water loss is based on the mass of water added to the mix and the mass loss of specimens during and after microwave curing at regular intervals as described in Section 2.5.

Figure 4 shows a typical graph of water loss due to evaporation for the normally and microwave cured repair materials during the microwave curing period. Normally cured specimens show a linear increase of water loss with time ranging from 0.27% to 0.60%, at the end of the microwave curing period. The microwave cured specimens exhibit a non-linear increase in water loss with time reaching a maximum at the end of microwave curing. The water loss is several times higher under microwave curing. The rising temperature with increasing curing time caused the non-linear rise in the rate of water evaporation. Figure 5 shows the graph of water loss for the rapid setting Material 6 during 15 minutes of microwave curing.

Figure 6 shows the water loss at the end of the microwave curing period for the normally and microwave cured specimens of all repair materials. Water loss for normally cured specimens ranged between 0.27% to 0.60% and for microwave cured specimens it ranged between 2.08% to 3.04%, with an average of 2.5% (excluding rapid setting Material 6). Figure 7 shows that the water loss for microwave cured repair materials increases with increasing total water content of the mix. Material 6 experienced the lowest water loss both for microwave and normally cured specimens. It is a rapid setting material and could only be exposed to microwave energy for 15 minutes due to a rapid increase in temperature. Within the 30 minutes after commencing mixing and before the start of microwave curing, the free water in Material 6 was consumed by early hydration and, therefore, less free water was available to evaporate during microwave curing.

Figure 7 shows the relationship between mass of water loss (g) at the end of microwave curing and total mass of water used in a repair material mix. It is a linear relationship with corelation R^2 =0.70.

Results from this section show that microwave cured repair materials exhibit significantly higher water loss than normally cured specimens. This is due to increased temperatures during microwave curing. The moisture loss at the end of microwave curing is linearly related to the mass of water added to the mix.

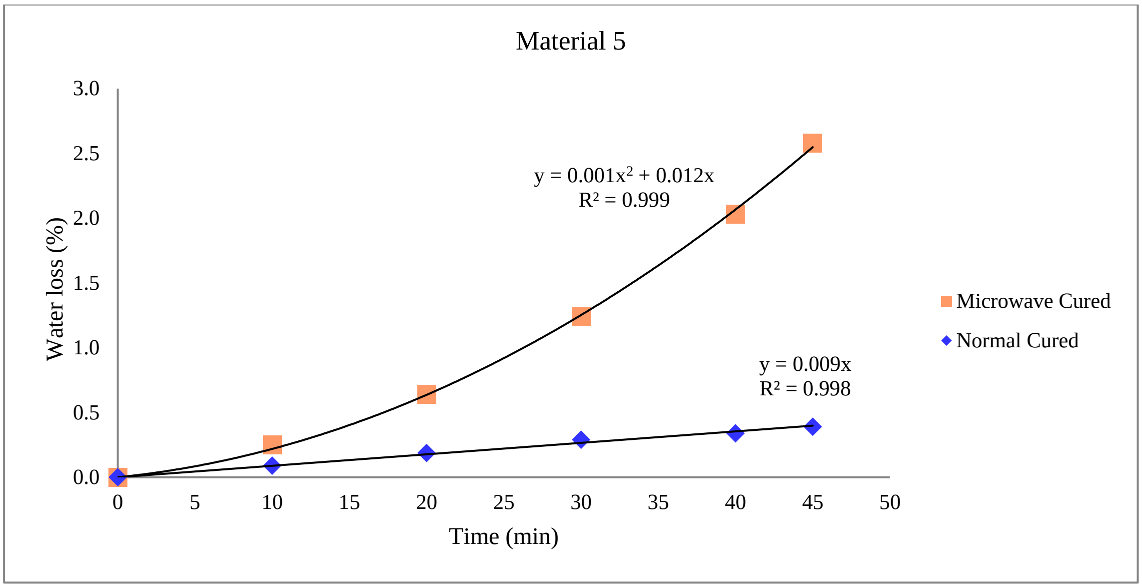


Figure 4. Water loss of normally and microwave cured repair Material 5 during 45 minutes of microwave curing time.

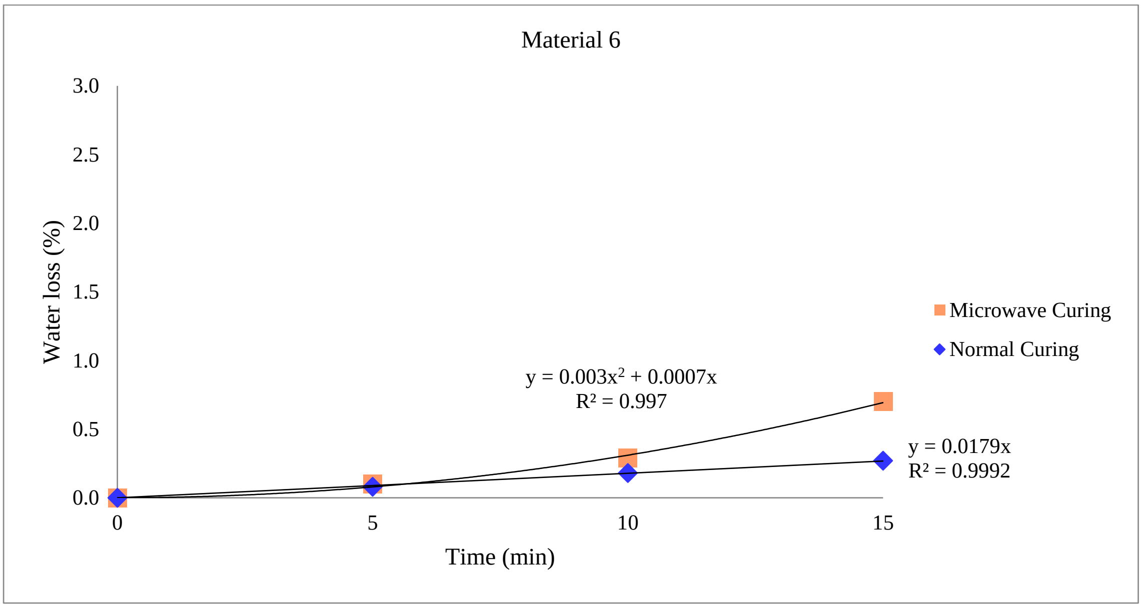


Figure 5. Water loss of normally and microwave cured repair Material 6 during 15 minutes of microwave curing period.

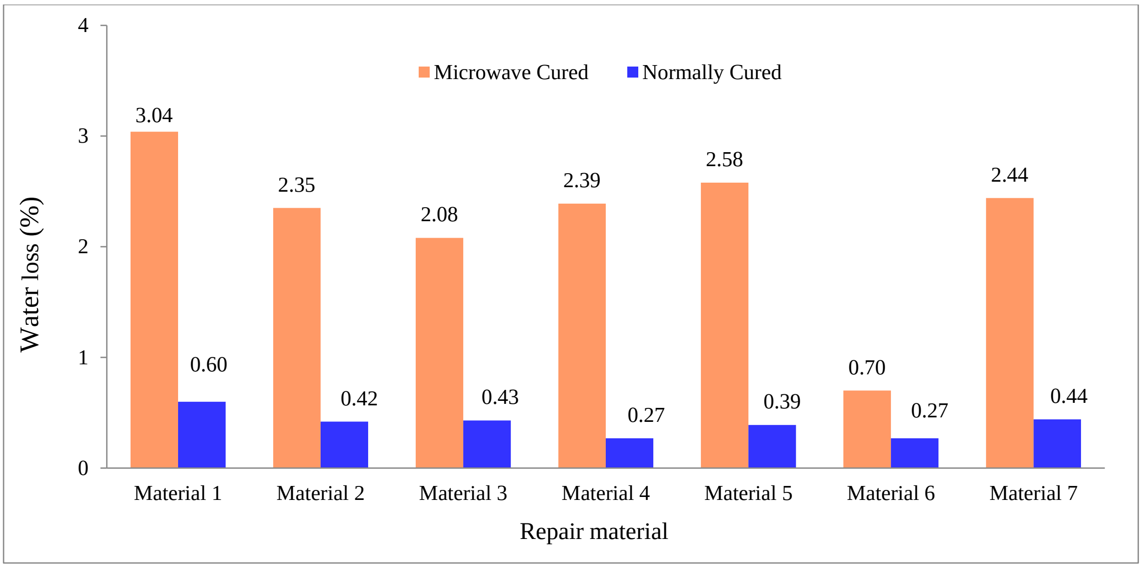


Figure 6. Water loss (% by mass of mix water) at the end of microwave curing period.

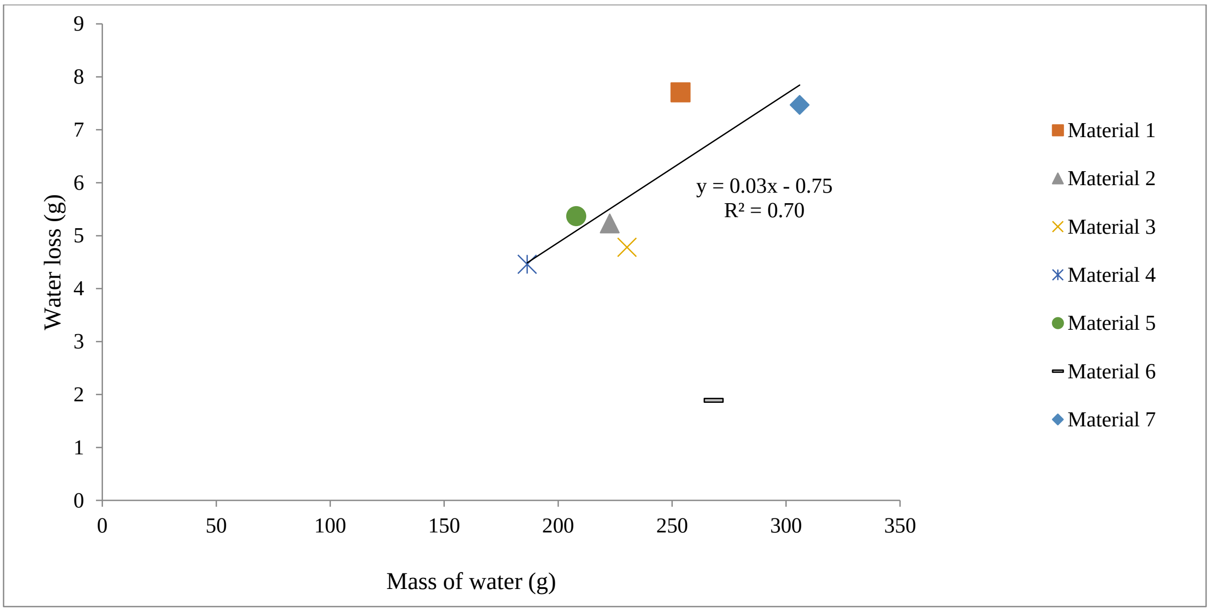


Figure 7. Relationship between water loss (g) at the end of microwave curing and total mass of water in a repair material mix (Material 6 is excluded from the trend).

3.2.2 Water loss after 24 hours

The graph in Figure 8 shows the water loss of normally and microwave cured cubes for all repair materials at 24 hours after commencing mixing. All specimens were stored in the laboratory air (20 °C, 60% RH) after the microwave curing period. The graph shows that microwave cured specimens experienced higher water loss for all repair materials. For example, normally cured Material 1 shows a water loss of 9.82% which increased to 16.65% under microwave curing, resulting in a 70% increase in water loss. Repair Materials 4 and 6 show an insignificant increase in water loss between normal and microwave curing compared to the other repair materials.

A comparison between Figure 6 and Figure 8 shows that water loss under normal and microwave curing is much higher after 24 hours than at the end of microwave curing. For example, Material 3 (poured repair material) shows a water loss of 0.43% and 2.08% under normal and microwave curing respectively at the end of microwave exposure time while the corresponding water loss increased to 9.47 and 12.03% for normal and microwave curing respectively at 24 hours. Microwave cured repair materials show a higher water loss than the normally cured ones due to their higher temperature both during microwave curing and afterwards during the peak hydration period (until reaching room temperature) (Mangat et al., 2021) whereas normally cured samples show a more modest temperature rise due to release of heat of hydration under laboratory temperature curing.

Figure 9 shows the relationship between porosity and water loss of the repair materials (low density and fast setting materials are excluded) at 24 h after casting. The linear equations provide a reasonable degree of correlation.

Results from this section show that after 24 hours, initial microwave curing results in greater moisture loss than initial normal curing of mortar and the proprietary repair materials except the very low-density Material 4 and the rapid setting Material 6. The moisture loss is linearly related to the mass of water added to the mix. Therefore, in practice the recommendation would be to protect the repair patches from moisture loss during microwave curing using suitable curing methods.

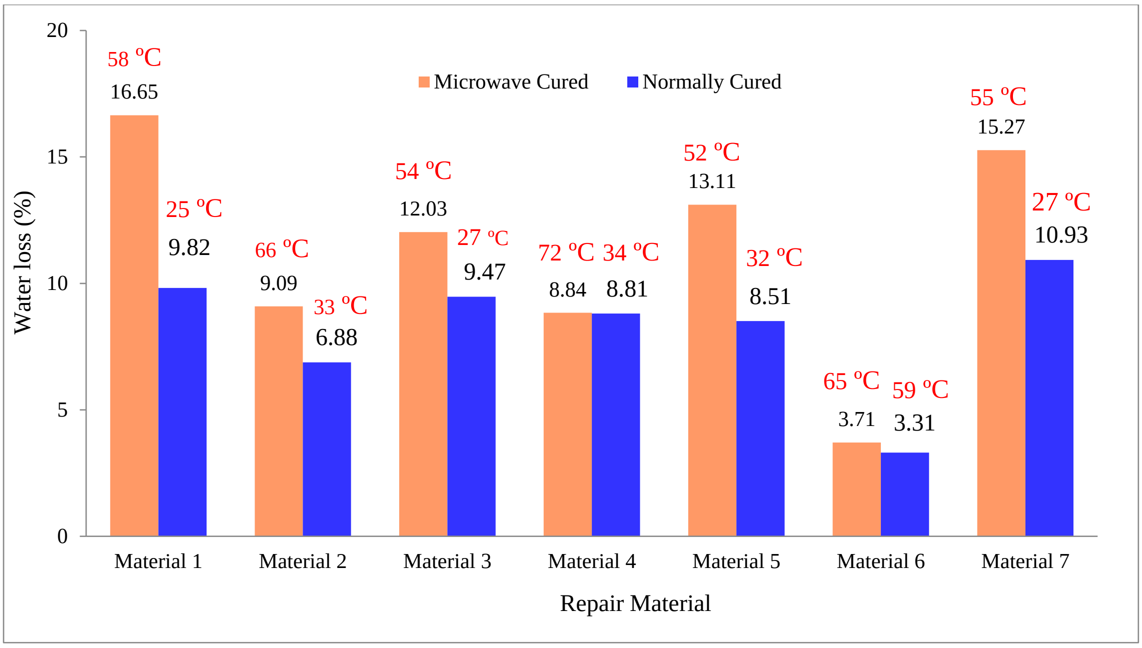


Figure 8. Water loss (% by mass of mix water) at 24 hours after casting.

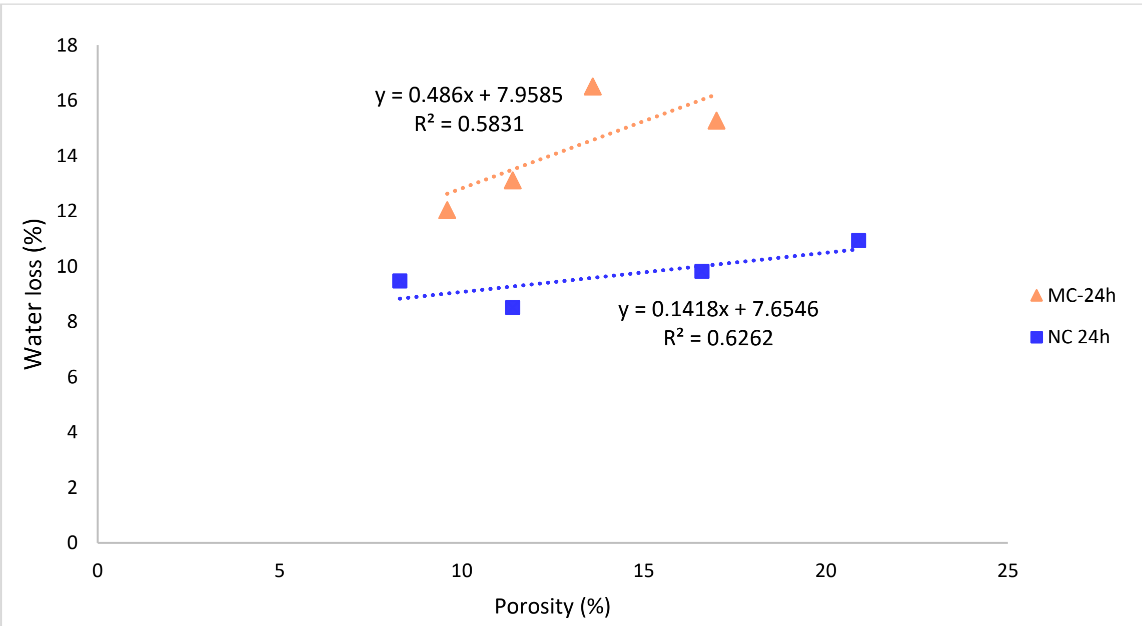


Figure 9. Relationship between porosity and water loss of repair materials (low density and fast setting materials are excluded) at 24 h after casting.

4. Conclusions

This paper presents the pore properties and moisture loss of six proprietary cement-based mortars and a CEM II mortar which were microwave cured for 40-45 minutes (15 minutes for one fast-setting material).

Results show that microwave curing results in a similar shape of pore distribution curves as normal curing but with a shift in the position of the critical pore diameter and the corresponding differential pore volume.

Microwave curing provides similar benefit to hydration as conventional heat curing, resulting in reduced porosity (up to 24%) of Portland cement based normal density repair materials, including mixes containing fly ash or polymer latex.

Cement based polymer modified low density repair materials (1500-1700 kg/mm^3) and flowing mortars suitable for poured repairs suffer an increase in porosity (up to 16%) under microwave curing due to the admixtures used to provide their special properties. Microwave curing of repair materials results in a significant water loss, ranging from 2.08 to 3.04% (of mix water), by the end of microwave curing under the worst-case condition of exposing unprotected (uncovered) specimens to microwave curing. In comparison, the corresponding water loss for normally cured specimens (20 °C, 60% RH) up to the end of microwave curing period ranged from 0.27% to 0.60%. These results show that repairs should be protected to prevent excessive moisture loss (e.g., by covers or curing membranes) when subjected to microwave curing. The moisture loss at the end of microwave curing is linearly related to water added to the mix.

The water loss at 24 hours for microwave cured specimens ranged from 3.71% to 16.65% compared with 3.31% to 10.93% for normal curing. This water loss is linearly related to the porosity of the hardened repair material. It increases with increasing porosity both under microwave and normal curing.

The results presented in this paper verify the validity of using microwave heating for accelerated curing of concrete repair. This technology will provide environmental (e.g., decarbonation) and economic benefits relative to other methods of accelerated curing. Methods such as curing membranes and impermeable covers, available in current practice, can be used to prevent early moisture loss during MC.

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Author Contributions

Mangat provided guidance to the test programme and analysis of data. All authors contributed to the design of the experiments. S. Abubakri conducted the experiments and collected data. He prepared the initial draft. All authors contributed to analysing the data and editing the manuscript.

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Competing Interests

The authors have declared that no competing interests exist.

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