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UNCOVERING THE ROLE OF TEMPERATURE TREATMENT OR MICROWAVE ON THE PROPERTIES OF MORTARS CURED BY WATER

WAJDE S. S. ALYHYA[1,*], RIDHA H. MAJEED[2], LAITH M. R. MAHMMOD[3]

[1,3]School of Engineering, University of Kerbala, Karbala, 56001, Iraq
[2]Kerbala Technical Institute, Alfurat Al-Awsat Technical University, Karbala, 56001, Iraq
*Corresponding Author: wajde.alyhya@uokerbala.edu.iq

Abstract

The consciousness of manufacturing influence on the environment and the necessity to increase the efficient production was the primary drive that has motivated researchers to create rapid curing for cement-based materials. This paper displays an experimental work on the effect of treatment by temperature and microwave on the properties of mortar cured by traditional water curing. To accomplish this purpose, two different curing regimes (various periods of microwave treatment or various values and periods of temperature) in combination with traditional water curing were investigated on 5 cm mortar cubes at 3 and 7 days In the first regime, four different periods of microwave treatment, after traditional water curing, were considered (3, 6, 9 and 12 minutes). While in the second regime, mortar cubes were subjected, post to traditional water curing, to five different temperatures ranging from 175 to 275 °C with an increase of 25 °C and for three different periods of 1, 2 and 3 hours. The mortar properties were determined by means of compressive strength development, porosity, and density observations. Test results demonstrated that the microwave curing tends to significantly increase the rate of cement hydration) higher hydration products) in all investigated periods. With longer microwaving times, higher strengths were obtained in which, the increases percentages equalled to 54.3% and 33.2% from 12 minutes microwave curing at 3 and 7 days respectively. Data also confirmed that applying temperature after water curing achieved a higher compressive strength development when compared with mortar cured by just water. For example, mortar samples subjected to a temperature of 275 °C for 3 hours produced higher strengths in which, the percentages of increases reached 55.7% and 45.4% at 3 and 7 days respectively. In contrast, both curing regimes produced mortar with lower density.

Keywords: Compressive strength, Curing, Density, Microwave, Porosity, Temperature.

1. Introduction

Gaining cement-based materials for high early strength is a crucial aspect that influences on their production rate in the prefabrication plant as well as it is necessary for evaluating their performance resulting in the allowance for demoulding and delivering members to the construction site [1]. Therefore, reducing curing time, in particular, can reduce production period, which in turn can lower energy consumption, production cost, workshop area as well as the adverse impact on the environment [2].

Over the past decades, different curing methods have been proposed for the curing of cement-based materials as it is necessary for the hydration process of cement to achieve a strong and durable material [3]. The most popular curing method, although it is sometimes impractical, is to continuously flood the surface with water for a specific period after placement (usually known as water curing). In addition to water curing, steam curing is highly adopted, particularly in the precast concrete factories to enhance the strength rate development. The high achieved strength in short curing period enables earlier removal of moulds and higher production rate resulting in a shorter delivery time of the final products [4]. Similarly, it has been found that temperature has a noticeable influence in accelerating the hydration of cement-based materials [5-11].

Morsy and Heikal [11] stated that the degree of hydration of C_3S could be enhanced when cured at a higher temperature at an early age and it decreases proportionately at later ages. Saul [3] illustrated that the rate of concrete strength development was found to be in close association with the influence of temperature and time on the hardening process. Price [12] illustrated the significance of the initial temperature of the curing experimentally. The author reported that concrete gains strength more swiftly when cured at higher temperatures in comparison to that cured isothermally at 20 °C. Ghani et al. [7] and Klieger [9] also highlighted how can short and long-term strengths be affected by various .curing temperatures Tank and Carino [13] found a constant rate model that considers the influence of temperature on strength gain of concrete.

Kim et al. [14] studied the effect of temperature of curing on strength and elastic modulus of concrete. According to the experimental results, concrete specimens subjected to high temperatures at early ages attained higher early-age mechanical properties (i.e., higher splitting and compressive strengths), but lower later age values in comparison with those subjected to normal temperature. McIntosh [15] investigated in detail the relationship between the compressive strengths of thermally and normally treated concrete. Results showed that the compressive strengths varied with the maximum applied temperature and treated time. Regarding the porosity, Goto and Roy [16] found that specimens cured at a higher temperature (i.e., 60 °C) with a w/c ratio of 0.40 produced a larger total pore volume and a larger permeability in comparison with specimens cured at a lower temperature (i.e., 27 °C). The main reason behind such results was thought to be the presence of pores in the range of 1500~4600 °A in diameter.

Apart from the aforementioned curing methods, curing by microwave, which is considered as an innovative material processing, stands as a strong candidate in developing rapid early strength for cement-based materials that has been emphasized by a significant number of the previous work [17-20]. Basically, the dielectric permittivity of cement-based materials facilitates the interaction with microwave radiation, which leads to fast heating [21]. Unlike conventional heating, microwave heating is of high efficiency in heating various materials particularly those with dielectric nature [18, 20]. Hence, microwave heating will be valuable for cement-based materials due to their excellent dielectric properties and abilities to absorb microwave energy efficiently. Recently, great numbers of studies have been carried out using microwave treatment for various cement-making materials applications, for instance; to accelerate the curing process [22, 23], to decontaminate surfaces [22], and to drill and melt substances [23-25]. Indeed, microwave technique has also been very useful in surveying ways and nondestructive examination in structures made of different cementitious materials [26, 27].

Chindaprasirt et al. [28] stated that conventional heating technique distributes in the specimen from the external to the internal part resulting in an inhomogeneous and extended duration of heating to accomplish the required temperature. In contrast, the microwave heating technique allows a uniform and fast heating due to the interaction between the polar molecules and microwave electric fields. Chindaprasirt et al. [28] also presented the results of the bulk densities of the geopolymer mortar. They found that microwave radiation enhanced the densification compared with those entirely cured with conventional temperature curing. A considerable volume of research [28-32] has numerically and experimentally studied accelerating the rate of strength development of cement using the microwave in curing. Leung and Pheeraphan [33] stated that curing concrete by microwave could offer high initial strength. It can also cause, after a short period of using microwave and post to concrete mixing, a reduction in the w/c ratio due to the removal of water in the plastic stage of concrete.

In addition, Leung and Pheeraphan [30] examined concrete properties of various w/c influenced by different microwave processing parameters such as power period, power level and delay time of curing. Most cases of his study achieved high early-age strength with only a few cases attained high later age strength, in comparison with that attained from cases cured at room temperature. The reason behind the reduction in the long-term strength in specimens cured by microwave was found to be connected with the increase in porosity and microcracking due to overheating.

Lee [34] investigated the effect of microwave and steam curing on the rate development of strength and durability of concrete, in which, four concrete mixes were subjected to two curing treatments by steam in addition to four curing times by microwave. The test results agreed well with other investigations indicating that treating by microwave could indeed improve the short-term strength of concrete.

Besides, Xuequan et al. [35] stated that the 28 days compressive strength of mortar could be improved by 3-7% when heating by microwave as well as the initial age strength. In contrast, Hutchison et al. [36] reported that applying microwave energy for a long time can cause a deterioration in strength because of over evaporation and overheating. Pheeraphan and Leung [22] illustrated that microwave curing could weaken the durability of concrete to freezing and thawing in concrete mixes of high w/c.

Although the effect of various curing methods, in particular, curing by temperature or microwave on the properties of mortar and concrete has been the subject of a number of investigations, it should be emphasized that there is still, however, a lack of studies that revealed the influence of compound curing (i.e., water and temperature treatment or water and microwave curing) on the cement hydration mechanisms. In this context, the end objective of the work presented in this paper is to fill the research gap of the influence of water and temperature treatment or water and microwave curing on the rate of strength development as well as the density and porosity of mortars. From a practical point of view, this study is of vital importance for the precast concrete industry as it reveals the potential application of the compound curing representing by water and temperature treatment or water and microwave curing. It will also primarily be very useful in areas with a scarcity of water.

2. Experimental Set-Up

Mortar specimens were moulded into 5×5 ×5 cm cubes using Portland cement type V with nominal compressive strengths of 17.2 and 25 MPa at 3 and 7 days, respectively. The chemical composition of the cement was tabulated in Table 1. The mortar was prepared by mixing the cement, standard sand (Table 2 provides its properties) and tap water with a fixed ratio of cement to the sand of 1:2.75 following the ASTM C109 standard [37] with a fixed w/c of 0.40. After being mixed and placed into moulds, the mortar specimens were covered by plastic sheets to prevent moisture loss.

After around 23±1 hr of mixing, the specimens were demoulded and cured in water until the date of testing to be then subjected to temperature or treated in a domestic type of microwave. In other words, three various procedures have been followed: The first procedure consists of specimens that have directly been testing after only water curing. In the second procedure, specimens are treated by a domestic microwave (900 W and 2.45 MHz multimode cavity with a rotating turntable) for four various times of 3, 6, 9 and 12 minutes after water curing.

While the last procedure involves subjecting the specimens, post to water curing, to five various temperatures ranging from 175 to 275 °C with an increase of 25 °C and for three different periods of 1, 2 and 3 hours. In the last two procedures, specimens were left to cool gradually until reaching room temperature.

For the whole process, 126 cube specimens are soaked in water of controlled temperature equal to 24.0±2.0 °C until the time of testing. 90 specimens were subjected to various temperatures for various times, while the microwave was used to cure another 24 specimens. The specimens cured by temperature or microwave were scaled before and after they were shifted to the temperature and microwave processes.

Table 1. Chemical composition of cement.

SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	C_3A
20.5	5.4	4.5	62	1.9	1.7	2.79

Table 2. Properties of standard sand for preparing mortar.

Sieve size, μ*m*	Passing percentage, %	Losing by washing with HCL, %
100	850	
7	600	0.16

3. Results and Discussion

3.1. Compressive strength

The compressive strengths at the ages of 3 and 7 days for various curing regimes (water curing only, compound curing of water and microwave treatments and temperature treatments) are given in Table 3. All figures given here represent the mean of three experimental values. As predicted, the time has a positive influence on the compressive strength of mortar samples cured by various curing regimes owing to the process of hydration.

Table 3. Compressive strength of mortar specimens exposed to various curing regimes at 3 and 7 days.

No.	Curing regime	Exposure conditions		*fcu*, MPa			
		Time, minimum	Temperature, °C	3 days	Percentage of increase	7 days	Percentage of increase
1	Water only	-	-	14.0	-	19.6	-
2	Microwave	3		15.4	10.1	21.1	7.7
		6		17.1	22.1	22.8	16.3
		9		20.6	47.1	24.9	27.0
		12		21.6	54.3	26.1	33.2
3.	Heat	60	175	15.8	12.9	21.5	9.7
			200	16.1	15.0	22.3	13.8
			225	17.4	24.3	23.9	21.9
			250	18.7	33.6	24.5	25.0
			275	19.6	40.0	25.6	30.6
		120	175	16.6	18.6	22.7	15.8
			200	18.4	31.4	23.5	19.9
			225	19.4	38.6	24.5	25.0
			250	19.8	41.4	24.7	26.0
			275	20.8	48.6	27.2	38.8
		180	175	16.6	18.6	23.1	17.9
			200	18.7	33.6	25.3	29.1
			225	19.2	37.1	25.9	32.1
			250	19.9	42.1	26.9	37.2
			275	21.8	55.7	28.5	45.4

Figure 1 displays the compressive strength of mortars from experiments at the ages of 3 and 7 days that are used the microwave for curing. The results were under comparison with those specimens that were cured only by water. It has been observed that mortar specimens cured in the microwave for a longer period (12 minutes) exhibit higher results for the compressive strength at both studied ages (3 and 7 days). Deep examining to Fig. 1 demonstrated that lower time for curing by microwave (3 minutes in this study) was not enough to gain strength (i.e., higher cement hydration products). In contrast, increase the exposure time to microwave (12 minutes) resulted in a primary overheating and to significant enhancement in the compressive strength.

Figure 2 illustrates the relative gain in the compressive strength at the ages of 3 and 7 days for the mortar specimens in different periods of curing by microwave. First looking to these figures can easily and quickly convey the mortar specimens cured by microwave for various periods of times from the plastic phase to the hardened one (i.e., gaining a higher amount of hydration products over time). Moreover, the compressive strength increases at a higher rate at the early ages than the later ages (3 and 7 days). This increase in the compressive strength may be owing to the removal of any excess water from the fresh mortar when the microwave is employed, causing mortar densification and a collapse in the pore system.

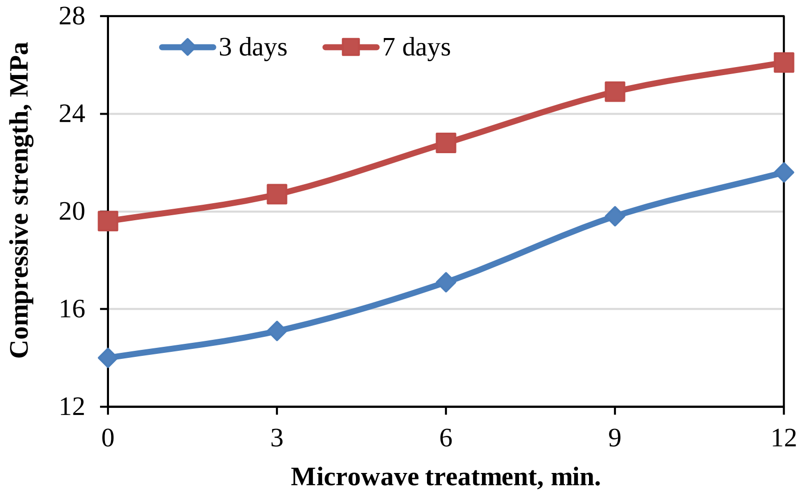

Fig. 1. Effect of microwave curing at various times on mortar compressive strength at ages of 3 and 7 days.

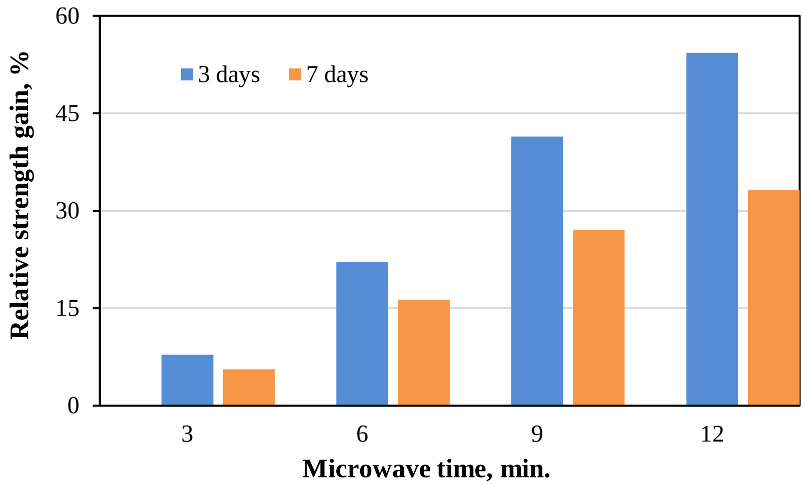

Fig. 2. Relative strength gains in 3 and 7 days resulting from microwave curing.

On the other hand, Figs. 3 to 5 demonstrate the compressive strength of mortar specimens that are treated by the temperature of 175 ºC, 200 ºC, 225 ºC, 250 ºC and 275 °C for periods of 1, 2 and 3 hours. It is obvious from these figures that the strength development at the considered ages (3 and 7 days), was greater in mortar specimens exposed to various temperature degrees when compared with those treated by only water.

For example, the mortar specimens exposed to a temperature equal to 275 °C for 3 hours attained a compressive strength of 21.8 MPa at the age of 3 days against only 14 MPa for specimens cured by only water. Furthermore, the mortar specimens that are exposed to a temperature of 275 °C for 3 hours has a 7-days compressive strength equals to 28.5 MPa in comparison with only 19.6 MPa for those cured by only water.

Apparently, the growth in the compressive strength could be related to the additional hydration of the remained unhydrated cement particles occasioning from the influence of interior autoclaving, as well as the "crossover effect'' phenomenon. This phenomenon defines as a maturity concept that comes from the shared effect of temperature and age on the development of the compressive strength [9, 34-35].

The higher amounts of CSH, which are recognized as hydration products, could be left in the formed pores that result from the evaporation process of water causing linking for the existed ones. Further, the enhancement in the compressive strength could also be partly owing to the supplemented hydrated cement during the free water's evaporation, which can enhance the Van der Waal forces.

In other words, the layers of the cement gel become closer to each other. Carino and Lew [38] mentioned that it is worth mentioning that the aforementioned results were in good agreement.

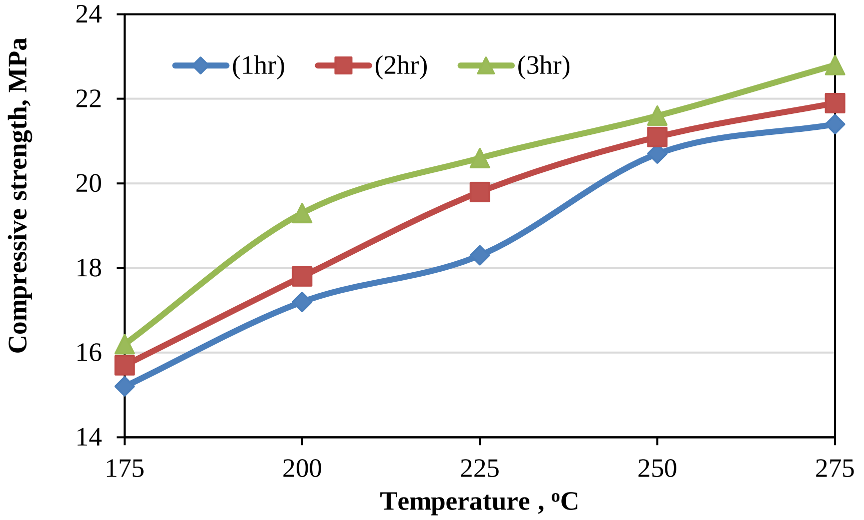

Fig. 3. Effect of various exposure times of temperature treatment on 3 days compressive strength of mortar specimens.

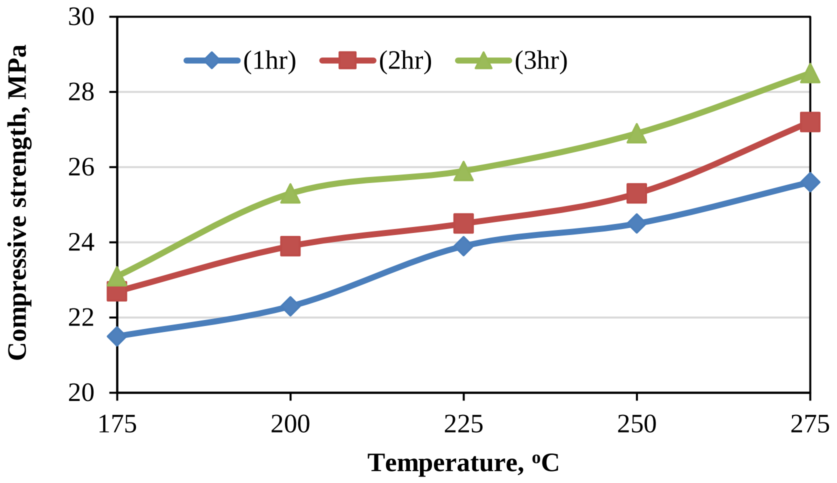

Fig. 4. Effect of various exposure times of temperature treatment on the 7 days compressive strength of mortar specimens.

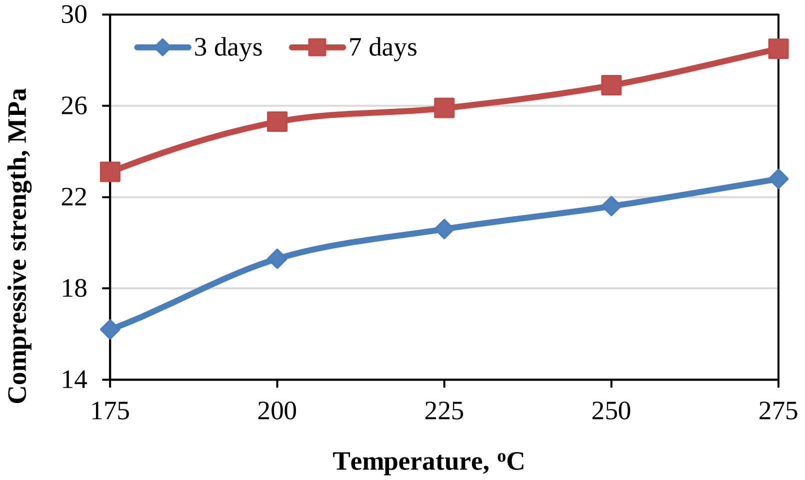

Fig. 5. Effect of temperature treatment for 3 hours on the 3 and 7 days mortar compressive strength.

It is clear from Fig. 6 that the 3 and 7 days compressive strength of the treated mortars by temperature were higher than those of mortars cured by only water, which is the reason that makes temperature treatment to be very beneficial. The temperature from the internal friction among flipping water molecules might help in the hydration of the cement grains, resulting in mortars with a fast track of the hydration products, i.e., high early strength.

For the sake of comparing results of various cases, it is most useful to take into consideration the percentage of increase in the compressive strength relative to the reference strength achieved (specimens that are cured only in water). This could eliminate the influence of any variation in materials from one batch to another.

Figure 7 shows the relative increase in the 3 and 7 days compressive strength in all various curing regimes. The bar chart (Fig. 7) represents the sets of results of the relative increase with respect to the reference strength that achieved from testing specimens cured only by water. The reference strength was considered to be the 3 and 7 days strength of watery cured specimens from the same batch (Fig. 7).

The relative increase in strength after 3 and 7 days was found to be affected by the heating temperature. For instance, specimens treated to a temperature equal to 275 °C for 3 hours achieved a relative increase in the 3 and 7 days strength of 63 and 46%, respectively. Furthermore, microwave curing presents a lower increase in the relative compressive strength in comparison with specimens treated by temperature.

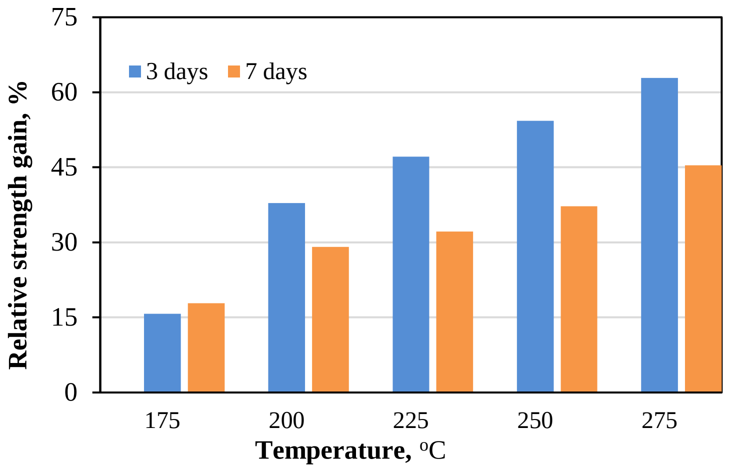

Fig. 6. Relative strength gains in 3 and 7 days resulting from temperature treatments.

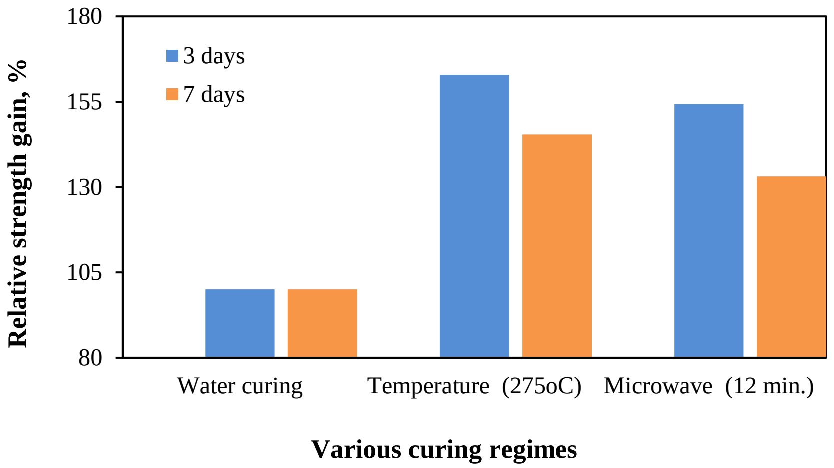

Fig. 7. Effect of various curing regimes on 3 and 7 days relative compressive strength gain of mortars.

3.2. Porosity

Three pieces from every single specimen were weighed underwater and in the saturated surface-dry (SSD) condition in order to calculate the bulk volume. Any change in volume during drying or re-saturation process was assumed to be negligible. Such volume was used to determine the bulk density of each sample after drying. Every single specimen was then subjected to a drying process in a carbon dioxide using an oven at 105 °C until reaching the constant weight. The porosity represents the weight difference between the water-saturated and oven-dry conditions as a percentage of the bulk specimen volume. The average of three replicates was used to represent all porosity data. The following equation was followed to calculate the porosity:

$$P = \frac{(W_{ssd} - W_d)}{(W_{ssd} - W_w)} \times 100\%$$

where *p* represents the porosity,

W_{ssd} is the weight of specimen in its saturated surface dry (SSD) condition (g),
W_d is the weight of dry specimen after 24 h in an oven (g), and
W_w is the weight of the saturated specimen (g).

This approach has been followed to determine the porosity of cement-based materials effectively [39-41]. Pores system has been classified into two main common use groups [42]. The first group takes into consideration the conventional classes of pores such as gel pores (<10 µm) and capillary pores (10 to 10000 µm) that are related to the development of the hydration products. The other group, which is also used in classification, covers macropores (50 to 10000 µm), mesopores (2.5 to 50 µm) and micropores (<2.5 µm) [42]. In most cases, the characteristics and the quantities of pores can remarkably affect the properties of hardened mortar and concrete as well. For instance, the pores ‘sizes and connectivity can dominate the short and long-term properties of concrete and mortar.

The results of the porosity of mortar specimens treated in various regimes are given and demonstrated in Table 4 and Figs. 8 to 11. It is quite clear from the figures that the porosity was found to be influenced by the various studied regimes of curing. From the test results, it can be noted that increasing the microwaving time has an impact on the structure of the pores. For example, the values of porosities at 3 and 7 days ages were equalled to 23.7 and 23.5% for 12 minutes as a microwaving time, respectively against 16.5 and 12.9 %, receptively for the 3 minutes after the traditional curing by water till the date of the test. It is wealth mentioning that the porosity keeps rising in spite of the continual hydration process of cement. Conversely, mortar specimens cured for various times to a wide range of temperatures as well as those used microwaves for curing appeared to have an alike increase in the porosity profile at all studied ages. The main reason behind the increase in the porosity could be due to the fact that both curing regimes cause fast curing, which could control the distribution of the pore size, particularly the volume of mesopores [42]. Moreover, the potential fast curing arisen by the two proposed curing regimes could cause a non-uniform distribution for the hydration product resulting in a high volume of pores’ microstructure. Another likely cause for such an increase in the porosity is the existence of unreacted cement grains that are enclosed by dense hydrated phases that causing the stoppage of new further hydration.

Table 4. Porosity of mortar specimens exposed to various curing regimes at 3 and 7 days.

No.	Curing regime	Exposure conditions		*fcu*, MPa			
		Time, minimum	Temperature, ºC	3 days	Percentage of increase	7 days	Percentage of increase
1	Water only	-	175	13.7	-	12.3	-
2	Microwave	3		16.5	20.4	12.9	4.9
		6		17.3	26.3	15.9	29.3
		9		20.7	51.1	18.9	53.7
		12		23.7	73.0	23.5	91.1
3.	Heat	60	175	15.8	15.3	21.5	74.8
			200	16.1	17.5	22.3	81.3
			225	17.4	27.0	23.9	94.3
			250	18.7	36.5	24.5	99.2
			275	19.6	43.1	25.6	108.1
		120	175	16.6	21.2	22.7	84.6
			200	18.4	34.3	23.5	91.1
			225	19.4	41.6	24.5	99.2
			250	19.8	44.5	24.7	100.8
			275	20.8	51.8	27.2	121.1
		180	175	16.6	21.2	23.1	87.8
			200	18.7	36.5	25.3	105.7
			225	19.2	40.1	25.9	110.6
			250	19.9	45.3	26.9	118.7
			275	21.8	59.1	28.5	131.7

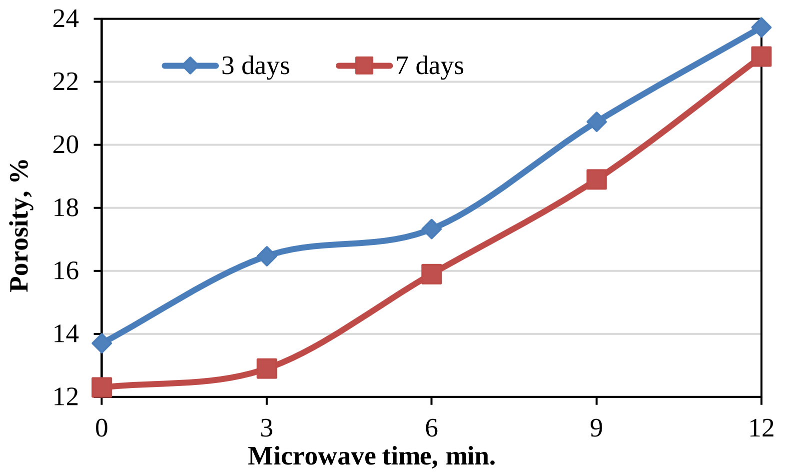

Fig. 8. Effect of microwave curing on the porosity of mortar specimens.

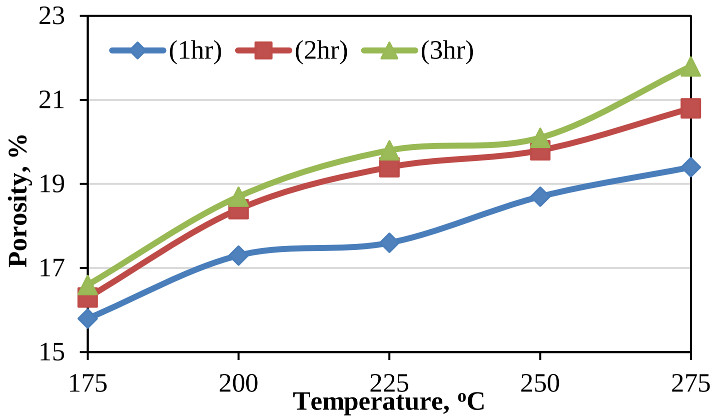

Fig. 9. Effect of treatment by temperature on the porosity of mortar specimens at the age of 3 days.

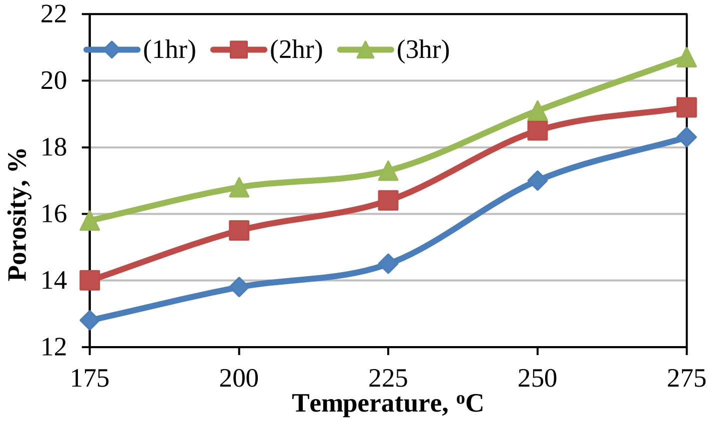

Fig. 10. Effect of treatment by temperature on the porosity of mortar specimens at the age of 7 days.

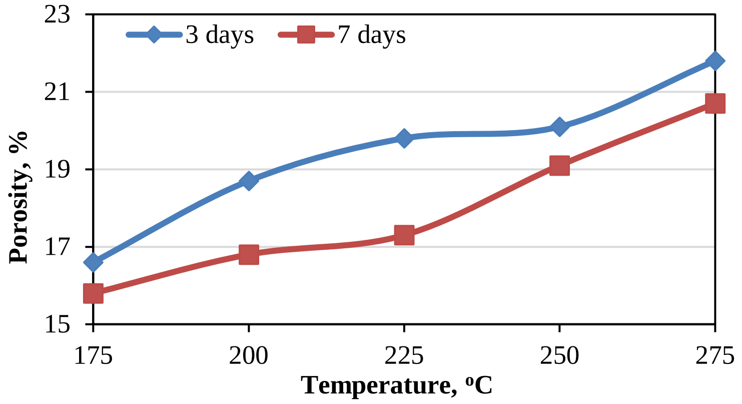

Fig. 11. Effect of treatment by temperature on the porosity of mortar specimens treated for 3 hours.

3.3. Density

The density can be used as an indication of how tightly or loosely are the molecules been packed in the network system. The network packing variance among specimens that are treated by temperature or microwave can be inspected through the density test. Figures 12-15 illustrate the mean density of the mortar specimens that are treated with temperature or microwave. It can be concluded that neither specimens cured by temperature nor ones cured by microwave exhibit higher densities when compared with those specimens cured by just water. This implies that the network structure in the temperature and microwave cured specimens were less compact than those with water curing. Moreover, the low densities could be due to the removal of any uncombined water that may be still available in the mortar skeleton. This proposes a dissimilar morphology of mortar specimens with the various curing.

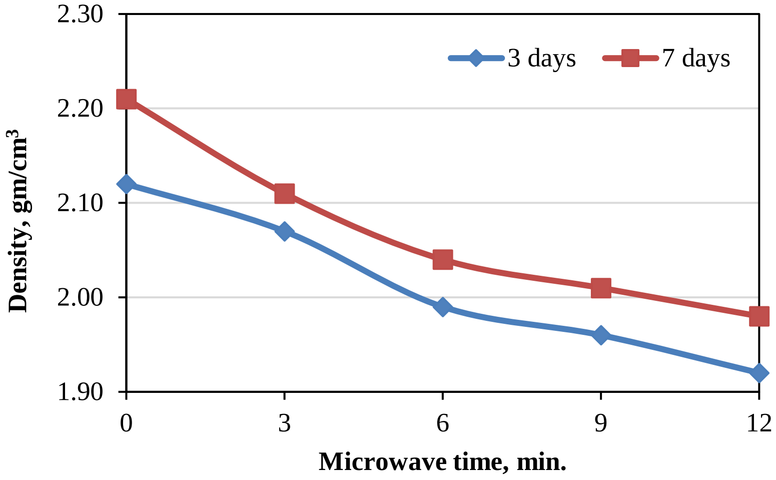

Fig. 12. Effect of microwave curing on the density of mortar specimens.

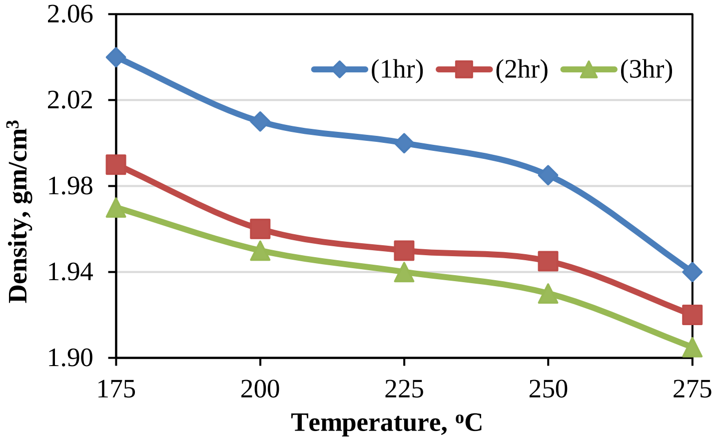

Fig. 13. Effect of temperature treatment on mortar specimens densities at 3 days age.

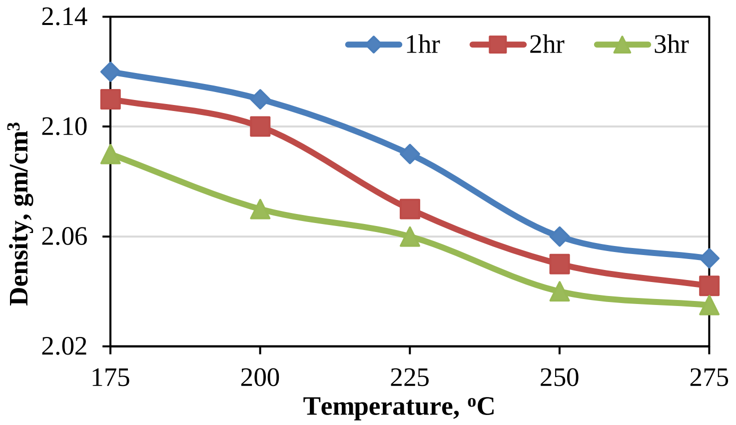

Fig. 14. Effect of temperature treatment on mortar specimen's densities at 7 days age.

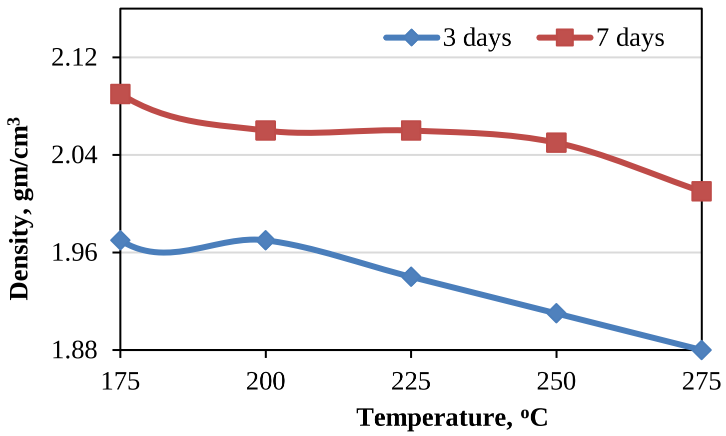

Fig. 15. Comparison of the effect of temperature treatment for 3 hours on mortar specimen's densities on 3 and 7 days ages.

4. Conclusions

The main findings that can be derived from this study can be summarised as follows:

- The experimental results show that mortar specimens subjected to various temperature (within the range of 175-275 °C) produce higher strengths than those mortar specimens cured by water only. Whereas, the specimens treated with various times of microwave has a similar, but lower strength gain.
- Compared with only water-cured mortars, temperature treatment or microwave curing cause a more open microstructure (i.e., high porosity) and relatively open interstitial spaces.
- It can reveal that the treatments by temperature or microwave appear to be effective at the ages of 3 and 7 days. Thus, the influence of the above treatments at later ages needs to be investigated, which is in ongoing research.

- Results of the studied curing regimes found to be encouraging and useful in the construction industry, such as pre-casting and pavement repair, and it can be potentially utilized to improve the rate of strength development.
- Both curing regimes produced mortar with lower density.

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