International Journal of Heat and Mass Transfer 127 (2018) 179–192

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

An experimental study of microwave drying under low pressure to accelerate the curing of Portland cement pastes using a combined unsymmetrical double-fed microwave and vacuum system

Natt Makul [a], Somsak Vongpradubchai [b], Phadungsak Rattanadecho [b,*]

[a] Department of Building Technology, Faculty of Industrial Technology, Phranakhon Rajabhat University, Changwattana Road, Bangkhen, Bangkok 10220, Thailand
[b] Center of Excellence in Electromagnetic Energy Utilization in Engineering (CEEE), Thammasat University (Rangsit Campus), Khlong Luang, Prathum Thani 12121, Thailand

ARTICLE INFO

Article history:
Received 8 April 2018
Received in revised form 24 June 2018
Accepted 24 June 2018

Keywords:
Microwave-assisted drying (MD)
Portland cement pastes (CM)
Low pressure
Temperature
Moisture content
Compressive strength

ABSTRACT

An experimental study was conducted on the use of microwave-assisted drying (MD) to accelerate the curing of Portland cement pastes (CM) under a low pressure by using a combined unsymmetrical double-fed microwave and vacuum system. The effects of microwave power (800 and 1600 W) and pressure level (30 and 50 kPa) on the temperature, moisture content, and gained compressive strength of CM were examined. The CM specimens were prepared with standard CM at water-cement ratios (w/c) by mass (0.38 (38% moisture content), 0.45 (45% moisture content), and 0.75 (75% moisture content)) before applying MD. In the experiments, when the CM specimens were dried using MD, the increases in was faster because of the high level of humidity. As it became less humid, the specimens could absorb less microwave energy and eventually remained at a stable temperature. A low pressure level affected the moisture content in CM, as a lower pressure resulted in a lower boiling point. The moisture in CM evaporated quickly, and the moisture content decreased faster than the high pressure did. Further, the w/c affected the temperature because a low w/c caused the CM temperature to be higher than that observed for a high w/c. Finally, the CM specimen that was dried using a microwave at 50 kPa and a 0.45-w/c attained the highest compressive strength.

1. Introduction

Currently, concrete production is highly competitive for economic and sustainability reasons, and research aiming to increase knowledge about the rapid curing process and obtain a higher quality of concrete is one of the main goals of both entrepreneurs and producers. In particular, the development of concrete that is high strength and more durable and has minimal quality loss in both the early-age and the long term is desired. When using the shortest production time, typically, if the concrete has high compressive strength development, curing will take more than several days, and the concrete must be cured continuously, for which there are various methods and technologies [1]. However, currently, these methods have many disadvantages, such as the loss in strength observed when the concrete drying is accelerated by an autoclave; a non-uniform heat distribution in the concrete; and the low thermal conductivity of the materials used in concrete, which causes the concrete's properties to vary. Moreover, it takes more than a day to get the concrete to develop as required. Further, if a curing substance is used, it will have a negative impact on the concrete's properties in the long term. Therefore, most concrete producers and industries need to have alternative technologies to overcome these problems, such as the innovative use of microwave-assisted curing technology for accelerated curing during the early-age state. This is a new technology because microwave energy is an effective energy source. Very clean heat is also constant, and there is uniform heat dissipation. The basic mechanism of heat generation under microwave conditions and the dielectric properties of dielectric materials are the main properties of concrete, as observed when changing microwave energy into heat energy. This is beneficial for the properties of concrete, but in various studies, the application of microwave energy in concrete curing was done by using a household microwave oven and conducting the curing process under a normal pressure condition (101.325 kPa) [2]. However, microwave curing under low-pressure conditions has not been researched extensively, especially microwave drying (MD) for the accelerated curing of cement concrete materials under low-pressure conditions.

* Corresponding author.
E-mail address: ratphadu@engr.tu.ac.th (P. Rattanadecho).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.119
0017-9310/

MD is an effective technique for thermal processes for improving the shortest drying time and the best overall quality of dried materials. It has more than twice the performance of conventional heating methods and is suitable for dielectric materials [3], such as food [4–12], biological tissue [12,13], wood [14,15], ceramic [16,17], and oil-water emulsions [18]. Principally, the mechanism and direction of heat generation and transfer differ from those of conventional heating methods [19]. In conventional heating methods, the material is heated by an external source, and the heat is transferred inward from the outside material. By contrast, microwave heating relies on the rapid polarization and depolarization of positively and negatively charged groups in the dielectric material, resulting in simultaneous internal heat generation and outward transfer. For this reason, microwave heating offers many advantages over conventional methods as follows [4,19–21]:

(a) Rapid heating rates and short processing times, which save energy,
(b) Deep penetration of the microwave energy, and
(c) Clean heating processes that do not generate secondary waste, among others.

This research aimed to experimentally investigate the use of microwave-assisted drying for the accelerated curing of CM under low-pressure conditions using a combined unsymmetrical double-fed microwave and vacuum system to study in depth the characteristics and kinetics of heating CM and the distribution of temperature, moisture and mechanical properties of CM when subjected to microwave irradiation and low pressure levels. Additionally, the mathematics based on the finite-element method for predicting the heat transfer within the CM while applying MD was proposed.

2. Materials and methods

2.1. Scope of research

As shown in Fig. 1, this research was carried out by drying CM using two asymmetric microwave feedings with a vacuum system to study the temperature distribution, moisture content, and compressive strength of the CM specimens that were tested after MD drying. The parameters used in the study were the magnetron position (1 (vertical magnetron) and 2 (horizontal magnetron), low pressure levels (30 and 50 kPa), and amount of specimen per drying process (12 and 24). The CM samples had water-cement ratios (w/c) of 0.38, 0.45, and 0.75 before drying.

2.2. Equipment

The commercialized combined unsymmetrical double-feed microwave and vacuum system is shown in Fig. 2 [22]. The microwave power was generated by unsymmetrical double-feed magnetrons (air-cooled magnetrons): 800 W, each at an operating frequency of 2450 MHz. The microwave power could be adjusted separately within a range of ±800 W. The microwave power was conveyed through a waveguide series with a rectangular size of 11.0 cm × 5.5 cm to a 0.13 m^3 vacuum cavity (0.24 m in diameter × 0.72 m in length).

The two levels of microwave power (800 W for one magnetron and 1600 W for two magnetrons turned on) and two levels of low pressure (30 and 50 kPa) were used.

2.3. Specimen preparation and testing methods

The CM specimens were made with dimensions of 5 cm × 5 cm × 10 cm. By mixing Type 1 Portland cement, which had the chemical composition and physical properties shown in Table 1, with tap water (pH = 7.0), as per the ASTM C305 standard [23], the water-cement ratios (w/c) were kept constant for all three cases (0.38, 0.45, and 0.75). The mix proportions of CM are shown in Table 2. After mixing and placing the CM slurry into a mold, a plastic sheet was used to cover the slurry and avoid moisture loss. At the age of 23.5 ± 0.5 h after mixing, the specimens were demolded and cured using different methods, including MD, water soaking, and air curing. In the water soaking method, 15 specimens were soaked in water at a controlled temperature of 25.0 ± 2.0 °C until testing. In addition, 15 specimens were cured at a temperature and relative moisture of 25.0 ± 2.0 °C and 60.0 ± 5.0%,

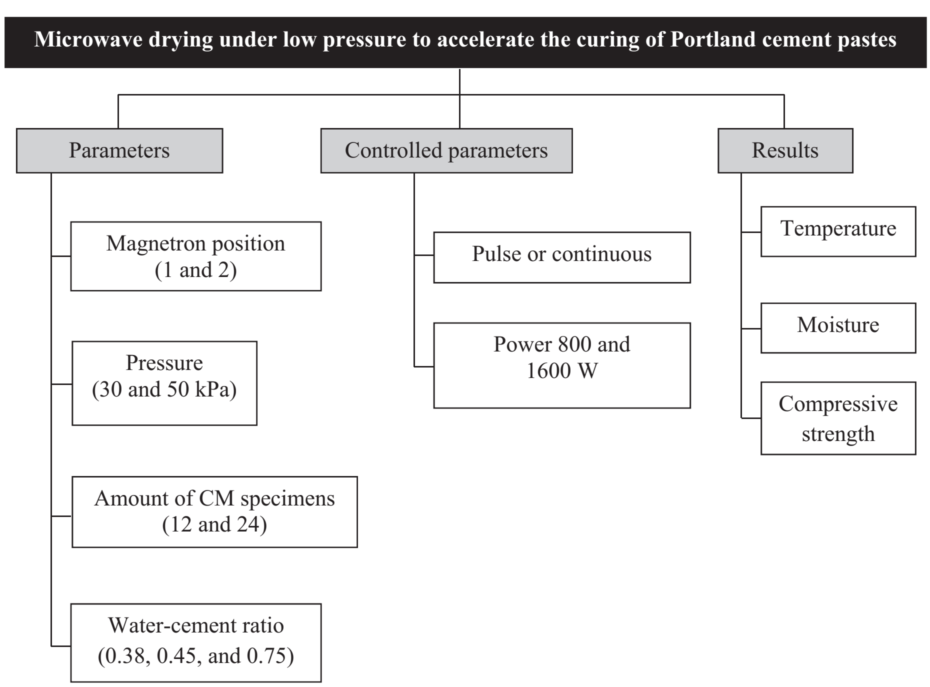


Fig. 1. Scope of the experiments.

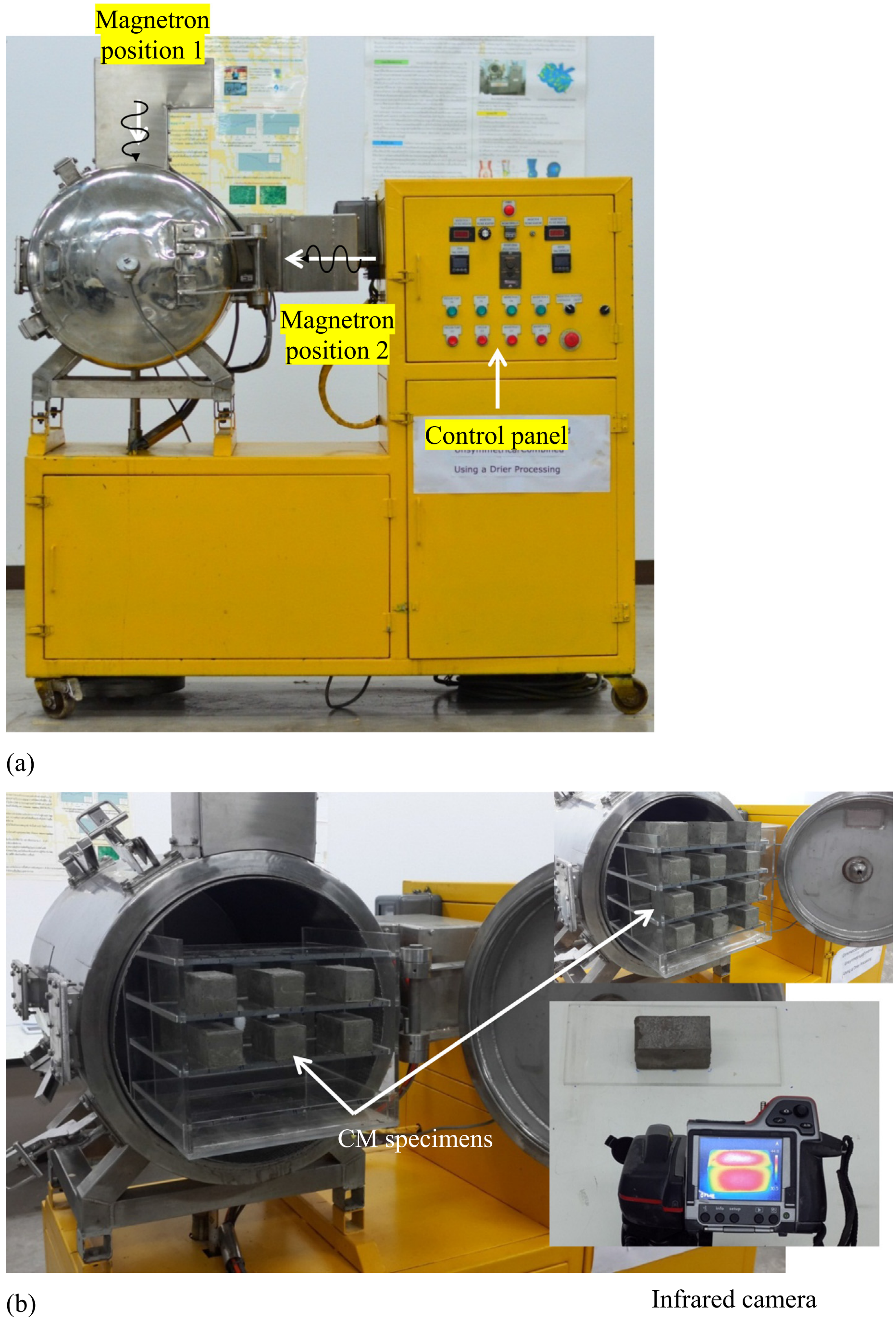


Fig. 2. (a) Commercialized combined unsymmetrical double-feed microwave and vacuum system [22] and (b) CM specimens in MD experiments.

respectively. The compressive strength of CM was tested at the ages of 3, 7, 14, and 28 days, complying with ASTM C39 [24].

2.4. MD procedures

This study investigated the drying of CM by using asymmetric two-magnetron microwave in combination with a vacuum system. The conditions under which the drying occurred are presented in Table 3. The CM was placed in a plastic mold and then wrapped in a plastic sheet to prevent water from evaporating from the CM specimens. CM was demolded at the age of 24 h after mixing, and the initial weight was recorded. The experiments studied the kinetics of the drying process by analyzing parameters such as the drying time of CM. The specimens were tested for the influences of low pressure on temperature rise of CM, low pressure on moisture content in CM, w/c on the temperature of CM, water-cement ratio on moisture content in CM, magnetron position on CM temperature, magnetron position on moisture content in CM, amount of CM on temperature of CM, amount of paste cement on moisture content in CM, temperature distribution on the surface of paste and temperature distribution in the cavity (see Table 4).

3. Results and discussion

In the experiment, the use of MD for accelerated drying under specific low-pressure conditions of CM subjected to an unsymmetrical microwave was used with a vacuum system to investigate the

Table 1
Chemical composition and physical properties of Type 1 Portland cement.

Chemical composition (% by mass)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	Free CaO
Type 1 Portland cement	20.4	5.21	3.21	66.4	1.26	0.21	2.43	0.91

Physical properties	
Loss on ignition (LOI) (%)	0.14
Moisture content (%)	0.52
Blaine surface area (cm^2/g)	3250
Fineness (Particle size,% Retained)	
≥75 μm	0.51
75 μm	5.24
45 μm	3.61
≤36 μm	90.63
Fineness (Retained) on 45 μm (No. 325)	5.76
Water requirement (%)	100
Bulk density (kg/l)	1.04
Specific gravity	3.14

Table 2
Mixture proportions of CM.

Water–cement ratio (w/c) (by mass)	Type 1 Portland cement (kg/m^3)	Water (kg/m^3)
0.38	1417	538
0.45	1288	580
0.75	967	725

Table 3
Case studies of CM for MD.

Case	Amount of CM specimens	w/c	Pressure within cavity (kPa)	Magnetron position
1	12	0.38	30	1
2	12	0.38	50	1
3	12	0.45	30	1
4	12	0.45	50	1
5	12	0.75	30	1
6	12	0.75	50	1
7	24	0.38	30	1
8	24	0.38	50	1
9	24	0.45	30	1
10	24	0.45	50	1
11	24	0.75	30	1
12	24	0.75	50	1
13	12	0.45	50	2
14	12	0.45	50	1 and 2
15	24	0.45	50	2
16	24	0.45	50	1 and 2

influence that low pressure has on the temperature, w/c, magnetron position, and amount of CM specimens. The experiments used microwave mode, a 2450 MHz multimode mode, two magnetrons, and a power output of 2 × 800 W. The results were determined by detecting the surface temperature and moisture content of the CM.

Table 2 shows the time and energy consumption (power) of CM during MD. The moisture content of CM prepared with a w/c of 0.38 decreases from 0.38 (dry basis) to an average of approximately 0.22 (dry basis), whereas CM with an initial moisture content of approximately 0.45 (dry basis) decreases to 0.38 (dry basis), and CM with a w/c of 0.75 decreases from the initial moisture content of 0.75 (dry basis) to an average of 0.38 (dry basis). It can be tentatively stated that for cases 1–6, the CM (12 specimens or workload) with 0.45 (cases 3 and 4) and 0.75 w/c (cases 5 and 6) require the power-time ratio to be less than that of the samples with a 0.38 w/c (cases 1 and 2). This is because the water content is more than 0.38, which classifies it as free water, which is located in the capillary pore and can move outward to the internal structure of CM. By contrast, the 0.38 water content is constrained as fixed water and is an essential part of the calcium-silicate-hydrate (C-S-H) structure, so it cannot move outward. It should be noted that when comparing the 0.45 w/c and 0.75 w/c CM samples, their power-time consumptions have nearly the same value, which indicates that the internal structures of CM containing free water at 0.45 w/c and 0.75 w/c are not different during the early-age MD application.

For cases 1–6 (12 specimens), CM consumes less energy than do cases 7–12 (24 specimens) due to the high amount of workload and the high water content of the specimens when applying MD processing. In addition to the significance of pressure at 30 (cases 1, 3 and 5 for 12 specimens) and 50 kPa (cases 2, 4 and 6 for 12 specimens), it should be noted that the pressure of 50 kPa requires a higher power-time ratio than is required for 30 kPa. This may be caused by the effect of low pressure circumstance for more extracting the internal free water of CM, as observed for the conditions of 30 (cases 7, 9 and 11 for 24 specimens) and 50 kPa (cases 8, 10 and 12 for 24 specimens).

For case 14, it can be seen that using magnetron positions 1 and 2 requires less energy for MD than is required in case 13, which indicates that magnetron positions 1 (vertical magnetron) and 2 can be used with high efficiency compared to the use of magnetron 2 alone (unsymmetrical magnetron). When comparing cases 2 (symmetrical magnetron) and 13 (unsymmetrical magnetron), the latter (13) position requires more power consumption than case 1 does because of the unsymmetrical microwave distribution, which causes the unsymmetrical power distribution within the

Table 4
Energy consumption of CM for MD.

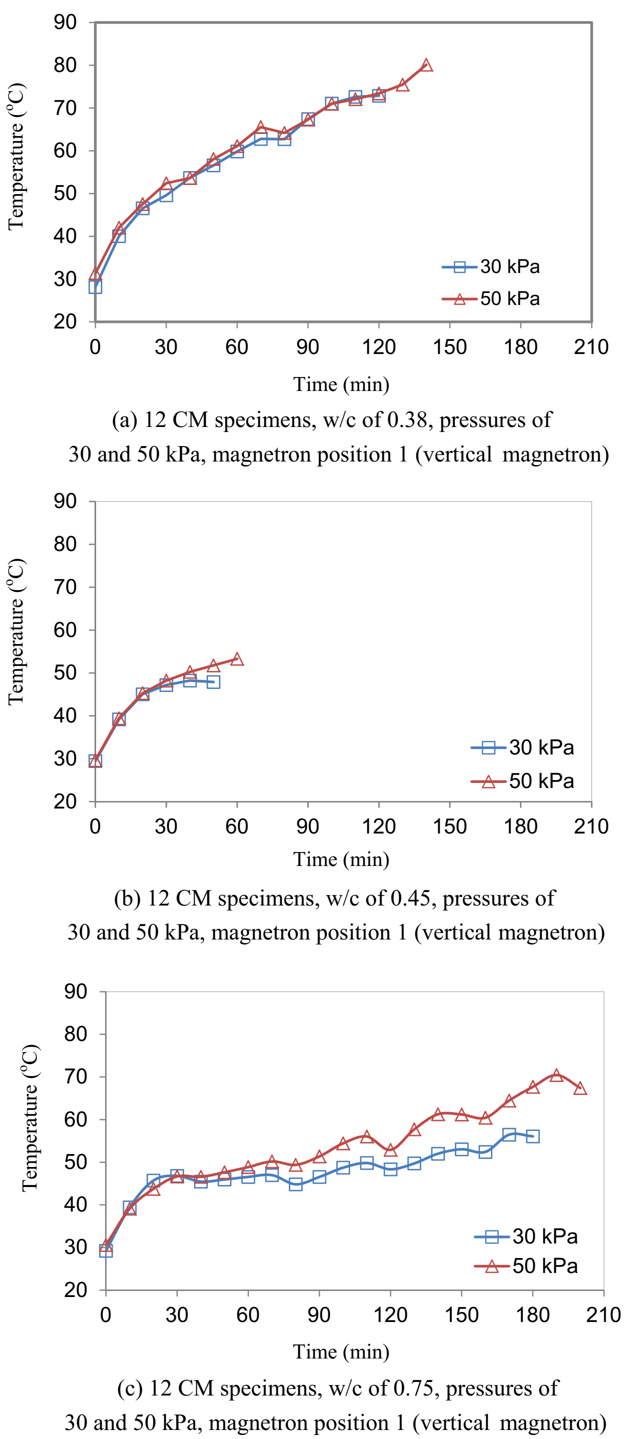
Case	Parameters and conditions	Time (min)	Power (kWh)	Power/time (kW)
1	12 CM specimens, w/c of 0.38, pressure of 30 kPa, magnetron position 1 (vertical magnetron)	100	4.50	2.70
2	12 CM specimens, w/c of 0.38, pressure of 50 kPa, magnetron position 1 (vertical magnetron)	100	4.90	2.94
3	12 CM specimens, w/c of 0.45, pressure of 30 kPa, magnetron position 1 (vertical magnetron)	50	2.2	2.64
4	12 CM specimens, w/c of 0.45, pressure of 50 kPa, magnetron position 1 (vertical magnetron)	40	2.0	3.00
5	12 CM specimens, w/c of 0.75, pressure of 30 kPa, magnetron position 1 (vertical magnetron)	50	2.2	2.64
6	12 CM specimens, w/c of 0.75, pressure of 50 kPa, magnetron position 1 (vertical magnetron)	40	2.0	3.00
7	24 CM specimens, w/c of 0.38, pressure of 30 kPa, magnetron position 1 (vertical magnetron)	180	7.9	2.63
8	24 CM specimens, w/c of 0.38, pressure of 50 kPa, magnetron position 1 (vertical magnetron)	160	7.8	2.93
9	24 CM specimens, w/c of 0.45, pressure of 30 kPa, magnetron position 1 (vertical magnetron)	60	2.7	2.70
10	24 CM specimens, w/c of 0.45, pressure of 50 kPa, magnetron position 1 (vertical magnetron)	60	3.0	3.00
11	24 CM specimens, w/c of 0.75, pressure of 30 kPa, magnetron position 1 (vertical magnetron)	240	10.6	2.65
12	24 CM specimens, w/c of 0.75, pressure of 50 kPa, magnetron position 1 (vertical magnetron)	220	10.1	2.75
13	12 CM specimens, w/c of 0.45, pressure of 50 kPa, magnetron position 2 (horizontal magnetron)	70	3.7	3.17
14	12 CM specimens, w/c of 0.45, pressure of 50 kPa, magnetron positions 1 (vertical magnetron) and 2 (horizontal magnetron)	30	1.9	3.80
15	24 CM specimens, w/c of 0.45, pressure of 50 kPa, magnetron position 2 (horizontal magnetron)	60	2.9	2.90
16	24 CM specimens, w/c of 0.45, pressure of 50 kPa, magnetron positions 1 (vertical magnetron) and 2 (horizontal magnetron)	40	2.6	3.90

cavity to result in uniform microwave heating. This phenomenon is similar to what occurs in cases 15 (magnetron position 1 (vertical magnetron)) and 16 (magnetron position 2 (horizontal magnetron)) as well.

For the suitable cases, the minimal energy-time ratio of MD was found by controlling the w/c to 0.45 and 0.75 for CM subjected to a 30-kPa pressure (case 3) and to 0.75 for CM subjected to a 30-kPa pressure (case 5) for 12 and 24 specimens, respectively. In these cases, the 0.38 w/c used for 12 and 24 specimens is neglected because the MD includes a basic process to decrease the water content in the CM specimen to 0.38 w/c [25]; further, decreasing the water content to below 0.38 had a negative effect on the quality of CM.

3.1. Influence of low pressure on temperature and moisture (water) of CM

Figs. 3 and 4 show a comparison of the temperature increase and duration of CM during MD with 12 and 24 specimens,

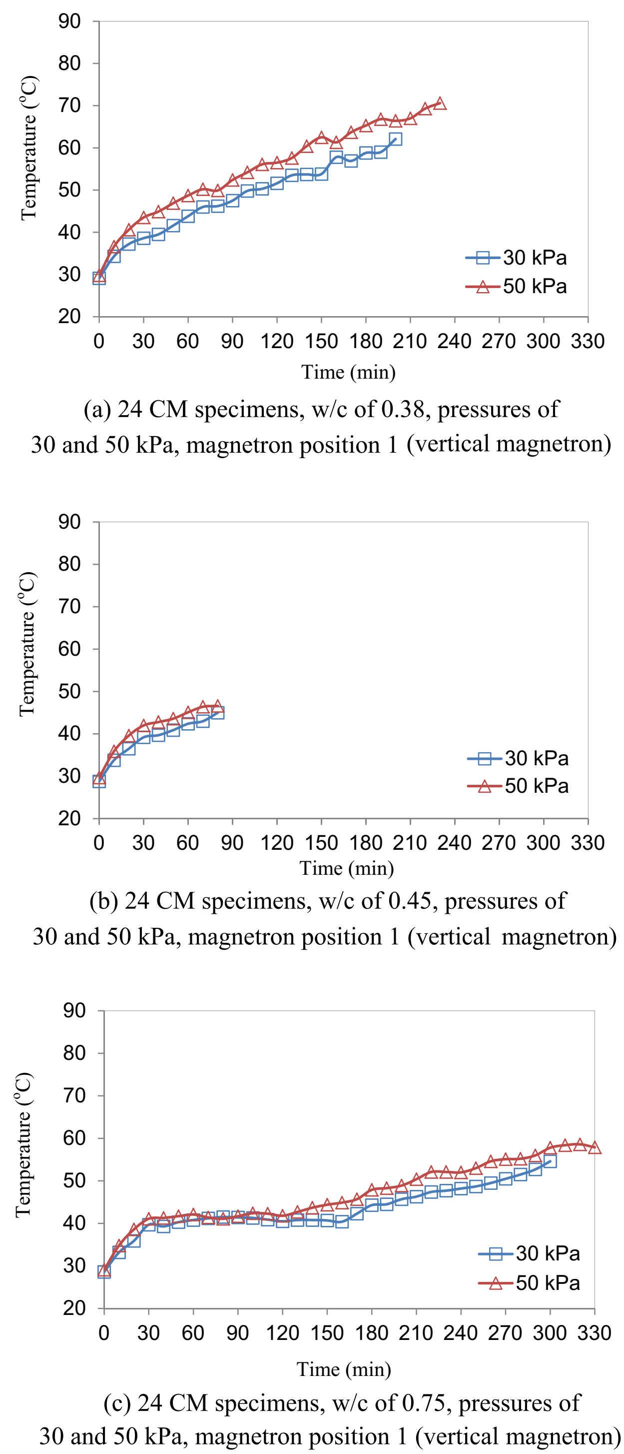


(a) 12 CM specimens, w/c of 0.38, pressures of 30 and 50 kPa, magnetron position 1 (vertical magnetron)

(b) 12 CM specimens, w/c of 0.45, pressures of 30 and 50 kPa, magnetron position 1 (vertical magnetron)

(c) 12 CM specimens, w/c of 0.75, pressures of 30 and 50 kPa, magnetron position 1 (vertical magnetron)

Fig. 3. Temperature and time at pressures of 30 and 50 kPa and magnetron position 1 (vertical magnetron) for 12 CM specimens prepared with a controlled w/c of (a) 0.38, (b) 0.45 and (c) 0.75.



(a) 24 CM specimens, w/c of 0.38, pressures of 30 and 50 kPa, magnetron position 1 (vertical magnetron)

(b) 24 CM specimens, w/c of 0.45, pressures of 30 and 50 kPa, magnetron position 1 (vertical magnetron)

(c) 24 CM specimens, w/c of 0.75, pressures of 30 and 50 kPa, magnetron position 1 (vertical magnetron)

Fig. 4. Temperature and time at pressures of 30 and 50 kPa and magnetron position 1 (vertical magnetron) for 24 CM specimens prepared with a controlled w/c of (a) 0.38, (b) 0.45 and (c) 0.75.

respectively. Fig. 3 shows the CM prepared with w/c values of 0.38, 0.45 and 0.75 and a workload of 12 CM specimens subjected to pressures of 30 kPa and 50 kPa and a power level of 800 W applied from magnetron position 1 (vertical magnetron) (vertical magnetron). At the initial stage of MD, CM has a high moisture content, dielectric constant and loss factor. It absorbs microwave energy well and turns it into heat, resulting in a rapidly increasing temperature during the middle and final stages of the MD of CM. The temperature of the CM increases more slowly in these stages than it does in the initial stage, but it continues to rise because of the heat that has accumulated in CM specimens. Compared to cases 1 and 2, the increasing temperatures in cases 3 and 4 are similar at pressures between 30 and 50 kPa until 20 min of MD has elapsed. In cases 7 and 8, the temperature increases begin at different points after 30 min of MD, but the maximum temperatures of the CM specimens of cases 7 and 8 are lower than those of cases 1, 2, 3 and 4 because the high initial water content must move outward, thus causing the free water to be well evaporated at the specimen surface, which leads to a decreasing temperature.

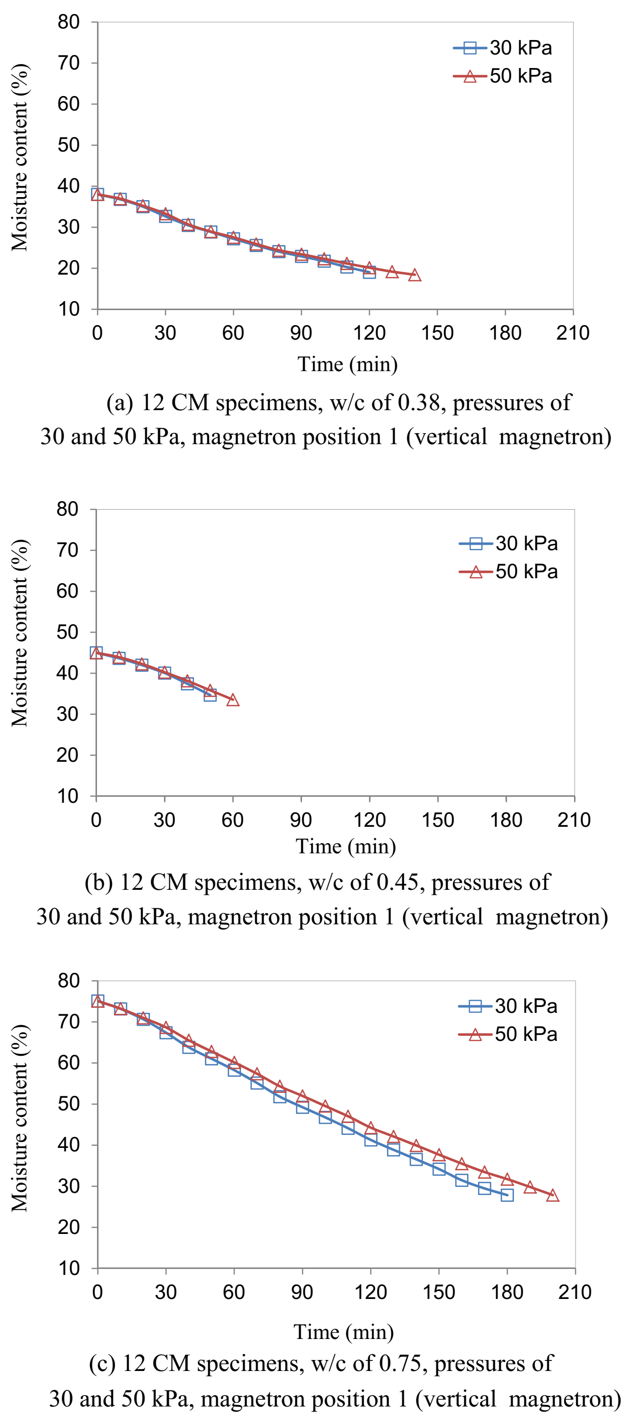


Fig. 5. Moisture content and time at pressures of 30 and 50 kPa and magnetron position 1 (vertical magnetron) for 12 CM specimens prepared with a controlled w/c of (a) 0.38, (b) 0.45 and (c) 0.75.

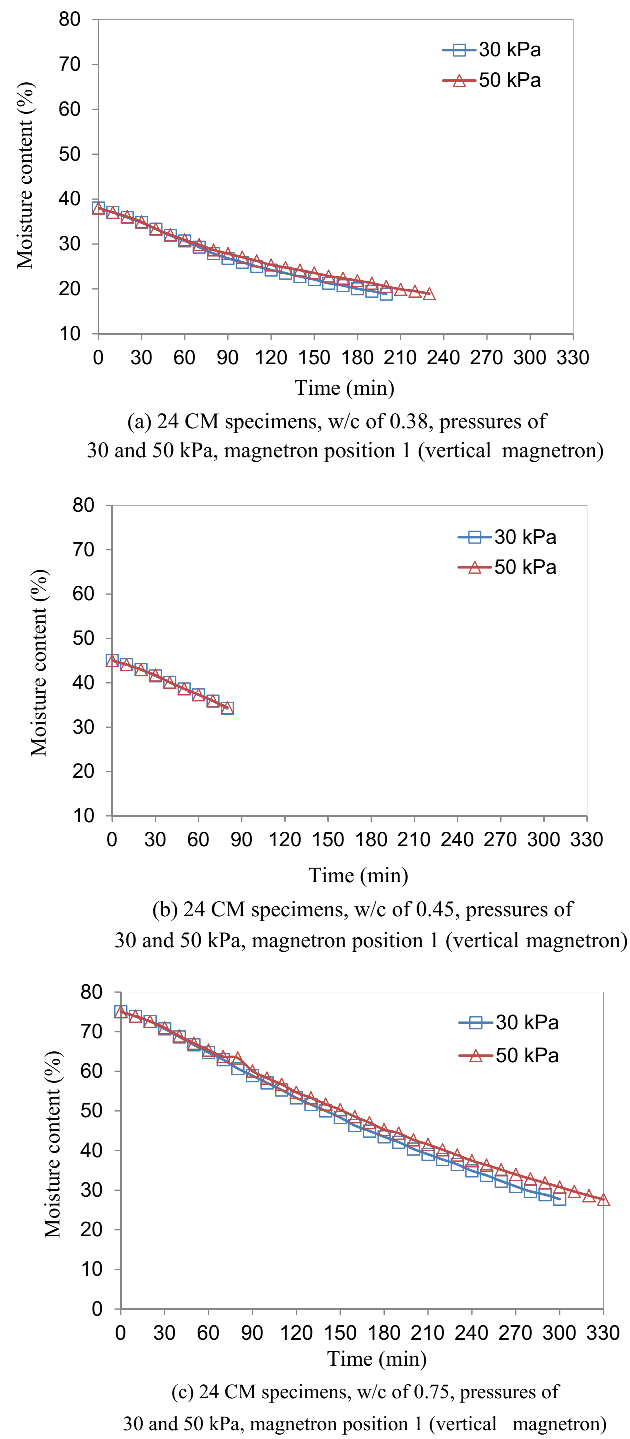


Fig. 6. Moisture content and time at pressures of 30 and 50 kPa and magnetron position 1 (vertical magnetron) for 24 CM specimens prepared with a controlled w/c of (a) 0.38, (b) 0.45 and (c) 0.75.

It can be seen that the temperature increased with a longer MD: in case 1, with 12 CM specimens that have a 0.38 w/c and are subjected to pressures of 30 and 50 kPa at magnetron position 1 (vertical magnetron), the temperature rises of CM are almost similar, but the MD subjected to 50 kPa is slightly higher than that obtained at 30 kPa. This may cause a lower pressure, which can increase the transference of internal water transfer outward and result in a small temperature decrease compared to that observed at 50 kPa. Furthermore, the decrease at a pressure of 30 kPa is lower than that a 50 kPa due to the low vacuum condition. The boiling point of the water is also low.

For the effect of the w/c of the CM specimens subjected to MD, it can be seen that the specimen with a 0.38 w/c has a higher temperature rise than do those w/c values of 0.45 and 0.75. This is because accelerating the drying of a CM specimen with microwave radiation can also help accelerate the hydration rate of the CM. In other words, MD generates heat within the specimens, causing a high rate of hydration reaction and the formation of C-S-H, which is also an exothermic reaction.

As shown in Fig. 4 (cases 7–12), the MD of CM behaves similarly in the cases of 12 specimens. However, the CM specimens subjected to pressures of 30 and 50 kPa are more different because the CM specimens subjected to 30 kPa have lower temperature rise than do those subjected to 50 kPa for the above reasons. Similar to the cases with 12 specimens of CM, 24 specimens at a w/c of 0.38 have a lower temperature rise than do those at 0.45 and 0.75.

Figs. 5 and 6 show a comparison between the moisture content and time of CM during MD with 12 and 24 specimens. For the 12-specimen cases (Cases 1–6), in the initial stage, CM is exposed to microwave energy and converted into thermal energy, with a high dielectric constant (ability to absorb microwave radiation) and loss factor (ability to convert the electric field into heat). This causes rapid moisture changes as the CM disperses moisture throughout the specimens. When the evaporation and condensation are still within the specimens, the evaporation rate of the early-age CM specimens is very high. Then, the rate of desiccation is reduced. When the CM enters the middle and final stages of MD, the moisture content in CM begins to decrease, which causes the moisture removal rate in the CM to decrease even more slowly during the initial stage. Therefore, it was found that at a pressure of 30 kPa, the moisture content decreased faster. The MD of CM will obtain a reasonable moisture content at a pressure less than 50 kPa, at which point water will evaporate faster than it will at an even lower pressure (30 kPa). Moreover, in cases 7–12, the moisture content changes while applying MD, similarly to the 12-specimen cases (cases 1–6).

When considering the efficiency of drying by means of MD, the final moisture content essentially determines the final w/c of CM, which affects the mechanics of the CM specimens. In detail, in case 1 (12 CM specimens, w/c of 0.38, pressures of 30 and 50 kPa, magnetron position 1 (vertical magnetron)), the final moisture content is lower than 0.38, resulting in a drawback in the compressive strength of CM; in cases 2 and 3, the final moisture content is 0.38, which should be at a suitable level for increasing the strength of CM.

3.2. Influence of w/c on the temperature increase and moisture (water) content of CM

Figs. 7 and 8 show a comparison between the temperature and time of MD of CM. The microwave power was 800 W and used magnetron position 1 (vertical magnetron) at low pressures of 30

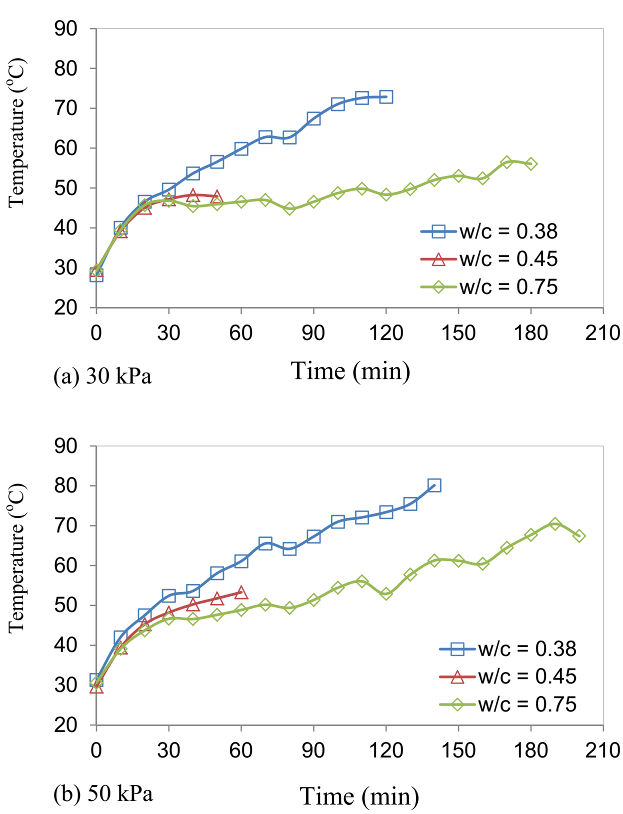


Fig. 7. Temperature and time with w/c values of 0.38, 0.45 and 0.75, magnetron 1 (vertical magnetron), and 12 CM specimens at pressures of (a) 30 kPa and (b) 50 kPa.

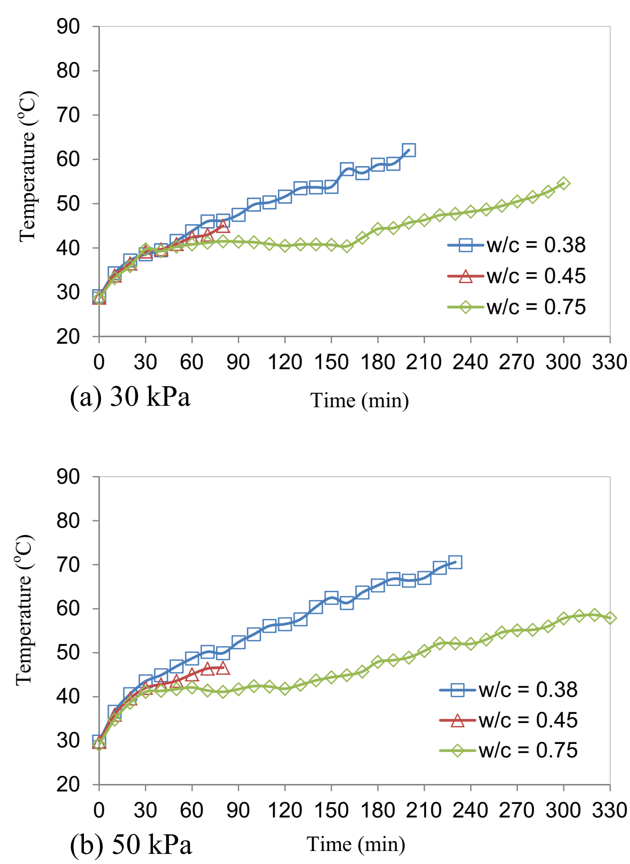


Fig. 8. Temperature and time with w/c values of 0.38, 0.45 and 0.75, magnetron 1 (vertical magnetron), and 24 CM specimens at pressures of (a) 30 kPa and (b) 50 kPa.

and 50 kPa with w/c levels of 0.38, 0.45 and 0.75 for 12 and 24 CM specimens. It can be clearly seen that the CM specimens prepared with a controlled w/c of 0.38 exhibit a continuous increase in temperature that is greater than the increases observed for the CM specimens with w/c values of 0.45 and 0.75 (Fig. 7(a) for cases 1, 3 and 5). Two factors may have more influence on the specimens: a higher w/c leads to a lower rate of hydration due to the exothermic reaction, and the highest amount of microwave is absorbed due to the high water content. MD enhances the rate of hydration reaction more than it increases the heat generated from the combined free water within the CM specimens. In other words, at a higher w/c and when subjected to low pressure, the result is free moisture moving outward, leading to a continuously increasing temperature in the CM specimens.

Compared to the cases of 1, 3 and 5, the CM specimens in cases 2, 4 and 6 (Fig. 7(b)) behave similarly; i.e., a higher w/c causes a lower temperature rise than does a lower w/c (0.75 < 0.45 < 0.38). However, the cases under 50 kPa exhibit higher temperature rises than do those under 30 kPa because at 30 kPa, there is a low boiling point of moisture, resulting in more evaporation and, consequently, a lower temperature rise. This phenomenon occurs similarly for the cases of 30 and 50 kPa (Fig. 8(a) and (b)).

Figs. 9 and 10 show a comparison between the moisture content and time of MD for CM. The microwave power was 800 W, at magnetron position 1 (vertical magnetron), low pressures of 30 and 50 kPa, and w/c levels of 0.45 and 0.75 for 12 and 24 CM specimens. The reason for using cases 3 and 5 instead of case 1, based on the aim of this study, is to decrease the w/c (water content) within the CM specimen to 0.38; i.e., a 0.38 w/c is the reference case, as explained above [25].

In Fig. 9((a) for 30 kPa and (b) for 50 kPa), the cases were rather interesting. The results show the same remaining moisture content rates for the 0.45 and 0.75 w/c specimens, although their initial moisture contents are different. In greater detail, the remaining moisture content rate behaves constantly, at approximately 15.76% per min (dry basis) for case 5, which is similar to case 3. Thus, the movement of moisture within the specimens is similar, as is the moisture at the surface of specimens in cases 3 and 5.

When comparing the cases subjected to 30 and 50 kPa, the same remaining water content rate can be observed, which indicates that the pressure rarely affects the moisture content change; this is also the case for the 24 CM specimens (approximately 15.75% per min (dry basis) for case 9). This occurs because magnetron 1 applies a uniform MD and consequently generates uniform heat generation, causing the moisture to transfer outward at a constant rate.

3.3. Influence of magnetron position on CM temperature and moisture content

Figs. 11 and 12 show the temperature, moisture content, and application time with a w/c of 0.45 at pressures of 30 and 50 kPa and at magnetron positions 1 (vertical magnetron), 2, and both 1 and 2 for 12 CM specimens, respectively. As shown in Fig. 11(a), it can be seen that using one magnetron (800 W) or two magnetrons (1600 W) increases the temperature of the CM specimens at a rapid rate in the early stage of applying MD due to the high amount of water content, which absorbs more of the microwave energy and converts into heat; subsequently, it decreases and gradually becomes constant. This is because a low water content reduces

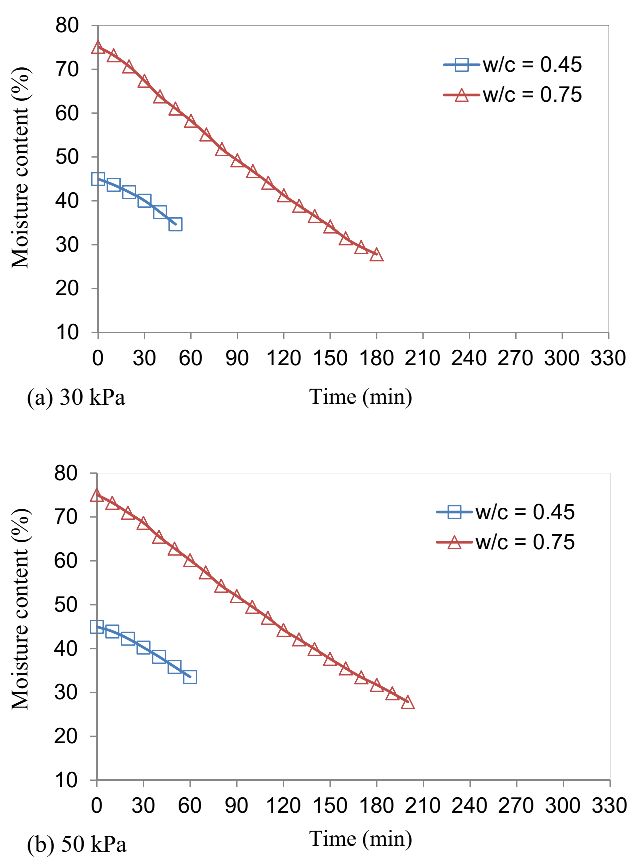


Fig. 9. Moisture content and time with w/c values of 0.45 and 0.75, magnetron 1 (vertical magnetron), and 12 CM specimens at pressures of (a) 30 kPa and (b) 50 kPa.

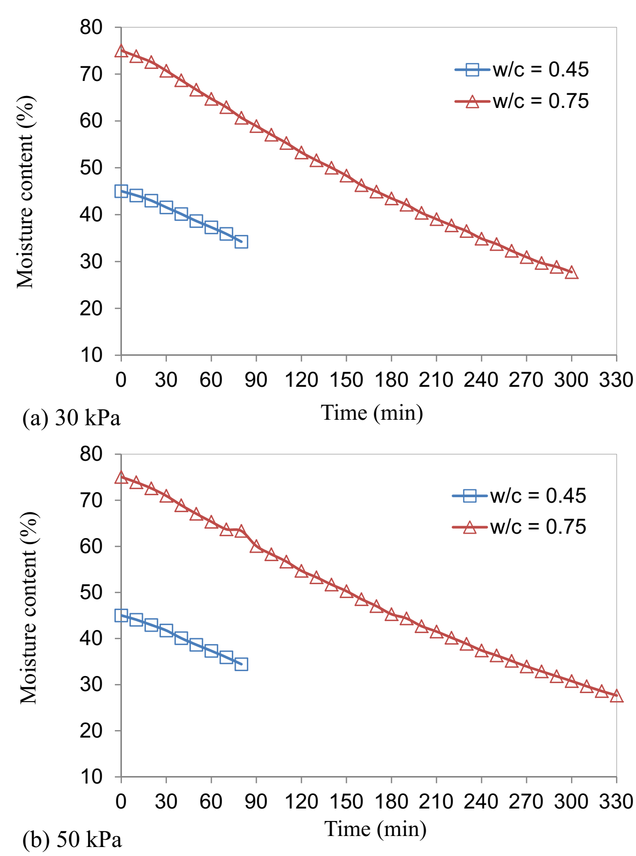


Fig. 10. Moisture content and time with w/c values of 0.45 and 0.75, magnetron 1 (vertical magnetron), and 24 CM specimens at pressures of (a) 30 kPa and (b) 50 kPa.

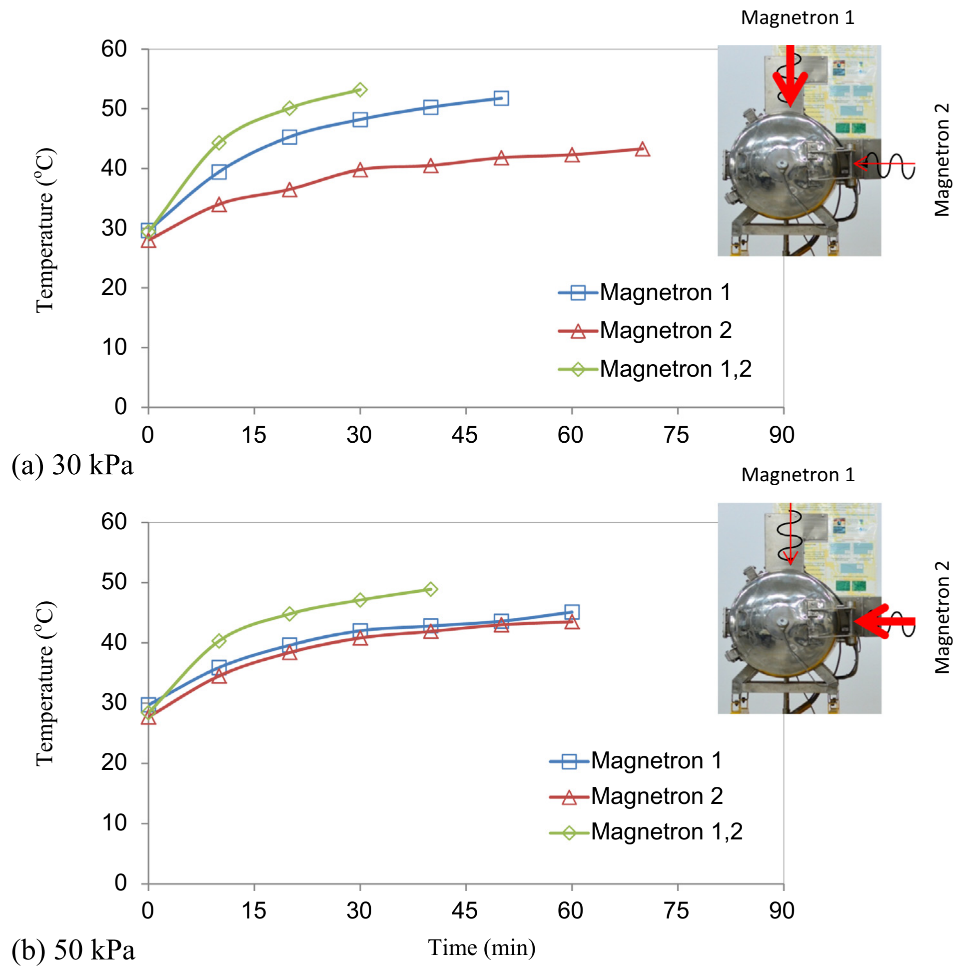


Fig. 11. Temperature and time with a w/c of 0.45 and a pressure of 50 kPa at magnetron positions 1 (vertical magnetron) 2 (horizontal magnetron), and both 1 and 2 for 12 CM specimens.

the absorbed microwave radiation. In addition, the evaporation of water also results in a decrease in the surface temperature.

When comparing the number of magnetron, two magnetrons (1600 W power) can increase the temperatures of the CM specimens more than one magnetron (800 W power) can because the microwave power increases in a shorter application time. Additionally, applying magnetron position 1 (vertical magnetron) is more efficient in increasing the temperature than magnetron position 2 is (horizontal magnetron). This occurs because applying microwave irradiation to CM specimens causes uniform heat generation with a longer MD application, as shown for the specimen located in the cavity, in Fig. 13, and the distribution of the surface temperature of CM, as shown in Fig. 14. For example, in Fig. 14(a), the distribution of the surface temperature of CM is at a pressure of 30 kPa, w/c of 0.38, magnetron 1, and 12 CM for (a.1) 10 min, (a.2) 40 min, and (a.3) 80 min. It is found that in the early state of MD, the appearance of two symmetrical hot spots in the CM specimens is consistent with the direction of the applied electric field, whereas in a later state of MD (more than 40 min of MD application), a combination of two hot spots leads to a uniform surface temperature. This phenomenon also occurs in cases 2–6. Further, it is noticed that at the early stages of MD, the hot-spot occurs on the right side (top and side views of the specimen in a.1, b.1, c.1, and d.1, etc.) of the CM specimen due to the distribution of microwave radiation (electric field). This behavior is consistent with the transfer of moisture outward. In other words, in the early stage of MD, the CM specimens have higher moisture contents at the surface, which induces the two hot-spots; however, in the later stage, the moisture at the surface is partly evaporated, which affects the heat generated from MD because a uniform temperature distribution occurs.

MD using magnetron position 2 (horizontal magnetron) can induce a lower temperature rise than can that using magnetron position 1. This is because the direction of the magnetron on that unsymmetrical electric field acts on the CM specimens, so the specimens are located close to the magnetron and absorb more microwave power, whereas the specimen located farther from the magnetron absorbs less microwave power.

When comparing Fig. 11(a) and (b), which show specimens subjected to 30 and 50 kPa, respectively, it is found that when using magnetron position 1 (vertical magnetron), the temperature rise is no less than that obtained using magnetron position 2 (horizontal magnetron). This result indicates that the surface temperature of the CM specimens is more sensitive to a low pressure in the cavity, which is consistent with the moisture content, as shown in Fig. 12(a) and (b).

In the comparison of cases 14 and 16, which show 12 and 24 CM specimens, respectively, it can be noticed that using MD with two magnetrons (1600 W) can result in a faster rate of temperature rise than can using one magnetron (symmetrical position 1 and unsymmetrical position 2) by keeping the remaining moisture content of the specimens consistent. In addition, using two magnetrons has

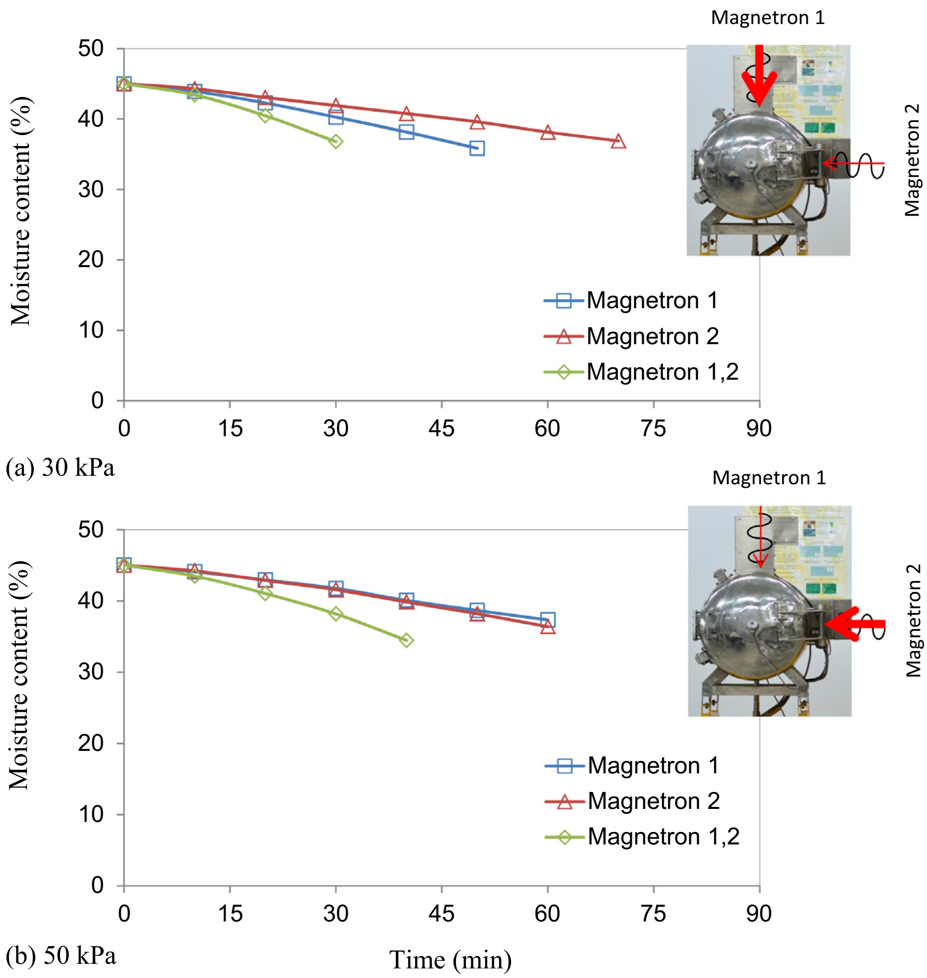


Fig. 12. Moisture content and time with a w/c of 0.45 and a pressure of 50 kPa, magnetron positions 1 (vertical magnetron), 2 (horizontal magnetron), and both 1 and 2 for 12 CM specimens.

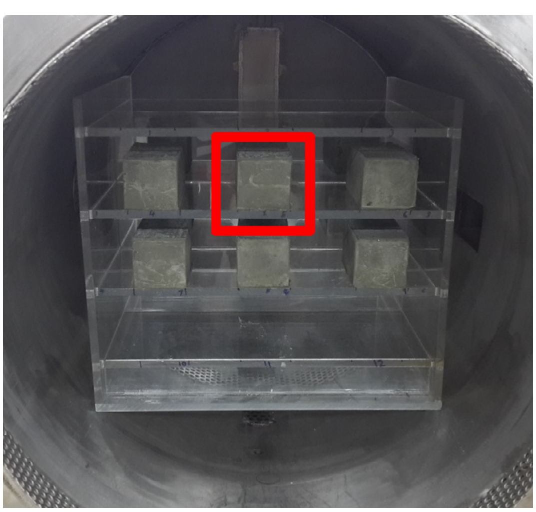


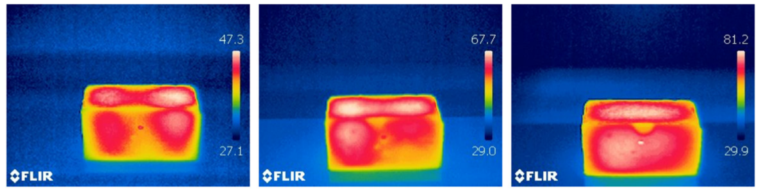
Fig. 13. Position used to measure the distribution of the surface temperature of CM.

an effect that is more similar to that observed when utilizing magnetron position 1 (vertical magnetron) than to that of position 2 due to the uniform heat generation and transferring within the CM specimens.

3.4. Influence amount of CM specimens on temperature and moisture content

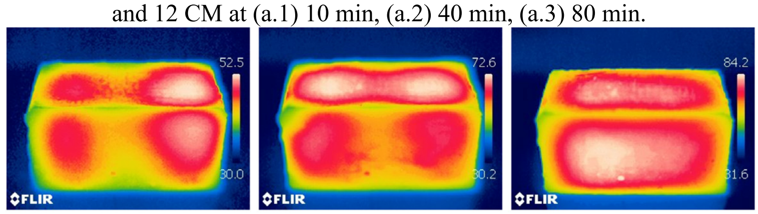
Figs. 15 and 16 show temperature, moisture content, and application time at a pressure of 50 kPa prepared with a controlled a w/c of 0.45 for 12 and 24 CM specimens (workloads) using magnetron positions 1 (vertical magnetron), 2 and both 1 and 2. The cases in Fig. 15 show the same tendency of a rapid increase in temperature in the early stage (first 30 min of MD) and a low rate after 30 min of MD processing. These results are consistent with the remaining moisture content (Fig. 16). Moreover, the 12 CM specimens have a higher temperature than do the 24 CM specimens, as shown in Fig. 15(a), (b), and (c). This is because, when using equal amounts of microwave power, a higher number (24) of CM specimens will absorb more microwave power than will a lower number (12), resulting in a lower increase in temperature.

When comparing magnetron positions 1 and 2, it can be seen that the number of specimens is more sensitive to magnetron position 1 (vertical magnetron) than to position 2. This is due to the feeding direction of the waveform microwave, which results in more efficient drying with increases in the temperature and moisture content of the specimens, whereas position 2 (unsymmetrical feeding direction) is less efficient than position 1, and the differences between the specimens (12 and 24) are very small. In addition, for MD using magnetron positions 1 and 2, the position is more likely to have an effect for magnetron position 1 than it is



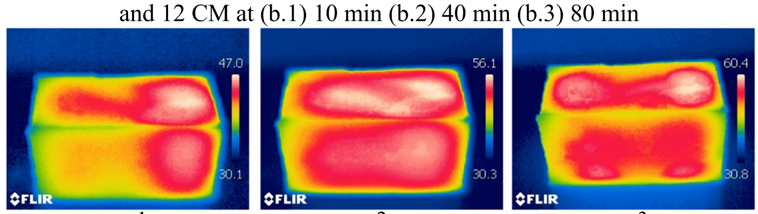
a.1 a.2 a.3

(a) Distribution of surface temperature of CM at a pressure of 30 kPa, w/c of 0.38, magnetron 1, and 12 CM at (a.1) 10 min, (a.2) 40 min, (a.3) 80 min.



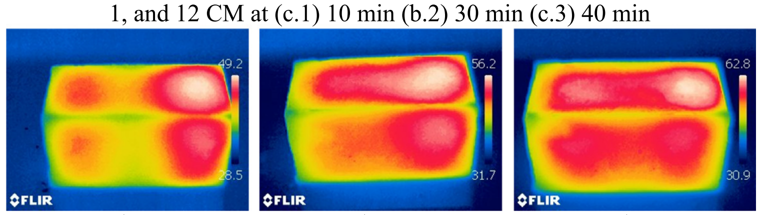
b.1 b.2 b.3

(b) Distribution of surface temperature of CM at a pressure of 50 kPa, w/c of 0.38, magnetron 1, and 12 CM at (b.1) 10 min (b.2) 40 min (b.3) 80 min



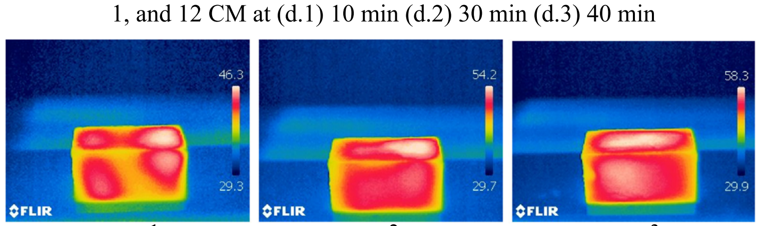
c.1 c.2 c.3

(c) Distribution of surface temperature of CM at a pressure of 30 kPa, a w/c of 0.45, magnetron 1, and 12 CM at (c.1) 10 min (b.2) 30 min (c.3) 40 min



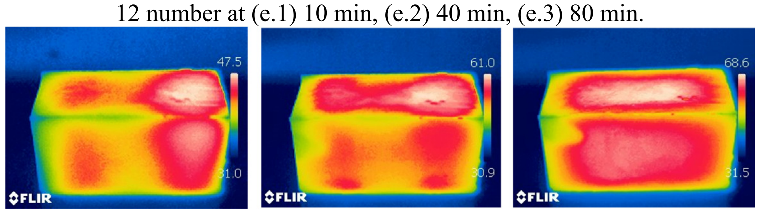
d.1 d.2 d.3

(d) Distribution of surface temperature of CM at a pressure of 50 kPa, a w/c of 0.45, magnetron 1, and 12 CM at (d.1) 10 min (d.2) 30 min (d.3) 40 min



e.1 e.2 e.3

(e) Distribution of surface temperature at a pressure of 30 kPa, a w/c of 0.75, magnetron 1, and 12 number at (e.1) 10 min, (e.2) 40 min, (e.3) 80 min.



f.1 f.2 f.3

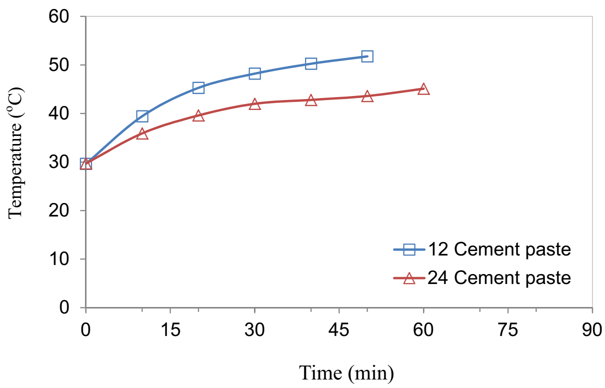
(f) Distribution of surface temperature at a pressure of 30 kPa, a w/c of 0.75, magnetron 1, and 12 CM at (f.1) 10 min, (f.2) 40 min, (f.3) 80 min.

Fig. 14. Distribution of surface temperature of CM.

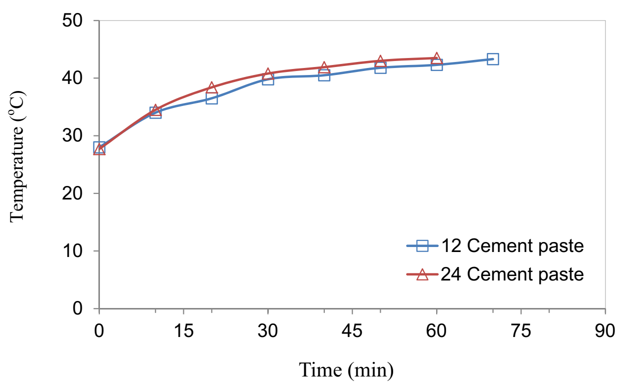
for position 2. As shown in Fig. 16, the remaining moisture content is related to the increase in temperature in the CM specimens (Fig. 15) because of the decrease in moisture that occurs when using magnetron positions 1 and 2 together due to the high microwave power.

3.5. Influence of low pressure and w/c ratio on compressive strength of CM

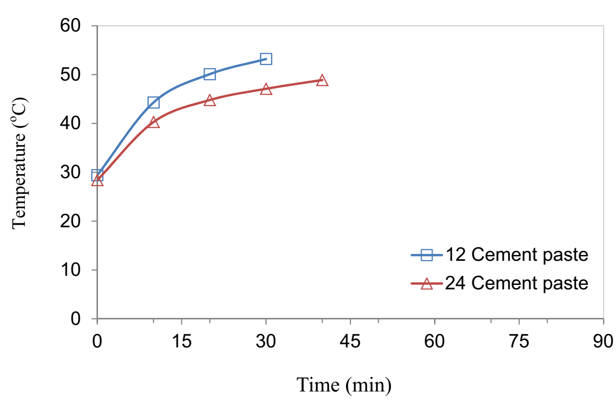
Compressive strength is a main property of CM and is used to determine a specimen's ability to resist an acting force/load until



(a) Magnetron position 1 (vertical magnetron)

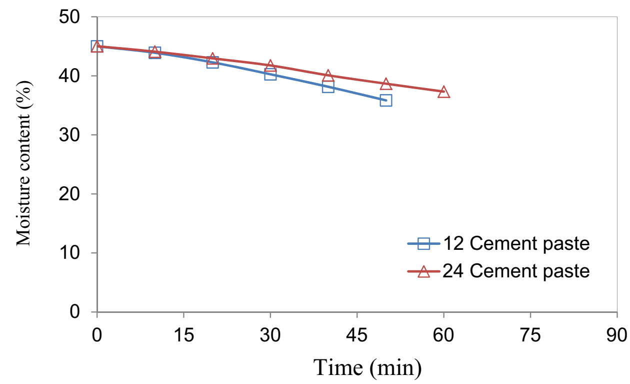


(b) Magnetron position 2 (horizontal magnetron)

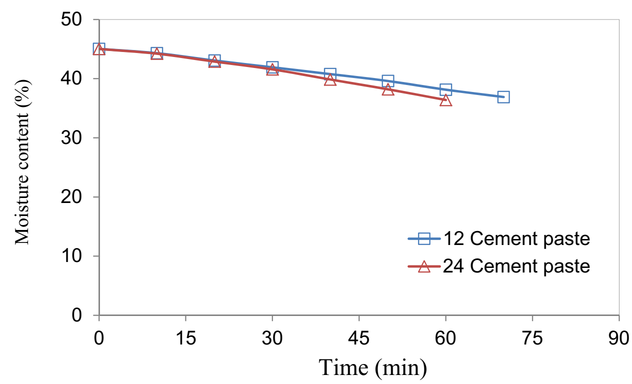


(c) Magnetrons position 1 (vertical magnetron) and 2 (horizontal magnetron)

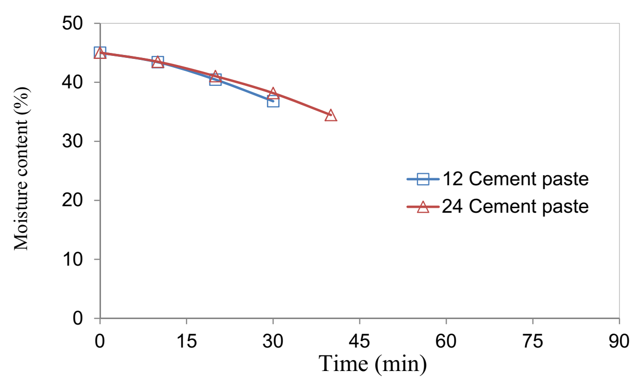
Fig. 15. Temperature and application time at a pressure of 50 kPa, with a controlled w/c of 0.45 and 12 and 24 CM specimens (workloads) using magnetron position 1 (vertical magnetron), magnetron position 2 (horizontal magnetron), and magnetron positions 1 and 2.



(a) Magnetron position 1 (vertical magnetron)



(b) Magnetron position 2 (horizontal magnetron)



(c) Magnetron positions 1 (vertical magnetron) and 2 (horizontal magnetron)

Fig. 16. Moisture content and application time at a pressure of 50 kPa, with a controlled w/c of 0.45 and with 12 and 24 CM specimens (workloads) using magnetron position 1 (vertical magnetron), magnetron position 2 (horizontal magnetron), and magnetron positions 1 and 2.

failure occurs. Fig. 17 shows the compressive strength development and elapsed time of CM with different w/c values of 0.38, 0.45 and 0.75 at pressure levels of 30 and 50 kPa by applying magnetron position 1 (vertical magnetron) to 12 CM specimens. It can be classified into two periods: period one spans from mixing and drying by MD to 3 days, and period two spans from 3 to 28 days. In the first period, cases 1 (w/c = 0.38 at 30 kPa) and 2 (w/c = 0.38 at 50 kPa) have higher compressive strengths than do cases 3 (w/c = 0.45 at 30 kPa) to 6 (w/c = 0.75 at 50 kPa). In addition, cases 5 (w/c = 0.75 at 30 kPa) and 6 (w/c = 0.75 at 50 kPa) have the lowest compressive strengths. These results can be explained by the w/c level of 0.38 being suitable for MD in this period because it is a standard level for developing the compressive strength with water to allow cement particles to react with full hydration and be a part of the calcium-silicate-hydrate (C-S-H) structure [25]. At a w/c level of 0.75, the CM specimens have the lowest rate of hydration (a high amount of water content negatively affects the hydration rate). However, the hydration rate of case 2 (w/c = 0.38 at 50 kPa) is higher than that of case 1 (w/c = 0.38 at 30 kPa) because more water loss occurs during MD application in case 1, so the amount of water is insufficient for the full hydration reaction to proceed in the early-age state, thus leading to a lower compressive strength.

From 1 to 3 days after mixing and applying MD processing, case 4 (w/c = 0.45 at 50 kPa) has more compressive strength than do

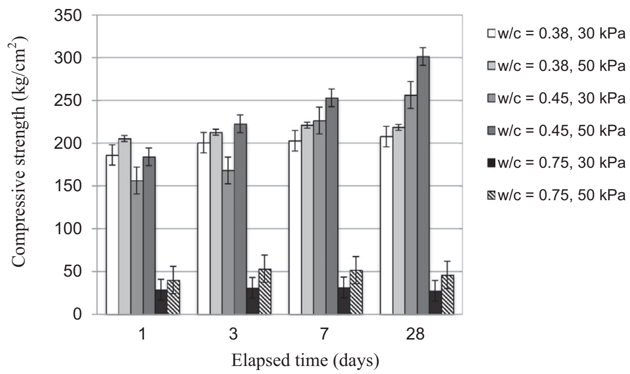


Fig. 17. Compressive strengths and elapsed time of CM with w/c values of 0.38, 0.45 and 0.75 at pressure levels of 30 and 50 kPa, magnetron position 1 and 12 CM specimens.

cases 1, 2 and 3, which indicates that when decreasing the w/c from 0.45 to 0.38 has a positive effect on the development of compressive strength and is a starting point for the development of compressive strength in period 2.

For period 2, the highest compressive strength of CM occurs in case 4 (w/c = 0.45 at 50 kPa) due to the previous explanation, while cases 5 and 6 have the lowest compressive strengths and are continuously affected from the conditions of period 1. These results imply that MD is unsuitable for the a high-strength CM, even if the water content is reduced to the standard level of CM (w/c = 0.38). However, in case 4, the optimal initial w/c of CM is lower at 0.45 than it is at 0.75. Additionally, from the engineering point of view, the long-term compressive strength after 28 days is considered to indicate the performance of CM under MD while applying under the conditions of case 4.

The magnetron positions are compared in Fig. 18, which shows that using magnetron position 1 (vertical magnetron) leads to the highest compressive strength development and is similar to water drying, which is the standard drying condition of CM. Moreover, this result for the CM specimen also affects the uniform MD and temperature distribution. On the other hand, using magnetron position 2 (horizontal magnetron) affects the non-uniform electric field that act on the CM specimens, resulting in uniform drying and low compressive strength. Additionally, using both magnetrons position 1 (vertical magnetron) and 2 has more negative effects on the compressive strength due to the previous reasons.

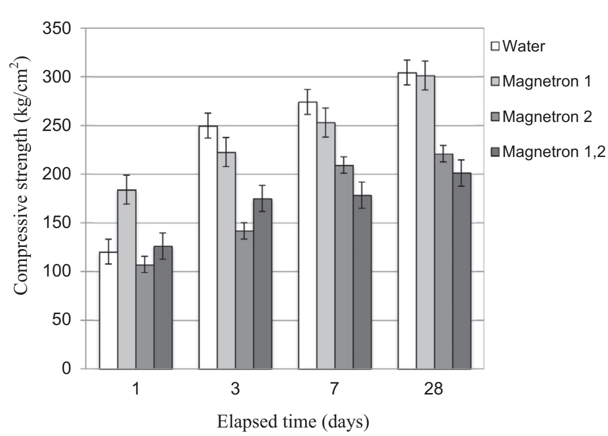


Fig. 18. Compressive strength and curing time of CM with the microwave at position 1 (vertical magnetron), magnetron position 2 (horizontal magnetron), and 1 and 2 magnetrons with a w/c of 0.45, a pressure of 50 kPa and 12 CM specimens.

4. Concluding remarks

Based on the experimental results obtained from the use of microwave-assisted drying (MD) to accelerate the drying of Portland cement pastes (CM) under specific low pressures using a combined unsymmetrical double-fed microwave and vacuum system, the following conclusions can be drawn:

- When CM specimens are subjected to MD, in the initial state, the temperature increases because of the high level of humidity. Additionally, the temperature of the CM increases more slowly after the initial stage, but it does continue to increase. The same tendency exists for temperature to rise at a rapid rate in the early stage: in the first 30 min, a w/c level of 0.38 is suitable for MD.
- Subjecting a CM specimen with a higher w/c to low pressure results in the free moisture moving outward and a continuously increasing temperature. Moreover, the remaining water content rate is constant, which indicates that the pressure rarely affects the moisture content.
- When decreasing the initial w/c from 0.45 to 0.38, a positive effect on compressive strength is observed at 28 days.
- The minimal energy-time ratio of MD is found by controlling the w/c of CM to 0.45 and 0.75 when subjected to a 30-kPa pressure and to 0.75 when subjected to a 30-kPa pressure for 12 and 24 specimens.
- The use of two magnetrons (1600 W power) can increase the temperatures of the CM specimens more than one magnetron can (800 W power) because the microwave power will increase in a shorter application time. However, applying magnetron position 1 (vertical magnetron) is more efficient for increasing the temperature than is magnetron position 2 (horizontal magnetron).

Conflict of interest

There is no conflict of interest in this study.

Acknowledgement

The authors gratefully acknowledge the Thailand Research Fund under the TRF contract No. RTA5980009 for supporting this research. Special thanks go to Mr. Sira Lertwiriyajitt for his assistance in testing experiments.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.119.

References

[1] N. Makul, P. Rattanadecho, D.K. Agrawal, Applications of microwave energy in cement and concrete – a review, Renew. Sustain. Energy Rev. 37 (2014) 715–733.
[2] N. Makul, P. Rattanadecho, A. Pichaicherd, Accelerated microwave curing of concrete: a design and performance-related experiments, Cem. Concr. Compos. 83 (2017) 415–426;
A.C. Metaxas, Microwave heating, J. Microw. Power Electromagn. Energy. 5 (1991) 237–247.
[3] A.C. Metaxas, R.J. Meredith, Industrial Microwave Heating, Peter Peregrinus, Herts, United Kingdom, 1998.
[4] A.S. Mujumdar, Handbook of Industrial Drying, 4th ed., CRC Press, Boca Raton, Florida, USA, 2014.
[5] Y. Choi, M.R. Okos, Thermal properties of liquid foods review, in: M.R. Okos (Ed.), Physical and Chemical Properties of Food, American Society of Agricultural Engineers, St. Joseph, MI, 1986, pp. 5–77.

[6] K. Chang, R.R. Ruan, P.L. Chen, Simultaneous heat and moisture transfer in cheddar cheese during cooling. I. Numerical simulation, Drying Technol. 16 (7) (1998) 1447–1458.
[7] W. Kaensup, S. Wongwises, S. Chutima, Drying of pepper seeds using a combined microwave fluidized bed dryer, Drying Technol. 16 (3–5) (1998) 853–862.
[8] W. Kaensup, S. Wongwises, Combined microwave/fluidized bed drying of fresh pepper corns, Drying Technol. 22 (4) (2004) 779–794.
[9] I. Alibas, Microwave, vacuum, and air drying characteristics of collard leaves, Drying Technol. 27 (2009) 1266–1273.
[10] F. Adam, Drying kinetics and quality of beetroots dehydrated by combination of convective and vacuum-microwave methods, J. Food Eng. (2010) 461–470.
[11] T. Basak, A. Meenakshi, A theoretical analysis on microwave heating of food slabs attached with ceramic plates: role of distributed microwave incidence, Food Res. Int. 39 (8) (2006) 932–944.
[12] M. Regier, H. Schubert, Microwave processing, in: H. Schubert, M. Regier (Eds.), The microwave processing of foods, Woodhead Publishing, Sawston, Cambridge, USA, 2001.
[13] N. Afrin, Y. Zhang, J.K. Chen, Thermal lagging in living biological tissue based on non-equilibrium heat transfer between tissue, arterial and venous bloods, Int. J. Heat Mass Transf. 54 (2011) 2419–2426.
[14] P. Perre, I.W. Turner, Microwave drying of softwood in an oversized waveguide: theory and experiment, AIChE J. 43 (10) (1997) 2579–2595.
[15] S. Vongpradubchai, P. Rattanadecho, Microwave and hot air drying of wood using a rectangular waveguide, Drying Technol. 29 (4) (2011) 451–460.
[16] T. Basak, A. Meenakshi, Influence of ceramic supports on microwave heating for composite dielectric food slabs, AIChE J. 52 (6) (2006) 1995–2007.
[17] T. Basak, Badri S. Rao, Role of ceramic composites and microwave pulsing on efficient microwave processing of pork meat samples, Food Res. Int. 44 (2011) 2679–2697.
[18] T. Basak, Role of resonance on microwave heating of oil–water emulsions, AIChE J. 50 (2004) 2659–2675.
[19] P. Ratanadecho, Microwave Heating Using a Rectangular Wave Guide Ph.D. Thesis, Nakaoka University of Technology, Japan, 2002.
[20] T. Basak, S.K. Samanta, A. Jindamwar, A novel concept on discrete samples for efficient microwave processing of materials, Chem. Eng. Sci. 63 (12) (2008) 3292–3308.
[21] E. Tsotsas, A.S. Mujumdar, Modern Drying Technology, vol. 5, VCH Wiley, Germany, 2014.
[22] Kusturee Jeni, Mudtapha Yapa, Phadungsak Rattanadecho, Design and analysis of the commercialized drier processing using a combined unsymmetrical double-feed microwave and vacuum system (case study: tea leaves), Chem. Eng. Process. Process Intensif. 49 (2010) 389–395.
[23] ASTM C305 - 14 Standard Practice for Mechanical Mixing of Hydraulic Concrete and Mortars of Plastic Consistency, Annual Book of ASTM Standard Vol. 4.01 (2014). Philadelphia, PA.
[24] ASTM C39/C39M - 17a Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, Annual Book of ASTM Standard Vol. 4.02 (2017). Philadelphia, PA.
[25] R.G. Hutchinson, J.T. Chang, H.M. Jennings, M.E. Brodwin, Thermal acceleration of Portland cement mortars with microwave energy, Cem. Concr. Res. (1991) 795–799.