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RESEARCH ARTICLE

EFFECT OF MICROWAVE CURING ON STRENGTH OF MORTAR and DRYING BEHAVIOUR

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ABSTRACT

Microwave curing (MC) is a method that can accelerate hydration of cement, which results in rapid strength increase of mortars. This study investigates effect of microwaving curing on the strength of mortar the effect of MC (460 W,5, 10, 15, 30 mins) and the effect of MC (700 W, 5, 10, 15, 30 mins). MC can be used to determine the hydration degree of the mortars and rapid strength increase of mortars. Additionally, Newton, Page, Henderson and Pabis, Geometric, Wang and Singh drying models were compared with each other to determine the moisture content at a given moment in the dryer. The performances of these models are compared according to the correlation coefficient (r), the estimated standard error (e_s) and the sum of the squares of the residuals (χ^2) between the observed and predicted humidity ratios. According to the results obtained, for all drying conditions the drying behaviors of the products are explained better by Page Model as compared others.

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INTRODUCTION

Heat curing has been applied to construction materials especially for the precast concrete to improve the strength development process. This concrete attains sufficient strength in shortcuring time, so the moulds can be reused, and the final products can be rapidly delivered to the site (Sohn and Johnson, 1999). Conventional heat curing techniques deliver thermal energy to thesurface of the material by radiant or convective heating, which istransferred to the bulk through conduction. This creates thermalgradients in the material and thus non-uniform heating that mightresult in less than desirable properties. An alternative is microwavecuring, where microwave energy is delivered directly to the materialthrough the interactions at the molecular level with the electromagneticfield. Microwaves penetrate the material and provide energy, resulting in volumetric heating. The electromagnetic energy isconverted to thermal energy which in turn is used to enhance thereaction kinetics and accelerate the strength gain. Hence microwavecuring relies on energy conversion rather than heat transfer (Das *et al.,* 2009; Agrawal, 1998). Since the energy transfer does not rely on diffusion of heat from the surfaces, rapid and uniform heating is possible (Thostenson, 1999). A few studies on microwave curing of concretes have been reported, mostly dealing with the strength development of concretes under microwave curing (Rattanadecho, 2008; Sohn and Johnson, 1999). Therefore, this research proposed the process to decreases the microwave curing time and energy using the short-time microwave radiation in addition to the convention heat curing for the mortar. Microwave radiation could bea factor in the mortar formation and strength increasing. Additionally, this method could shorten the curing time of mortar, and give the high compressive strength at an early age compared to the conventional curing. Moreover, another purpose in this study is to generate a control system that will decrease the energy cost of the drying period, reduce the total drying period. Furthermore, it is to raise the relationship between the mathematical model and the real behavior to a better level, and to enable the dynamic behaviors of the dried concrete to be determined beforehand.

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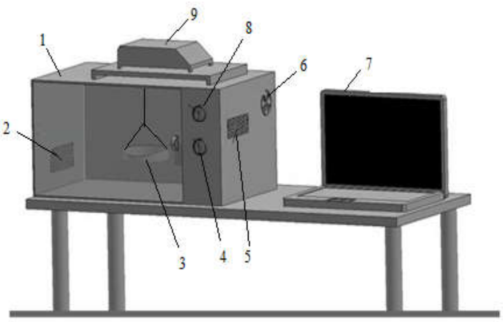
MATERIALS AND METHODS

Cement (CEM I 42.5 R) was supplied from Akçansa in Turkey. The physical, chemical and mechanical compositions of the cement, obtained from cement supplying company, are given in Table 1. This study was performed to assess the acceleration of strength development by microwave heating and to evaluate the strength of these concretes. The prisms meant for microwave curing, needs to get a minimum strength before microwave curing. The cubes were cured in the microwave oven 40 x 40 x 160mm mortar prisms were prepared according to TS EN 196-1 and used to investigate the effects of microwave and two steam curing (400 W and 700W) on the compressive strength development. The cement/sand ratio was kept constant at 1:3 and the water/binder ratio was kept constant at 0.5 for samples.

Table 1. The physical, chemical and mechanical propertie s of cement

	PROPERTIES	UNIT	Cement
Chemical properties	Insoluble Residue	%	0.2500
	SO_3	%	3.2200
	Loss on Ignition	%	1.0000
	Cl^-	%	0.0445
Physical properties	Specific Gravity	g/cm^3	3.15
	Initial setting time	min	146
	Final setting time	min	193
	Volume expansion	mm	1
	Specific Surface Area	cm^2/g	3710
	Fineness 45 µm	%	5.8
	Fineness 90 µm	%	0.3
Mechanical properties	Compressive Strength, 2 days	MPa	28.9
	Compressive Strength, 7 days	MPa	43.8
	Compressive strength, 28 days	MPa	58.3

The compressive strength of the specimens (40x40x160 mm) was measured according to TS EN 12390-3. The drying experiments were performed using a microwave oven (with Beko brand, 2450 MHz frequency, maximum 800 W power and 19L inner space, rotary table) with internal cavity dimensions of 390 mm (width) x 268 mm (height) x 400 mm (depth) was used as seen in Figure 1.



1. Microwave oven
2.Ventilation holes
3.Tray
4.Timer
5. Magnetron
6. Fan
7. Computer
8. Power switch
9. Scales

Figure 1. Microwave Drying System

Mathematical Modelling of Drying Behavior

For the investigation of drying characteristics of concret, it is important to model the drying behaviour effectively. In this study, the experimental drying data of concret at different microwave powers were fitted into five commonly used thin-layer drying models, listed in Table 2. Moisture ratio of samples during drying is generally calculated by the following equation (Çelen et al., 2016).

Table 2. Various mathematical models used in drying (Kahveci and Cihan, 2008)

Model	Model equation
Newton	$mr = \exp(-kt)$
Page	$mr = \exp(-kt^n)$
Henderson and Pabis	$mr = a\exp(-kt)$
Geometric	$mr = at^{-n}$
Wang and Singh	$mr = 1 + at + bt^2$

The least squares method is commonly used to simulate the drying behavior, especially of biological material models presented up to now. In this method, the coefficients in the models are determined by minimizing the sum of the squared differences between the experimental and the theoretical moisture ratios. A better suitability between the model results and the empirical data is reached when the correlation coefficient (r) will be closer to 1 and the standard error (e_s) and the chi-square (χ^2) will be closer to 0. These parameters are defined in Eq. 2-4 (Çelen et al., 2010). The moisture ratio (MR) in the model equations is defined in Eq.1 (Çelen et al., 2016).

$$MR = m/mo \quad (1)$$

$$r = \frac{n_o \sum_{i=1}^{n_o} MR_{pre,i} MR_{\exp,i} - \sum_{i=1}^{n_o} MR_{pre,i} \sum_{i=1}^{n_o} MR_{\exp,i}}{\sqrt{n_o \sum_{i=1}^{n_o} (MR_{pre,i})^2 - \left(\sum_{i=1}^{n_o} MR_{pre,i}\right)^2} \sqrt{n_o \sum_{i=1}^{n_o} (MR_{\exp,i})^2 - \left(\sum_{i=1}^{n_o} MR_{\exp,i}\right)^2}} \quad (2)$$

$$e_s = \sqrt{\frac{\sum_{i=1}^{n_o} (MR_{pre,i} - MR_{\exp,i})^2}{n_o}} \quad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^{n_o} (MR_{pre,i} - MR_{\exp,i})^2}{n_o - n_c} \quad (4)$$

where $MR_{pre,i}$ is the I *th* predicted moisture ratio, $MR_{exp,i}$ is the i*th* experimental moisture ratio, n_o is the number of observations and n_c is the number of coefficients in the drying model.

RESULTS AND DICUSSION

Microwave Drying Model

Models given in Table 1 are used to express the drying behavior of concrete. Curve fitting computations were carried out on five drying models relating the drying time and moisture ratio. The best fitness model between models in Table 3-5 is gives the Page model. In addition the drying curves based on the Page model are presented with the experimental moisture ratios in Figures 3-4. The acceptability of the drying model is based on a value for the corelation coefficient r which should be close to one, and low values for the standard error e_s and the mean squared deviation χ^2. The results show that the most appropriate model in describing drying curves of concrete is the Page model with r in the range of 0,895–0,999, and with e_s in the range of 0,004-0,053 and with χ^2 in the range of 0,00009-0,0229 for dried concrete.

Drying behavior changes of samples that had different heat during the microwave drying were shown in Fig. 3.1 - 3.2.

Compressive Strength

The results of strength tests on the mortar samples for microwave curing are shown in Table 5 and Figure 5 and Figure 6. The specimens gained the strength with age and the strengths at 7 and 28 days were 20.0 and 35.8 MPa, respectively. The amount of the strength gain was about 10 MPa by using a 30 minute at 460 W, 15 minute at 700 W microwave heating.

Table 3. Analysis results of the models for concrete at 700W with microwave power

Model Microwave power		Constants	r^2	e_s	χ^2
Newton 700 W	5min	k=0,015	0,875	0,009	0,00008
	10min	k=0,028	0,969	0,037	0,0013
	15min	k=0,080	0,957	0,151	0,0228
	25min	k=0,097	0,927	0,154	0,0238
	45min	k=0,114	0,921	0,091	0,0082
Page 700 W	5min	k=0,011 / n=1,221	0,895	0,010	0,00005
	10min	k=0,005 /n=1,853	0,999	0,004	0,00001
	15min	k=0,003 / n=2,410	0,999	0,008	0,00006
	25min	k=0,011 / n=1,221	0,989	0,053	0,00276
	45min	k=0,013 / n=1,930	0,980	0,048	0,02297
Henderson and Pabis 700 W	5min	a=1,002 / k=0,016	0,875	0,010	0,00010
	10min	a=1,071 / k=0,038	0,965	0,021	0,00042
	15min	a=1,381 / k=0,117	0,927	0,101	0,01015
	25min	a=2,170 / k=0,176	0,969	0,064	0,00415
	45min	a=1,984 / k=0,190	0,990	0,032	0,00101
Geometric 700 W	5min	a=0,990 / n=0,036	0,744	0,015	0,00022
	10min	a=1,064 / n=0,135	0,776	0,052	0,00273
	15min	a=1,698 / n=0,595	0,750	0,184	0,03369
	25min	a=10,241 / n=1,506	0,943	0,089	0,00786
	45min	a=10,849 / n=1,637	0,991	0,026	0,00065
Wang and Singh 700 W	5min	a=-0,010/ b=-0,001	0,913	0,009	0,00008
	10min	a=-0,007/ b=-0,002	0,997	0,007	0,00004
	15min	a=-0,024/ b=-0,003	0,987	0,044	0,00194
	25min	a=-0,074/ b=-0,001	0,912	0,141	0,01978
	45min	a=-0,077/ b=0,001	0,886	0,092	0,00853

Table 4. Analysis results of the models for concrete at 460W with microwave power

Model Microwave power		Constants	r^2	e_s	χ^2
Newton 460 W	5min	k=0,059	0,980	0,027	0,00074
	10min	k=0,049	0,930	0,075	0,00567
	15min	k=0,067	0,921	0,153	0,02327
	30min	k=0,074	0,970	0,177	0,03104
Page 460 W	5min	k=0,096 / n=0,628	0,954	0,014	0,00018
	10min	k=0,004 /n=2,229	0,999	0,008	0,00005
	15min	k=0,001 / n=2,629	0,990	0,035	0,00123
	30min	k=0,002 / n=2,406	0,992	0,046	0,00210
Henderson and Pabis 460 W	5min	a=0,939 / k=0,041	0,983	0,008	0,00006
	10min	a=1,134 / k=0,069	0,917	0,054	0,00288
	15min	a=1,325 / k=0,098	0,889	0,115	0,01332
	30min	a=1,657 / k=0,121	0,931	0,125	0,01565
Geometric 460 W	5min	a=0,909 / n=0,095	0,876	0,022	0,00049
	10min	a=1,100 / n=0,225	0,697	0,103	0,01055
	15min	a=1,592 / n=0,506	0,702	0,188	0,03526
	30min	a=5,148 / n=1,081	0,841	0,185	0,03404
Wang and Singh 460 W	5min	a=-0,909/ b=-0,095	0,876	0,022	0,00049
	10min	a=1,100/ b=0,225	0,697	0,103	0,01055
	15min	a=1,592/ b=0,506	0,702	0,188	0,03526
	30min	a=5,148/ b=1,081	0,841	0,185	0,03404

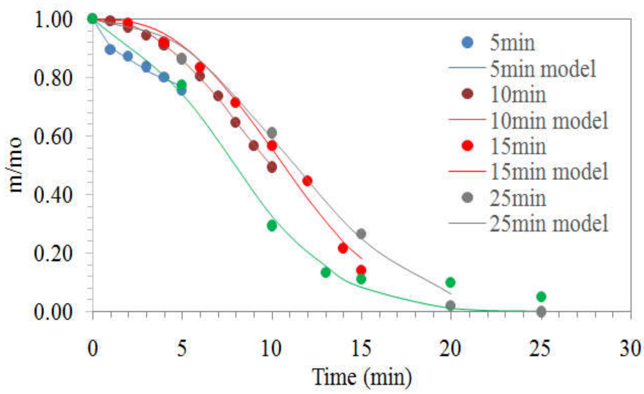


Figure 3. Changing of dimensionless moisture rate during microwave drying of samples with 460W

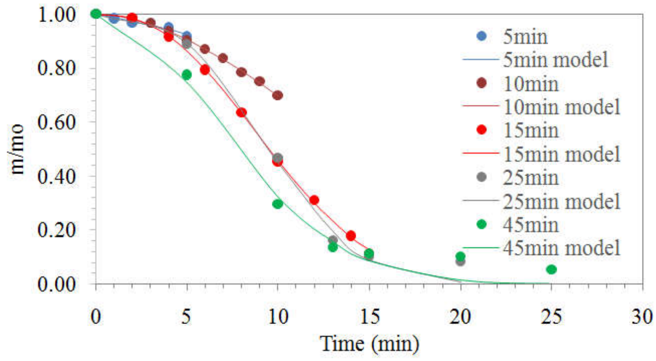


Figure 4. ChDanging of dimensionless moisture rate during microwave drying of samples with 700 W

Table 5. Compressive strengths of mortars at various curing conditions

Curing Conditions, W	Time	Wi,g	Wf,g	ΔW,g	Compressive Strength, MPa
460	5 min	513,14	494,0	19,14	5.9
	10 min	514,63	484,94	29,64	8
	15 min	527,22	484,2	43,02	8.1
	30 min	530,30	474,7	55,6	10.4
700	5 min	529,39	523,71	5,68	5.7
	10 min	512,79	493,54	19,25	5.7
	15 min	520,41	468,16	52,25	10
	30 min	522,83	465,6	57,23	11.4

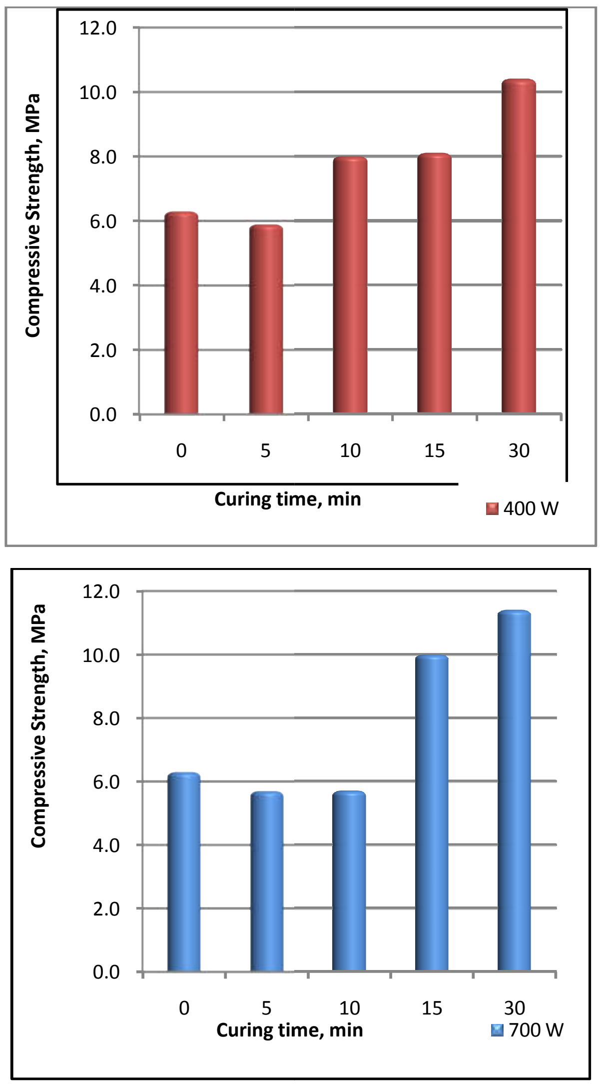
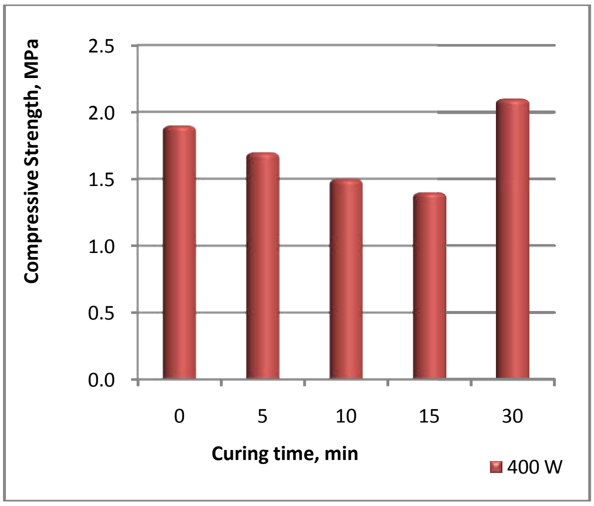


Figure 5. Compressive strengths of mortars



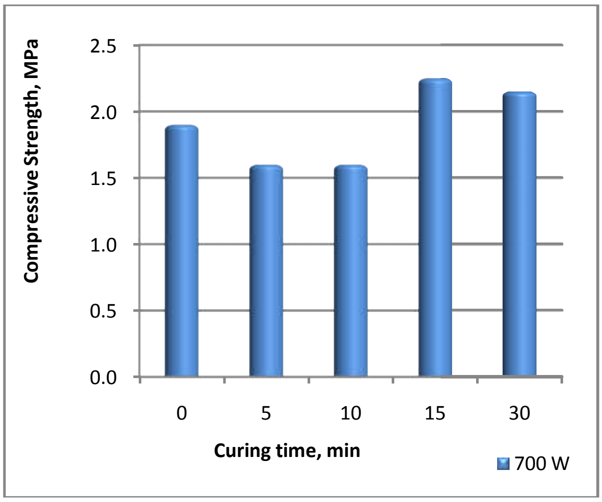


Figure 6. Tensile strengths of mortars

Conclusion

The current trends in clean energy parallel with a more sustainable development and more environmental friendly processes microwave energy is becoming a more popular energy source for heating and drying in various industrial applications (Prommas, 2011). The focus of this study was mainly on the compressive strength and tensile strength of mortars under microwave curing, and microwave drying behavior.The results show that the higher curing temperature or longer curing time produced higher early strength for all mortar mixes.In addition, when the concrete for all the drying conditions is modeled time dependently, it is seen that Page Model is more suitable than other drying models.

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