การศึกษาสมบัติทางกลของคอนกรีตชนิดไหลตัวได้ผสมวัสดุปอซโซลาน ภายใต้การบ่มโดยพลังงานไมโครเวฟ

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บทคัดย่อ

งานวิจัยนี้เป็นการศึกษาการนำพลังงานไมโครเวฟใช้ในการปรับปรุงการพัฒนากำลังอัดช่วงเริ่มต้นของคอนกรีตชนิดไหลตัวได้ผสมวัสดุปอซโซลาน อันได้แก่ เถ้าแกลบ เถ้าลอย และผงฝุ่นหิน เครื่องไมโครเวฟชนิดป้อนคลื่นหลายโหมดที่มีระดับความถี่ใช้งานเท่ากับความถี่ 2.45 กิกะเฮิร์ต (GHz) และอัตราส่วนผสมคอนกรีตชนิดไหลตัวได้ถูกกำหนดให้มีอัตราส่วนน้ำต่อวัสดุประสานเท่ากับ 0.22 และ มีปริมาณปูนซีเมนต์ปอร์ตแลนด์ชนิดที่ 1 เท่ากับ 450 กก/ม^3 และเถ้าแกลบ เถ้าลอย และผงฝุ่นหินถูกนำมาแทนที่ในปูนซีเมนต์ที่อัตราส่วนร้อยละ 20 โดยน้ำหนัก โดยทดสอบกำลังอัดของคอนกรีตช่วงเริ่มต้นที่ระดับพลังงานไมโครเวฟ และระยะเวลาในการบ่มที่แตกต่างกัน เพื่อเปรียบเทียบกับคอนกรีตในสภาพบ่มด้วยน้ำ ผลจากการศึกษาพบว่า คอนกรีตที่ผ่านการบ่มไมโครเวฟสามารถพัฒนากำลังอัดที่อายุ 1 วันได้มากกว่าคอนกรีตที่ผ่านการบ่มด้วยน้ำถึงร้อยละ 40

คำสำคัญ : พลังงานไมโครเวฟ / การบ่ม / กำลังอัด / คอนกรีตชนิดไหลตัวได้

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Study of Mechanical Properties of Self-Compacting Concrete Incorporating Pozzolan Materials When Subjected to Microwave Curing

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Abstract

This research is to study the microwave energy to improve the early-age compressive strength development of self-compacting concrete (SCC) incorporating low reactivity rice husk ash (RHA), pulverized fuel ash (FA), and limestone powder (LS). A multi-mode microwave system operating at a frequency of 2.45 GHz was used in this study. The SCC mixtures were formulated using a water-to-binder mass ratio of 0.22 and a cement content of 450 kg/m^3, the pozzolan material was replaced in Portland cement at level 20% by mass. The effects of curing by microwave power level, and exposure time on early strength were examined and the compressive strengths were compared to concrete samples which cured by using lime saturated-deionized water. From the test results, it was found that samples cured using microwave energy developed 1-day compressive strengths up to 40% greater than the conventionally cured samples.

Keywords : Microwave / Curing / Compressive Strength / Self-compacting Concrete

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1. Introduction

Microwave heating is a well established technique with a wide range of industrial applications. The two principal microwave frequencies assigned for industrial and research purposes by the International Microwave Power Institute (IMPI) are 0.915 ± 0.013 GHz and 2.45 ± 0.05 GHz. With its rapid and volumetric internal heating, microwave energy is used to heat, sinter, dry, or melt various materials such as paper, concrete, ceramics, metals, wood, and rubber [1]. Microwave-material processing has many advantages over conventional heating methods such as time and energy savings, microstructural refinement resulting in improved mechanical properties, and eco-friendliness.

Hydraulic-type Portland cements are commonly used in the construction industry. However, hydraulic cements take longer to develop sufficient strength and elasticity. The most important quality control parameter in concrete production and construction is the compressive strength of the hardened material. High early compressive strength development benefits concrete production by reducing construction time and labor, saving formwork and energy costs, and minimizing environmental impact. High early strength may be achieved through rapid thermal curing of concrete. Many techniques have been designed and developed over time to accelerate the curing process, such as the use of high early-strength Portland cement or Type III cement with added accelerators. Accelerated curing methods involve the use of high temperatures at either atmospheric or elevated pressures [2]. Microwave heating may be used in rapid curing methods and effectively increases the rate of strength development compared to conventional thermal curing methods [3-4]. Chatveera et al. [5] reported that microwave curing improved the compressive strength of concrete, with optimal effects occurring when 100 watt of microwave power was applied for 15 minutes after an initial 30 min delay period. Resistance to sulfate attack was also increased in samples in which 20 wt% of the Portland cement was replaced with rice husk ash (RHA) [6].

Self-compacting concrete (SCC) was first developed in 1988 to address a shortage of skilled construction workers. SCC is self-compacting when fresh, resistant to early-stage defects, and provides protection against external factors when hardened [7]. The mixture is characterized by high fluidity under its own weight, good consolidation properties without vibration, and an absence of defects due to segregation and bleeding [8]. Because of advantages in workability and hardened properties, the use of SCC in civil engineering projects has markedly increased. An example of SCC utilization in large-scale projects is the 238-m-high Roppongi Hills Mori Tower in Tokyo. In this case, the building structure consists of 2 m-diameter steel tubes filled with concrete to increase dimensional stability. The use of SCC made it possible to cast sections of up to 100 m in height without segregation of aggregates [9]. During the fabrication of precast prestressed girders it was found that the girder dimensions prevented obtaining a satisfactory surface finish using conventional concrete. In contrast, the use of SCC resulted in a good quality surface [10]. In order to increase segregation and bleeding resistance, large amounts of Portland cement and superplasticizer are used in SCC mixtures. However, the cost of concrete increases rapidly with increasing Portland cement and admixture content. Using mineral admixtures such as fly ash, rice husk ash, and limestone filler reduce the material cost of SCCs while also improving the workability and hardened properties of the mixtures [11-13].

SCC offers many advantages in both precast and cast-in-place concrete production, and reducing the necessary curing period further increases productivity while reducing capital costs and workshop area. To accelerate the curing of SCC mixtures, we examined the effect of microwave heating on the early-age compressive strength of SCC containing additional pozzolanic material in the form of rice husk ash, fly ash, or limestone powder. Several power levels and irradiation times were tested and the strength of the resulting concrete was compared to samples cured using lime-saturated water.

2. Experimental program

2.1 Materials

Type 1 Portland cement (OPC) complying with ASTM C150 [14] was used in the experiments. Ground rice husk ash (RHA) and fly ash (FA) were obtained from Electrical Power Plant in Chainat and Prachinburi Provinces of Thailand, respectively. Limestone powder (LS) was obtained from an industrial rock crushing plant located at Saraburi Province of Thailand. The physical properties and chemical compositions of the cement and mineral admixtures are provided in Table 1.

Table 1 Chemical and physical analyses of OPC, RHA, FA, and LS.

	OPC	RHA	FA	LS
Chemical composition (% by mass)				
SiO_2	16.37	93.00	47.39	8.97
Al_2O_3	3.85	0.35	20.51	1.02
Fe_2O_3	3.48	0.23	6.71	0.37
MgO	0.64	0.41	1.35	2.38
CaO	68.48	1.31	9.05	46.77
Na_2O	0.06	0.15	0.63	0.02
K_2O	0.52	1.61	1.50	0.13
SO_3	4.00	0.03	2.59	0.33
Physical properties				
Loss on Ignition (% by mass)	1.70	1.90	8.63	39.54
Particle Size Distribution [D(4,3)] (μm)	23.32	24.32	30.56	15.63
Specific gravity	3.2	2.2	2.26	2.76
Specific surface area (cm^2/g)	6100	8400	8110	13000

The particle size distributions of Type 1 Portland cement (OPC), ground rice husk ash (RHA), fly ash (FA) and Limestone powder (LS) were also compared in Fig.1. They were determined using a laser granulometer (Mastersizer 2000). Their morphology was detected using Scanning Electron Microscope (SEM) image obtained at about 1000x magnification and are reported in Fig. 2(a)-2(d).

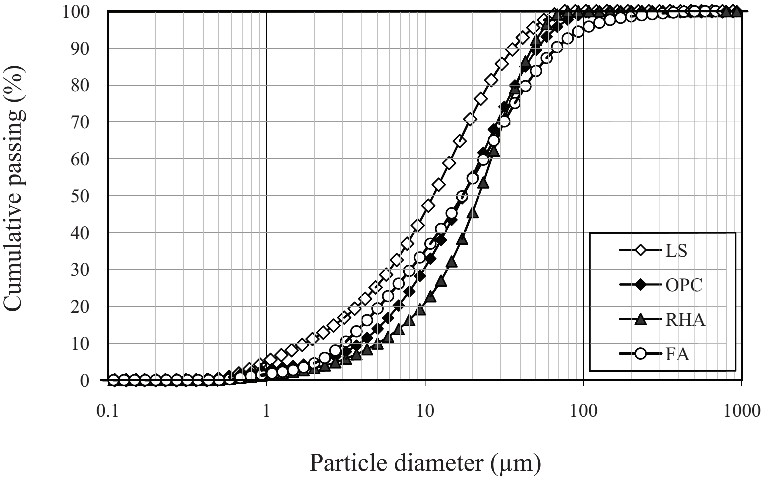
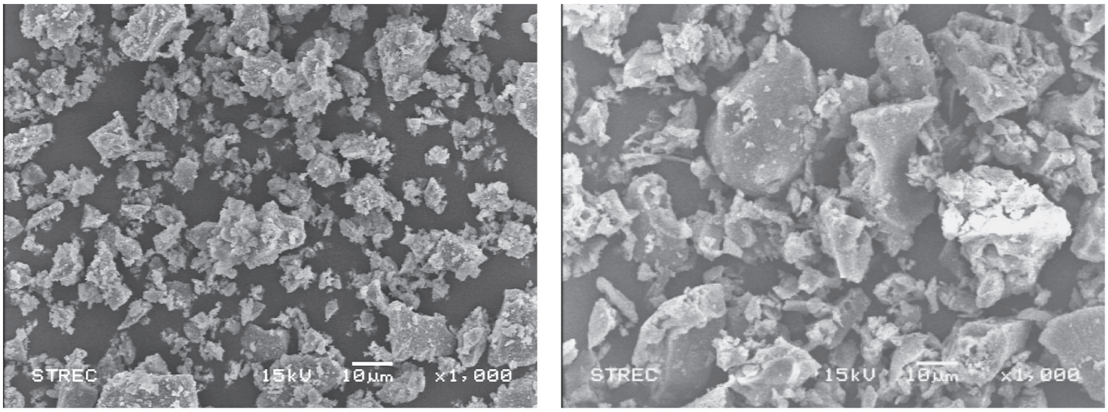


Fig. 1 Particle size distributions of cement and other powder in semi-logarithmic scale.

The fine aggregate was river sand with a nominal maximum size of 4.75 mm and the coarse aggregate was crushed limestone rock with a nominal maximum size of 10.0 mm.

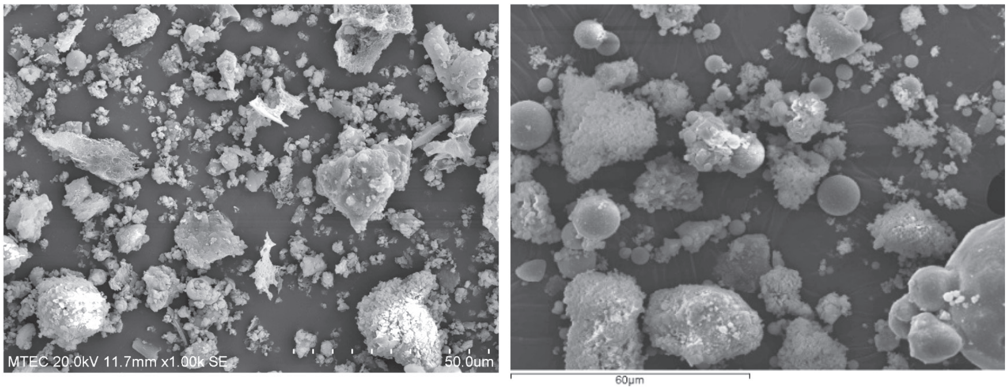
In order to improve workability, a polycarboxylate-based superplasticizer (SP) conforming to ASTM C494 [15] standard type F was used, with a specific gravity of 1.05 added at a concentration of 2.0 wt% of the binder materials.



(a) OPC

(b) Ground RHA

Fig. 2 Scanning electron micrographs (1000x) of (a) OPC, (b) Ground RHA (c) Fly ash and (d) Limestone powder.



(c) Fly ash

(d) Limestone powder

Fig. 2 (Cont.) Scanning electron micrographs (1000x) of (a) OPC, (b) Ground RHA (c) Fly ash and (d) Limestone powder.

2.2 Mixtures proportions

Four concrete mixes with different mineral admixtures were designed to meet the required properties. Each concrete mixes having the same binder material content and the water-cement ratio (W/C) were kept constantly of 450 kg/m^3 and 0.22, respectively. OPC was partially replaced with RHA, FA and LS at the replacement level of 20% of the total weight of binder materials. The mixture compositions are summarized in Table 2.

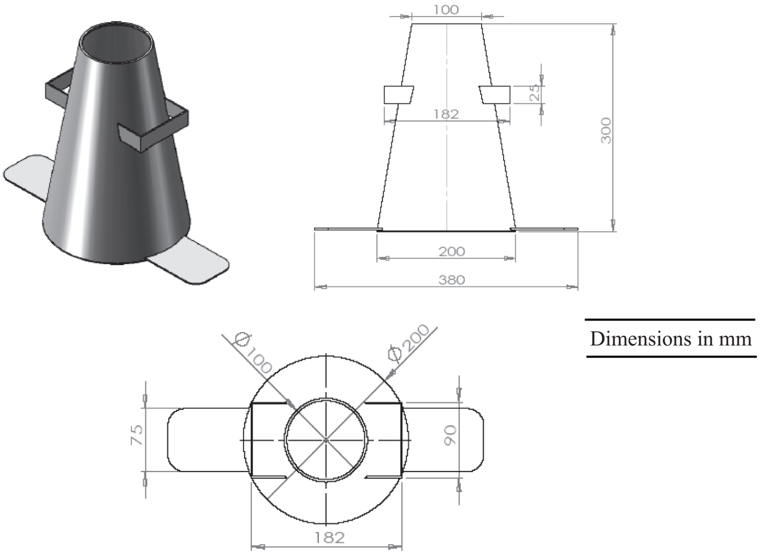
Table 2 Proportions of SCC mixtures.

Materials (kg/m^3)	SCC Types			
	100C	20RHA	20FA	20LS
Cement	450	360	360	360
Rice husk ash	-	90	-	-
Fly ash	-	-	90	-
Limestone powder	-	-	-	90
Fine sand	922	922	922	922
Coarse aggregate	804	804	804	804
Water	99	99	99	99
Superplacticizer (%)	2	2	2	2

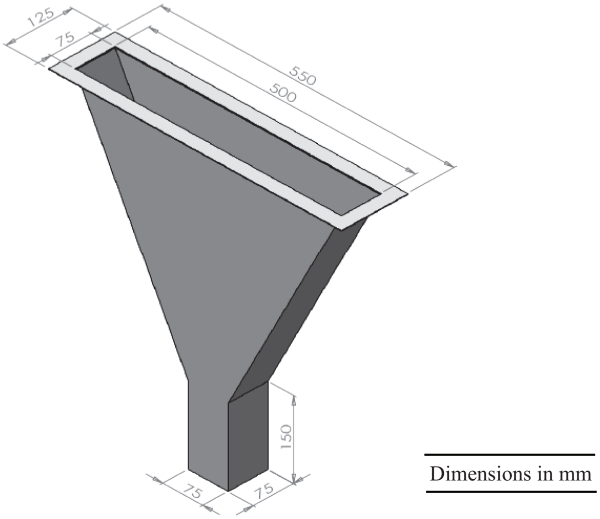
Remark: The symbols representing the SCC mixtures were assigned as xC, yRHA, yFA, and yLS where x is the percentage of cement content and y is the percentage of RHA, FA, or LS replacing OPC.

2.3 Specimen testing

The properties of the freshly-prepared SCC were examined using slump flow and V-funnel tests. Slump flow tests were performed in an inverted mould without tamping in accordance with ASTM C1611 [16]. The reported spread diameters are the averages of four measurements. The filling ability was tested using a V-funnel according to the procedure described in EFNARC [17] illustrated in Fig. 3. Unit weights were measured as specified in ASTM C29 [18]. Cylindrical specimens with the diameter of 150 mm and the height of 300 mm were made, once removed from their moulds after 24 hours, they cured in lime-saturated water until to reach the test. Compressive strength tests were performed after 1, 7 and 28 days in accordance with ASTM C39 [19].



(a) Slump flow test



(b) V-funnel test

Fig. 3 Slump flow and V-funnel test apparatus.

A domestic microwave oven with internal dimensions of 310 mm (width) x 190 mm (height) x 280 mm (depth) was used for microwave treatments. The specimens were mixed and cast in cylindrical polyethylene containers 75 mm in diameter and 150 mm in length. Temperature was measured using a shielded type-K thermocouple inserted directly into the specimen, the thermocouple output was directed to a controller that regulated the oven power. The temperature was monitored and recorded at 15 second intervals for 15 minutes. The microwave processing parameters are listed in Table 3.

After heating, the specimens were stored in saturated containers until early compressive strength testing at 24 hours.

Table 3 Microwave processing parameters.

Processing parameter	Determined value
1.Application time after mixing	Immediately
2.Duration of application	5,10, and 15 minutes
3.Microwave power	100, 300, 450 and 600 watt
4.Early-age compressive strength test	24 hours

3. Results and discussion

3.1 Workability

The slump flow diameter, slump flow time (T50), V-funnel flow time, and unit weight of each sample are presented in Figs. 4-6.

The slump flow diameter ranged from 65 to 70 cm, conforming to EFNARC [17] recommendations. The slump flow time ranged from 4 to 18 seconds, depending mainly on use of the mineral admixture. The lowest slump flow time of 4 seconds occurred with the control concrete while the mixture containing 20% RHA had the longest flow time of 18 seconds. This behaviour seems to be related to a lack of cohesion in the mixture and greater compactness of the concrete granular skeleton.

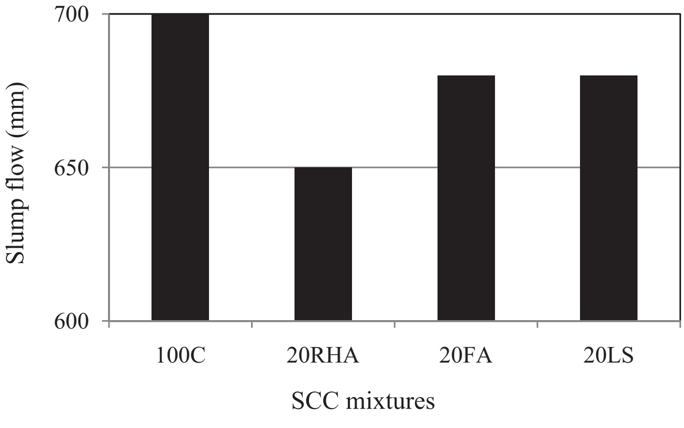


Fig. 4 Slump flow.

The V-funnel flow times were between 6-33 seconds and depended mainly on the mineral admixture used. The lowest V-funnel flow time of 6 seconds was measured for the control concrete while the mixture with 20% RHA had the longest flow time of 33 seconds. Incorporating FA or LS generally made the concrete more viscous. The concrete containing 20% RHA absorbed a large amount of the added water, resulting in a highly viscous mix.

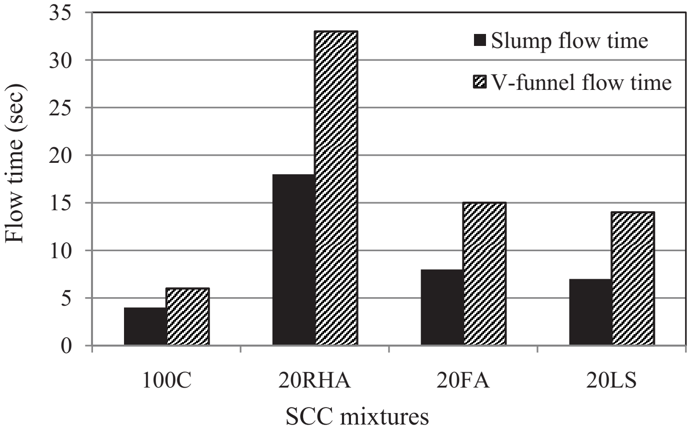


Fig. 5 Slump flow time and V-funnel.

The unit weight of the SCC mixtures depends on the type of mineral admixtures. It is well known that the unit weight is a function of the specific gravity of mineral admixtures - the specific gravity of OPC is more than that of RHA, FA and LS. Therefore, the unit weight of concrete was decreased when the amount of mineral admixtures was replaced in the mixtures

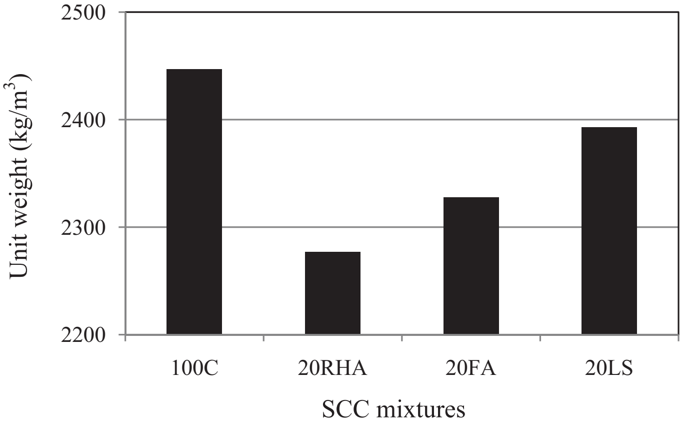


Fig. 6 Unit weight for fresh.

3.2 Temperature rise

The temperature during hydration and microwave heating was recorded at the center of each concrete sample (Figs. 7-10). The temperature increase varied with application time between 30-43 °C at 100 watt of applied power. Mixtures containing 100% ordinary Portland cement (OPC) concrete reached the highest temperatures, while mixtures in which fly ash was used to replace 20 wt% of the Portland cement achieved the lowest temperature (Fig. 7). The temperature spread was similar at 300 watt (Fig. 8), with mixtures containing 100% Portland cement reaching 86 °C and those containing 20% fly ash reaching 71 °C.

Similar observation were made for the power level of 450 watt as shown in Fig. 9., that 100%OPC concrete reached highest temperature of about 103°C and 20%FA concrete in which fly ash replaced 20% OPC by mass showed the lowest temperature of about 96°C, in addition for 100% OPC concrete had the highest heating rate from 5 to 10 minutes about 6.4 °C/minutes.

The results at 600 watt are shown in Fig. 10, in this case the rate of heat liberation was the extremely high from 5 to 10 minutes, that 20RHA concrete in which rice husk ash replaced 20% OPC by mass reached highest rate of heating about 8.2 °C/minutes and 100%OPC concrete showed the lowest rate heating about 2.8 °C/minutes. For the last 15 minute all the concrete mixture reached the highest temperature of about 103 °C.

The increase in temperature during accelerated curing is due to a combination of heat liberated from hydration reactions and interactions between the microwave radiation and water within the mixture. The reduction in maximum curing temperature observed in samples containing filler materials was the result of fewer hydration reactions due to the lower amount of Portland cement in the mixtures. The additional heat from the microwave energy may also modify the kinetics of hydration in accordance with Arrhenius' law.

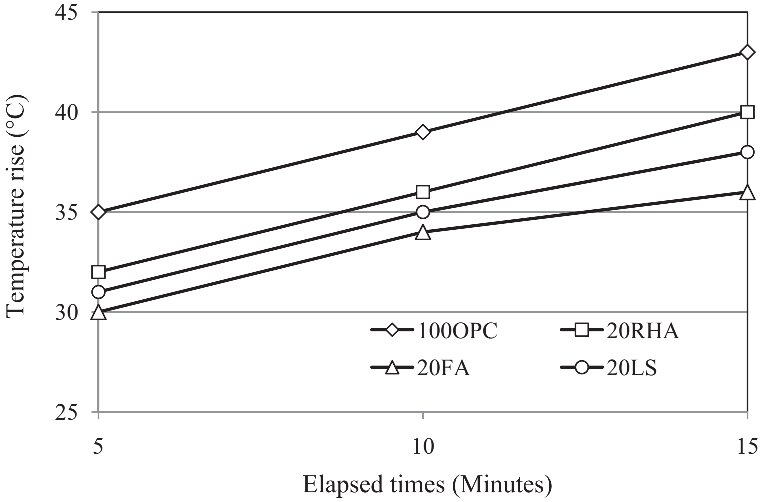


Fig. 7 Microwave heating at 100 watt.

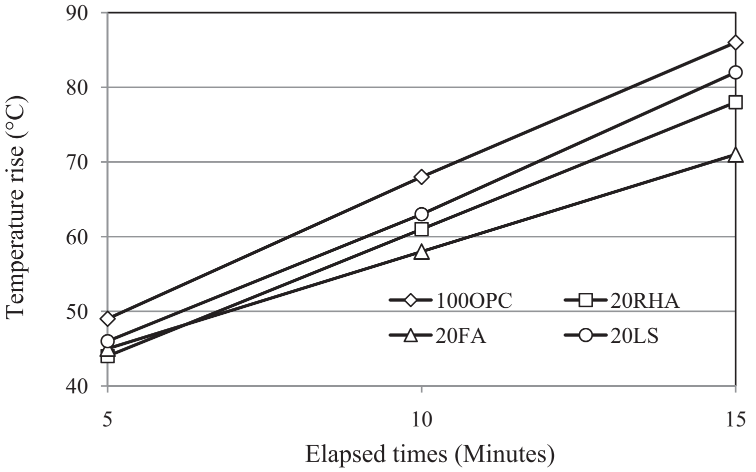


Fig. 8 Microwave heating at 300 watt.

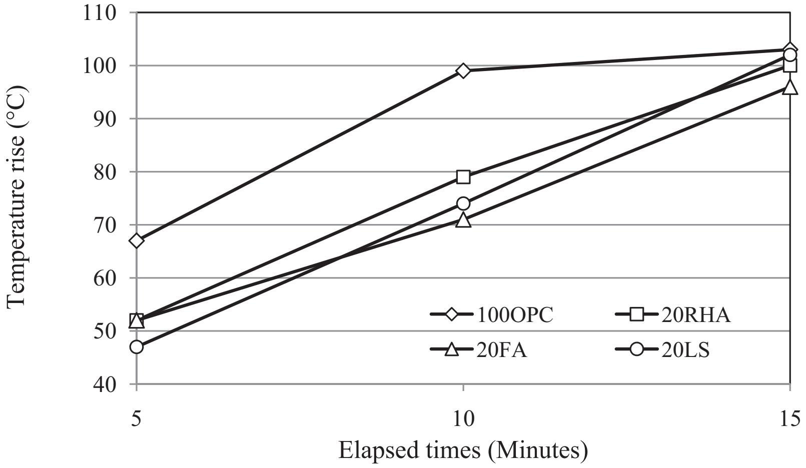


Fig. 9 Microwave heating at 450 watt.

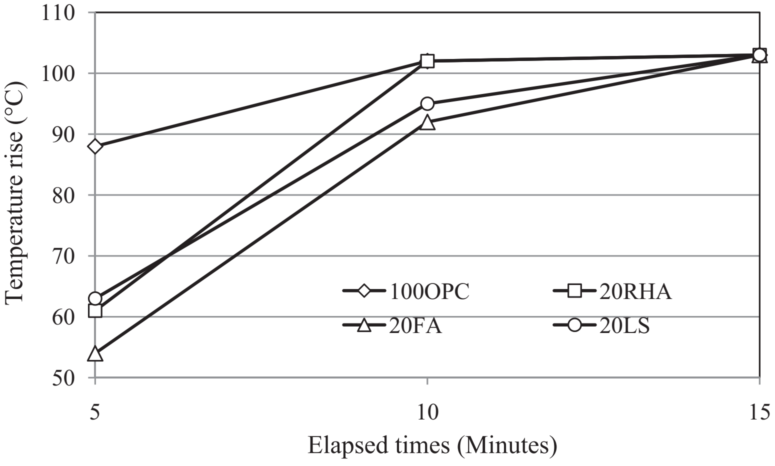


Fig. 10 Microwave heating at 600 watt.

3.3 Compressive strength

The compressive strengths of microwave-cured samples were compared to those of conventionally-cured SCC samples. Since preliminary tests indicated that the strength of concrete prepared using ordinary Portland cement could be measured at 24 hours, the early-age test time was fixed at 24 hours. The results of the compressive strength tests for samples undergoing normal cure procedures are presented in Table 4.

Table 4 Compressive strengths of normally-cured concrete and microwave heating samples.

Compressive strength [kg/cm^2]			
Microwave heating concrete (%wrt. 1-day normally cured)			
Parameter	5 minutes	10 minutes	15 minutes
100OPC			
100watt	196(96%)	210(103%)	262(128%)
300watt	249(122%)	244(120%)	181(89%)
450watt	172(84%)	136(67%)	91(45%)
600watt	154(75%)	91(45%)	45(22%)
20RHA			
100watt	226(102%)	249(113%)	281(127%)
300watt	249(113%)	204(92%)	190(86%)
450watt	217(98%)	163(74%)	158(71%)
600watt	158(71%)	113(51%)	68(31%)
20FA			
100watt	182(102%)	210(118%)	250(140%)
300watt	248(139%)	204(115%)	158(89%)
450watt	195(110%)	113(63%)	100(56%)
600watt	136(76%)	102(57%)	45(25%)
20LS			
100watt	228(98%)	288(98%)	323(139%)
300watt	298(128%)	237(102%)	188(81%)
450watt	222(96%)	162(70%)	132(57%)
600watt	158(68%)	88(38%)	68(29%)
Normally- cured concrete			
SCC Mixes	1- days	7-days	28-days
100OPC	204	229	293
20RHA	221	255	316
20FA	178	206	265
20LS	232	270	341

As shown in Fig. 11, the compressive strengths of mixtures containing Portland cement substitutes varied with the nature of the cementitious materials. The 20LS samples exhibited the highest compressive strength, followed in order by the 20RHA, 100OPC, and 20FA samples. All mixtures irradiated at 100 watt for 15 minutes or 300 watt for 5 minutes exhibited higher 1-day strength than the conventionally-cured samples.

Microwave heating is the result of energy transfer from the electromagnetic field to water molecules within the concrete. Excitation by the external field causes the bonds to vibrate, and the mechanical energy is dissipated as heat and transferred throughout the concrete, yielding elevated temperatures and accelerating hydration reactions. Consequently, free water located within the capillary pores of the concrete may be quickly removed from the internal concrete structure before setting, inducing plastic shrinkage and collapse of the capillary pores and densifying the concrete microstructure.

The greatest compressive strengths in all mixtures were obtained at a power level of 100 watt using an exposure time of 15 minutes. This treatment resulted in greater 1-day and 7-day strengths than in normally cured concrete, but lower 28-day strength. However, the 28-day strength was greater than 80% of the normally cured strength. The compressive strength decreased with increasing power level and irradiation time.

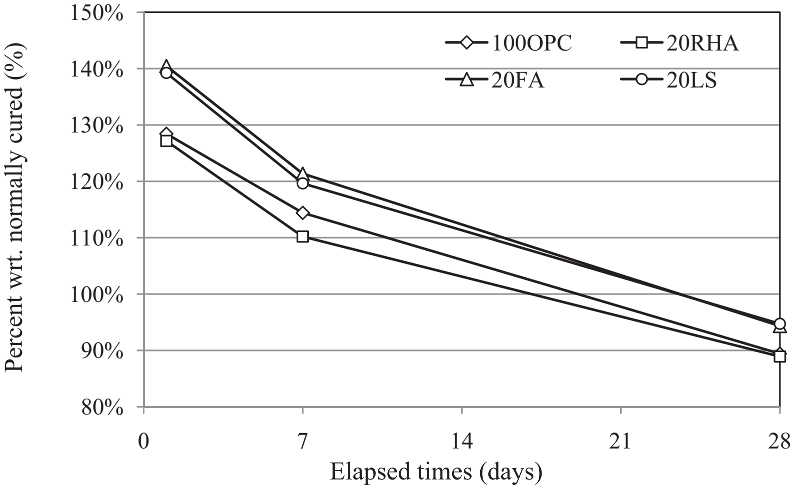


Fig. 11 Maximum compressive strength of concrete at power level 100 watt 15 minutes compared to normally-cured concrete.

3.4 Relationship between temperature rise and compressive strength

Fig. 12 displays the relationship between temperature rise and compressive strength for all mixtures.

The compressive strength decreases with increasing of heat liberation, for the high performance concrete (HPC) recommend minimum values of early ages compressive strength more than 20 MPa (204 kg/cm^2) [20], it is concluded that the SCC mixtures with the temperature rise not more than 60 °C produced satisfactory early age compressive strength. In addition, the optimum heating conditions for the control, 20RHA, 20FA or 20LS mixture were 100 watt for 15 minutes. Conversely, the higher temperature was unsuitable for microwave curing. The temperature rises are summarized in Table 5, theirs varied in the range of 36-43 °C.

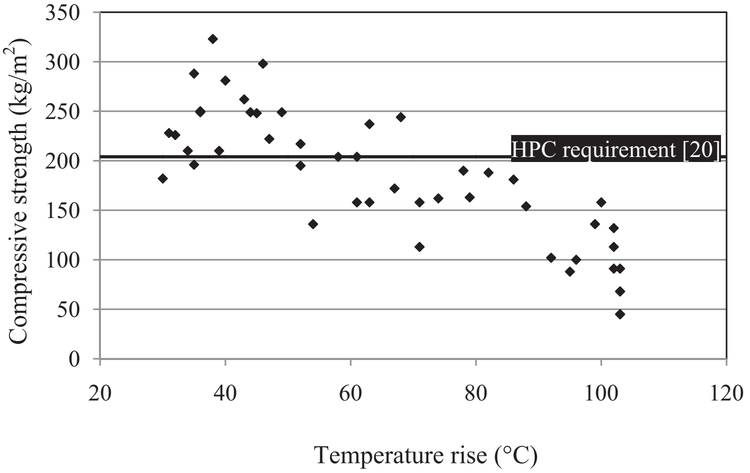


Fig. 12 Relationship between temperature rise and compressive strength compared to early-age compressive strength of HPC.

Table 5 Compressive strengths and temperature rise in SCC mixtures when subject to microwave accelerated curing

SCC mixture	Compressive strength [kg/cm^2]		Temperature rise [°C]	
	Maximum	Minimum	Maximum	Minimum
100OPC	262	45	43	103
20RHA	281	68	40	103
20FA	250	45	36	103
20LS	323	68	38	103

4. Conclusions

Following this experimental study, we concluded that:

1. The workability of SCC depends mainly on the type of mineral admixture used. Among those considered, use of FA and LS improved the workability more than RHA. However, based on slump test measurements neither of these additives increased workability more than OPC.

2. The optimum heating conditions for the control, 20RHA, 20FA, and 20LS mixtures was 100 watt for 15 minutes. Power levels of 450 or 600 W were unsuitable for microwave curing.

3. The early-age compressive strength in microwave-cured 20FA concrete mixtures could be increased by more than 40% over the 1-day strength of conventionally cured concrete. The strength of the 20LS, 100OPC, and 20RHA mixtures were increased by 39%, 28%, and 7% over the 1-day strength of conventionally cured concrete.

4. The highest compressive strengths for all mixtures were obtained after treatment at 100 watt for 15 minutes. The resulting compressive strengths were higher than in normally-cured concrete at 1 day and 7 days, but lower at 28 days. Hover, the microwave-cured samples achieved over 80% of

the 28-day strength of the normally-cured samples.

5. The optimum relationship between heat liberation and compressive strength occurred at temperatures lower than 60 °C, and temperatures above 60 °C were unsuitable for microwave curing.

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