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The Strength and Rapid Chloride Permeability of Microwave Cured Concrete

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Abstract: This study investigates the effects of steam and microwave curing on the strength development and permeability of concrete. Two steam curing treatments, four microwave curing times and four types of concrete mix were used in this study. The test results indicated that microwave heating could further increase the compressive strength of mortar and concrete. Pozzolanic reaction of silica fume, fly ash and blast-furnace slag was observed to be further promoted by steam-microwave curing. Mortar and concrete samples with 10% silica fume added responded well to microwave curing. The strength gain development of mortar and concrete appeared to level off after 40 minutes of microwave curing. Thus, a 40-minute microwave heating time appeared to be the optimal time for energy saving consideration. The microwave-cured concrete did not show an increase in permeability relative to the concrete that was steam-cured, but showed an increase in strength. Thus, microwave heating may be a potentially attractive method for accelerating cement hydration.

Keywords: microwave heating; steam curing; compressive strength; rapid chloride permeability.

Introduction

The quality of a steam cured precast concrete is affected by curing time and temperature variables [1]. Steam curing might cause micro-cracks along the interface of aggregate and cement paste. It has been reported that the strength of concrete by steam curing could decrease in later stages such as 28 days or 90 days, while compared with concrete cured in air or in water [2, 3]. Additionally, it requires a relatively long period for curing since heat must diffuse inward from the surface and the inherently non-uniform temperature can generate thermal cracking. Thus, microwave heating may be a potentially attractive method for accelerating cement hydration [4].

The pioneering study of Watson shows that 28-day compressive strength of microwave cured concretes displayed only half the strength of the normally cured concretes [5]. However, his results were uncertain because the temperature of the specimens might have fluctuated due to the pulsed microwave energy which he used. Also, an internal temperature of 90 ˚C was reached at which cracks could be generated, resulting from the escape of steam from the interior side [6]. However, Wu et al reported that microwave heating improved the 28-day compressive strength of mortar as much as 3-7 % as well as enhancing short-term strength [7]. They emphasized op-

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timization of the internal temperature and the final water cement ratio of the specimen, controlling processing time and microwave power. Too much microwave energy could cause a decrease in strength due to overvaporation and overheating [8]. The results from Pheeraphan et al indicated that microwave curing could impair the freeze-thaw durability of high w/c concrete but not for low w/c concrete. Also, under microwave curing, the decrease in strength due to air entrainment becomes more significant. Based on these observations, it is recommended that for microwave cured air-entrained concrete, a low w/c ratio should be employed [9 -11].

The main aim of the work presented here is to assess the acceleration of strength development in steam curing and/or microwave heating and to evaluate the strength and permeability of these concretes.

Experiments

Preparation of material is first described, followed by the specimen preparation, curing method, and the rapid chloride permeability test.

Materials

Both mortar and concrete specimens are made with a Type I Portland cement but with different mineral admixtures. A Type I cement, a class F fly ash, a ground blast furnace slag and a silica fume were used. The chemical compositions of the cement and admixtures used are shown in Table 1 [11].

An Ottawa sand was used to make the mortar samples, while local construction sand and crushed gravel were used to make the concrete samples.

Table 1. Chemical Compositions of Cement and Mineral Admixtures [11]

Compositions	Type I Cement	Fly Ash	Furnace Slag	Silica Fume
CaO	64.05	3.26	40.82	0.52
SiO_2	21.02	56.14	33.68	95.00
Al_2O_3	5.78	22.26	14.32	0.10
Fe_2O_3	3.20	7.48	3.23	0.03
MgO	1.65	1.36	7.88	1.10
SO_3	2.35	0.58	0.73	0.50
Na_2O	0.21	0.50	0.29	0.02
K_2O	0.63	3.10	0.23	0.20
Free Lime	0.96	-	-	-
C_3S	55	-	-	-
C_2S	19	-	-	-
C_3A	10	-	-	-
C_4AF	7	-	-	-
Loss on Ignition	1.13	3.55	0.22	2.45
Fineness (m^2/g)	0.33	0.30	0.36	25.00
Specific Gravity	3.15	2.22	2.95	2.20

Specimen preparation

Mortar Samples — 50-mm mortar cubes with or without different mineral admixtures, were prepared according to ASTM C105 and used to investigate the effects of microwave and steam curing on the compressive strength development. For mortar samples, the cement/sand ratio was fixed at 1:2.75 and the water/binder ratio was fixed at 0.45. The factors considered and the combinations of mortar samples used are shown in Table 2.

Table 2. Test Combinations of Mortar Samples

Binder Water Ratio	Binder Replacement	Steam Curing Temperature	Steam Curing Time	Microwave Curing Time
0.45	(1) Type I Cement[a] (2) 10 % Fume Ash (3) 20 % Fly Ash (4) 40 % Furnace Slag	(1) 65 ˚C (2) 75 ˚C	7 hours steam curing + 17hours water curing	(1) 0 min (2) 20 min (3) 40 min (4) 60 min

Note: [a]Type I Cement Content--500 kg/m^3

Concrete Samples — Concrete cylinders, 50 mm in diameter and 100 mm in height, were used for the compressive strength test. The other concrete cylinders, 100 mm in diameter and 200 mm in height, were used for the rapid chloride permeability test. For concrete samples, the water/binder ratio was fixed at 0.55. The factors considered and the combinations of concrete samples used are shown in Table 3.

Table 3. Test Combinations of Concrete Samples

Binder Water Ratio	Binder Replacement	Steam Curing Temperature	Steam Curing Time	Microwave Curing Time
0.55	(1) Type I Cement[a] (2) 10 % Fume Ash (3) 20 % Fly Ash (4) 40 % Furnace Slag	(1) 65 ˚C (2) 75 ˚C	7 hours steam curing + 17hours water curing	(1) 0 min (2) 20 min (3) 40 min (4) 60 min

Note: [a]Type I Cement Content--360 kg/m^3

Curing method

This study was conducted to assess the acceleration of strength development by steam curing and/or microwave heating and to evaluate the strength and permeability of these concretes. Two steam-curing temperatures (65 and 75 ˚C) and one curing time (7 hours) were used in this investigation. Two combinations of steam-curing cycle were chosen as (a) 65 ˚C & 7 hours and (b) 75 ˚C & 7 hours. After the steam-curing cycle and demolding, the mortar or concrete samples were cured in water for 17 hours. The microwave curing method for accelerating cement hydration was then applied at this stage. A Tatung Electronics Model TMO-2071M microwave oven with 700 watts power was employed [11]. Four microwave heating treatments (0, 20, 40 and 60 min.) were used. The specimens were placed in a glass container with 1000 ml of water in it, and the glass container was placed in the microwave oven for the specified amount of time (see Figure 1). After microwave heating treatments (20, 40 and 60 min.), the samples were heated and water in glass container was vaporized and its temperature could reach 100 ˚C. The curing factors considered and the combinations of mortar and concrete samples used are shown in Table 3 and 4, respectively. After microwave heating, the samples were cooled to room temperature and immediately placed in lime-saturated water until testing was begun.

Figure 1. Specimen in Microwave Oven

Table 4. Comparison of Compressive Strength of Mortar with Different Mineral Admixture Replacements

Replacement / Curing Method	Compressive Strength, MPa (Mean, Cv[a])			
	Type I Cement	10 % Fume Ash Replacement	20 % Fly Ash Replacement	40 % Furnace Slag Replacement
SC65+MC0[b]	26.61, 1.59%	32.96, 2.92%	19.83, 2.58%	19.71, 2.05%
SC65+MC20[c]	35.71, 2.83%	48.25, 2.32%	27.14, 1.35%	28.13, 1.95%
SC65+MC40[d]	43.16, 2.12%	57.18, 3.67%	32.90, 5.29%	31.69, 1.00%
SC65+MC60[e]	45.89, 3.21%	57.11, 5.89%	33.77, 11.77%	31.89, 2.73%
SC75+MC0[f]	30.79, 2.86%	37.12, 1.31%	24.12, 3.59%	21.15, 5.65%
SC75+MC20[g]	37.79, 6.06%	48.56, 3.88%	32.14, 1.58%	29.44, 1.85%
SC75+MC40[h]	49.26, 6.27%	62.98, 3.67%	37.27, 2.11%	33.88, 1.48%
SC75+MC60[i]	50.43, 7.52%	63.40, 2.73%	38.33, 2.17%	35.07, 2.89%
7-day Water Curing	37.92, 2.39%	47.42, 1.21%	31.22, 1.97%	28.74, 3.77%
14-day Water Curing	45.25, 1.05%	59.89, 2.10%	41.91, 2.60%	39.24, 0.88%
28-day Water Curing	51.96, 4.41%	66.11, 0.89%	47.93, 0.68%	43.27, 0.57%

Note: [a]Cv --Coefficient of Variation
[b]SC65+MC0 --7 hours Steam Curing at 65 ℃ + 17hours water curing + 0 min Microwave Curing
[c]SC65+MC20--7 hours Steam Curing at 65 ℃ + 17hours water curing + 20 min Microwave Curing
[d]SC65+MC40--7 hours Steam Curing at 65 ℃ + 17hours water curing + 40 min Microwave Curing
[e]SC65+MC60--7 hours Steam Curing at 65 ℃ + 17hours water curing + 60 min Microwave Curing
[f]SC75+MC0 --7 hours Steam Curing at 75 ℃ + 17hours water curing + 0 min Microwave Curing
[g]SC75+MC20--7 hours Steam Curing at 75 ℃ + 17hours water curing + 20 min Microwave Curing
[h]SC75+MC40--7 hours Steam Curing at 75 ℃ + 17hours water curing + 40 min Microwave Curing
[i]SC75+MC60--7 hours Steam Curing at 75 ℃ + 17hours water curing + 60 min Microwave Curing

Rapid chloride permeability test

The rapid chloride permeability test (RCPT), designated as ASTM C1202- Standard Test Method [12] for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, was the test proposed for rapid qualitative assessment of chloride permeability of concrete. The RCPT method has been used previously to investigate mineral admixture effects on resistance to chloride ion penetration, the influence of aggregate fractions, and curing conditions and pore size related to the penetration of chloride ions [13]. This test is not a true measure of concrete permeability. The test measures the electrical conductance of the concrete, which can be correlated to concrete permeability. The test measures the amount of electrical charge (in coulombs) which passes through a 50 mm thick x 100 mm diameter saturated concrete specimen during a 6-hour period. A potential difference of 60 volts is maintained across the ends of the specimen. A concrete with a high permeability will allow a high amount of current to pass through the concrete and therefore have a high coulomb value. A concrete with a low permeability will result in a low amount of current passing through the concrete and therefore have a low coulomb value. A concrete having a total charge passed of less than 2000 coulombs and more than 4000 coulombs is considered to have a low permeability and a high permeability, respectively.

The RCPT testing of steam and microwave cured concrete was performed on the laboratory cured 100 x 200 mm concrete cylinders at the ages of 2 and 28 days.

Experimental results and discussion

Mortar

The results of 1-day compressive strength tests on the mortar samples for the eight combinations of steam and microwave curing methods are displayed in Table 4. The results show that the higher curing temperature or longer curing time produced higher early strength for all four mortar mixes. The results also indicate that the strength of cement mortars increases as a result of microwave heating. The amount of the strength gain was about 10 MPa by using a 20-minute microwave heating. The amount of the strength gain was from 15 to 25 MPa by using 40 or 60 minutes of microwave heating. The percent strength development due to microwave curing, which is the ratio of the strength of the microwave-cured sample minus that of the steam-cured sample to the 28-day strength of the normally cured sample, was computed for the different steam-cured temperature and mix. The results of percent strength development are shown using line graphs in Figures 2 and 3. These graphs give a good indication of the percent strength development of the various mortar mixes. The mortar incorporating 20% fly ash or 40% slag developed strength at a relatively slower rate than the control mortar. The samples with 10% silica fume added responded to microwave curing very well and had a high percent strength development.

Concrete

A. compressive strength testing

The results of 1-day and 28-day compressive strength tests on the concrete samples for the eight combinations of steam and microwave curing methods are displayed in Tables 5 and 6, respectively. The results show that the higher curing temperature or longer curing time produced higher early strength for all four concrete mixes. The results also indicate that the strength of concrete was increased by microwave heating. The amount of the strength gain was close to 5 MPa by using 20 minutes microwave heating. The amount of the strength gain was from 10 to 15 MPa by using 40 or 60 minutes of microwave heating. The difference of the strength gain between mortar and concrete by using 40 or 60 minutes of microwave heating could be cement content or size effect. High early compressive strength of steam and microwave cured concrete was obtained while its 28-day strength was slightly lower than the 28-day strength of normally water-cured ones. Percent strength development due to microwave curing, which is the ratio of the strength of the microwave-cured sample minus that of the steam-cured sample to the 28-day strength of the normal cured sample, was computed for the different steam-cured temperatures and mixes [11]. The results of percent strength development are shown using line graphs in Figures 4 and 5. These graphs give a good indication of the percent strength development of the various concrete mixes. The concrete incorporating 20% fly ash or 40% slag developed strength at a relatively slower rate than the control concrete. At 28-day curing, the strength of the fly ash concrete or the slag concrete was still generally slightly lower than that of the control concrete. The strength development due to microwave heating appears to level off after 40 minutes of microwave heating. Thus, a 40-minute microwave heating may be the optimum length of time for energy saving consideration [11]. The samples with 10% silica fume added responded very well to microwave curing and had a high percent strength development.

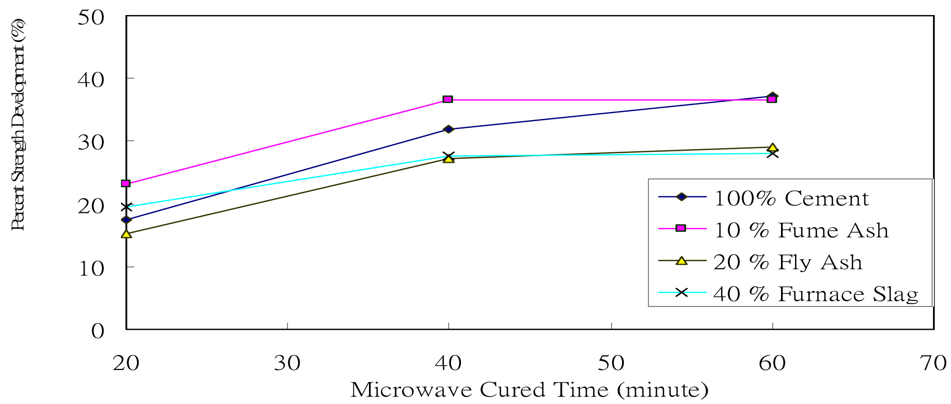


Figure 2. Percent Strength Development by Microwave Curing of Mortars at 65 ˚C Steam Curing

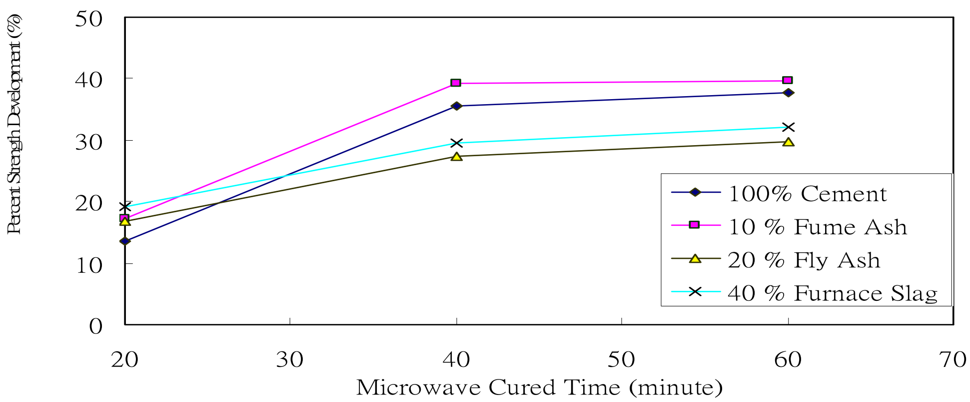


Figure 3. Percent Strength Development by Microwave Curing of Mortars at 75 ˚C Steam Curing

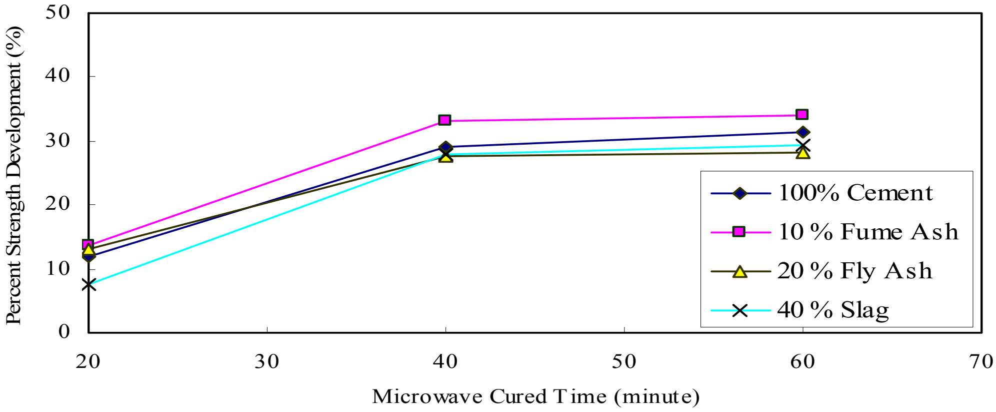


Figure 4. Percent Strength Development by Microwave Curing of Concretes at 65 °C Steam Curing

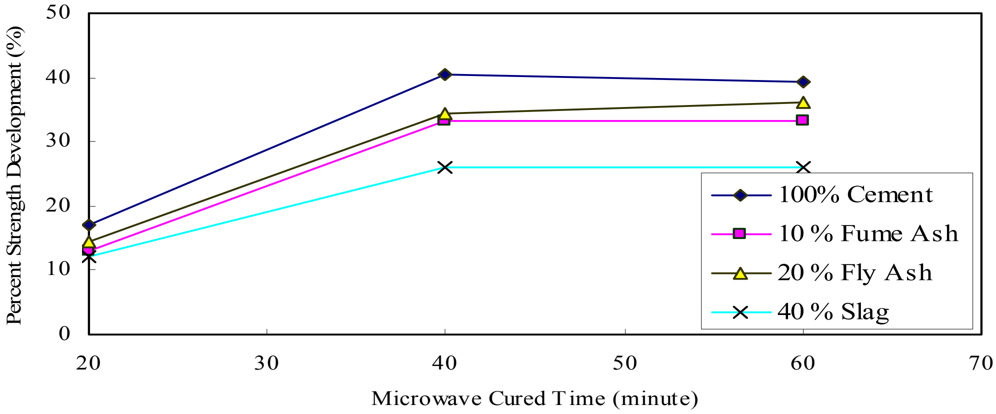


Figure 5. Percent Strength Development by Microwave Curing of Concretes at 75 °C Steam Curing

Table 5. Comparison of Compressive Strength of Concrete with Different Mineral Admixture Replacements

Replacement / Curing Method	Compressive Strength, MPa (Mean, Cv[a])			
	Type I Cement	10 % Fume Ash Replacement	20 % Fly Ash Replacement	40 % Furnace Slag Replacement
SC65+MC0[b]	20.10, 3.42%	17.05, 3.08%	14.26, 3.63%	10.51, 1.90%
SC65+MC20[c]	24.82, 2.53%	23.29, 3.11%	18.91, 3.18%	13.00, 2.08%
SC65+MC40[d]	31.50, 2.16%	32.18, 4.83%	24.09, 3.51%	19.55, 4.29%
SC65+MC60[e]	32.45, 1.05%	32.63, 0.75%	24.29, 3.38%	19.98, 4.88%
SC75+MC0[f]	21.81, 2.57%	18.35, 2.06%	15.53, 2.42%	13.63, 2.67%
SC75+MC20[g]	28.50, 4.84%	24.28, 1.82%	20.72, 1.93%	17.53, 3.35%
SC75+MC40[h]	37.67, 4.70%	33.53, 2.09%	27.80, 2.32%	22.06, 2.65%
SC75+MC60[i]	37.24, 1.50%	33.54, 1.80%	28.43, 2.42%	22.02, 3.86%
7-day Water Curing	31.82, 1.83%	33.35, 1.74%	24.79, 3.93%	21.20, 2.50%

Note: [a], [b], [c], [d], [e], [f], [g], [h] and [i] are the same as TABLE 4.

Table 6. Comparison of Compressive Strength of Concrete with Different Mineral Admixture Replacements After 28-day Different Curing

Curing Method \ Replacement		Compressive Strength, MPa (Mean, Cv[a])			
		Type I Cement	10 % Fume Ash Replacement	20 % Fly Ash Replacement	40 % Furnace Slag Replacement
SC65+MC0[b]	+ 27-day Water Curing	35.28, 3.98%	41.25, 2.83%	32.07, 3.88%	29.10, 2.85%
SC65+MC20[c]	+ 27-day Water Curing	37.23, 2.75%	37.26, 3.45%	28.37, 3.72%	24.73, 2.87%
SC65+MC40[d]	+ 27-day Water Curing	39.38, 2.69%	43.44, 3.97%	30.11, 3.93%	26.39, 4.91%
SC65+MC60[e]	+ 27-day Water Curing	35.70, 2.95%	37.12, 3.79%	26.72, 3.89%	24.98, 4.98%
SC75+MC0[f]	+ 27-day Water Curing	33.52, 3.17%	39.18, 3.09%	30.46, 3.02%	27.64, 3.61%
SC75+MC20[g]	+ 27-day Water Curing	35.37, 5.45%	35.40, 3.92%	26.94, 2.98%	23.50, 3.97%
SC75+MC40[h]	+ 27-day Water Curing	37.84, 5.16%	39.10, 2.98%	28.60, 2.93%	25.07, 3.68%
SC75+MC60[i]	+ 27-day Water Curing	37.12, 3.13%	35.27,3.87%	26.38, 2.99%	24.48, 3.11%
28-day Water Curing		39.20, 0.64%	45.83, 1.13%	35.63, 1.75%	32.33, 3.45%

Note: [a], [b], [c], [d], [e], [f], [g], [h] and [i] are the same as TABLE 4.

B. Rapid Chloride Permeability Testing

The results of the rapid chloride permeability testing are summarized in Table 7 for the samples after 2-day Curing and Table 8 for the samples after 28-day Curing. It can be seen from these tables that the test values for one of the curing methods (SC65+MC20) are significantly higher than the values of the other curing methods. Among the four types of concrete evaluated, the silica-fume concrete shows the lowest permeability at all curing methods and ages. It can be seen that the concrete permeability drastically decreases with the silica fume addition. At 2-day Curing, the fly ash concrete showed substantially higher permeability value than the control concrete, while the silica-fume concrete and the slag concrete had a lower permeability than the control one. At 28-day Curing, the fly ash concrete was very close to the control concrete in the RCPT test, while the silica-fume concrete and the slag concrete had lower permeability than the control one.

Table 7. Rapid Chloride Permeability Test Results of Concrete Samples After 2-day Curing

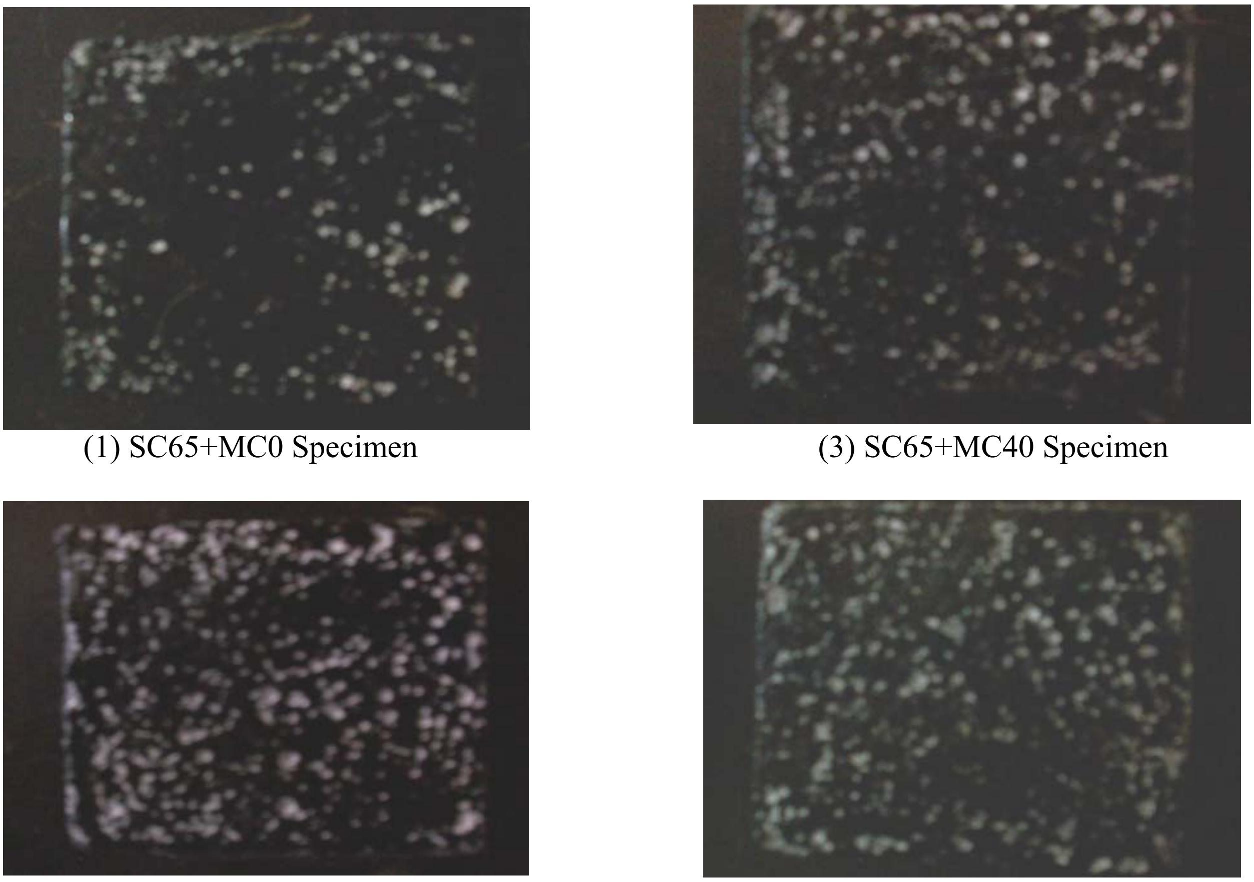
Curing Method \ Replacement		Total Charge Passed （coulombs）			
		Type I Cement	10 % Fume Ash Replacement	20 % Fly Ash Replacement	40 % Furnace Slag Replacement
SC65+MC0[b]	+ 1-day Water Curing	8984	4558	8992	5698
SC65+MC20[c]	+ 1-day Water Curing	9203	5335	9613	6669
SC65+MC40[d]	+ 1-day Water Curing	6839	3954	7160	4943
SC65+MC60[e]	+ 1-day Water Curing	6986	4848	8825	6060

Note: [b], [c], [d] and [e] are the same as TABLE 4.
Note: Each value is the average of 2 test specimens.

One objective of this study was to determine if the steam-microwave curing of the specimens increases the permeability of the concrete. The test results show that the steam-microwave cured tests had slightly higher permeability values as compared with the concrete that was water cured for 28 days. Therefore, for the conditions used in this study, the steam-microwave curing of the concrete had little effect on the concrete permeability. The microwave-cured concrete did not show an increase in permeability relative to the concrete that was steam-cured but showed an increase in strength development. As can be seen from the above data, the average permeability of the 28-day cured concrete was significantly lower than that of the 2-day cured concrete. This shows that the curing age and the supplementary cementitious materials have a large impact on the permeability of the concrete.

Pores and Micro-cracks in Microstructure under Steam and Microwave Curing

To further investigate the effect of steam curing and microwave curing on cement mortar specimens, sections were cut from various cured specimens (SC65+MC0, SC65+MC20, SC65+MC40, SC65+MC60) and painted with a black paint. White zinc oxide powder was then spread onto the surface of cured specimens to reveal pores and/or microcracks. Pictures of various cured specimen surfaces are shown in Figure 6. By comparing the pictures for steam cured and microwave cured specimens, it is clear that microwave heating generates much more pores and micro-cracks in the mortar specimens. Figure 7 shows an SEM image of the micro-cracks on a concrete specimen after steam and microwave curing.



(1) SC65+MC0 Specimen

(3) SC65+MC40 Specimen

(2) SC65+MC20 Specimen

(4) SC65+MC60 Specimen

Figure 6. Pore and Microcracks in Mortar Specimens under Steam and Microwave Curing

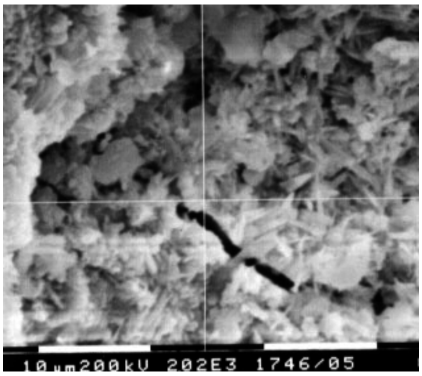


Figure 7. Micro-crack in Concrete Specimen under Steam and Microwave Curing

Conclusions

The main findings from this study are summarized as follows:

(1) The mortar test results indicated that microwave heating could further increase the compressive strength of the mortar. The amount of strength gain was about 10 MPa by using 20 minutes microwave heating, and was from 15 to 25 MPa by using 40 or 60 minutes microwave heating.
(2) High early compressive strength of the steam and microwave cured concrete was obtained while its 28-day strength was slightly lower than the 28-day strength of normally water-cured ones.
(3) Pozzolanic reaction of silica fume, fly ash and blast-furnace slag could be further promoted by steam-microwave curing. Mortar and concrete samples with 10% silica fume added responded well to microwave curing.
(4) The strength gain development of mortar and concrete appeared to level off after 40 minutes of microwave curing. Thus, a 40-minute microwave heating time appeared to be the optimal time for energy saving consideration.
(5) The addition of silica fume resulted in a reduction in the permeability of concrete.
(6) To produce concrete with low permeability, pozzolanic materials (ie. silica fume, furnace slag) should be used.
(7) The microwave-cured concrete did not show an increase in permeability relative to the concrete that was steam-cured, but showed an increase in strength. Thus, microwave heating may be a potentially attractive method for accelerating cement hydration.

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