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DETERMINATION OF OPTIMAL PROCESS FOR MICROWAVE CURING OF CONCRETE

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ABSTRACT

Operations such as precasting and repair of concrete can benefit significantly from rapid strength development. Previous investigations have shown that microwave curing is an effective means to develop high early strength in concrete. Moreover, with certain combinations of processing parameters (including microwave power, application time and duration of microwave), the later age strength (at 7 days) can be comparable to that of specimens cured at room temperature. The present investigation illustrates how optimal processes, which provide high strength at both the early and later stage, can be obtained with the help of feedback temperature control. Using 0.4 w/c ratio concrete as an example, the optimal power history (in terms of a continuously varying curve) is identified. To enable processing with low cost microwave generators (such as the ones in the domestic oven), the optimal power curve is approximated with discrete power levels. The discretized optimal power is found to give very good results for concrete with 0.4 w/c and below. Compared with the use of fixed power, the use of variable discrete power can provide better combinations of early age and long term strength with less energy consumption. As examples, at the early age of 4.5 hrs, compressive strength of 29.5 MPa and 35.4 MPa are achievable with w/c equal to 0.40 and 0.325 respectively. In both cases, the strength at 7 day shows no deterioration compared with specimens cured at room temperature. © *1997 Elsevier Science Ltd*

Introduction

The rapid strength development of concrete can greatly facilitate construction operations such as precasting and repair. Recent work [1-4] on microwave curing of concrete has shown the following interesting results: (i) with microwave curing, very high early strength, from 19 to 27 MPa (2,750 to 3,950 psi) can be achieved in 4.5 hrs for w/c ratio of 0.55 to 0.40, and (ii) with microwave applied shortly after the concrete is mixed, water is removed when concrete is still in the plastic stage, resulting in a reduced w/c ratio, (iii) with some combinations of processing parameters (including microwave power, application time after mixing, duration of application) the later age strength (measured at 7 days for type III cement) is comparable to that achieved by curing at room temperature. From the experimental results, it is clear that microwave curing is superior to conventional thermal curing in two important aspects: (i) very high strength can be achieved in a few hours, and (ii) it is possible to achieve high early strength with little or no strength deterioration in the long term. The previous investigations therefore establish the potential of microwave curing as a rapid curing technique for practical applications.

Leung and Pheeraphan [4] studied the effect of various processing parameters (including w/c ratio, power level, power duration and delay time) on the microwave curing of concrete. While high early age strength can be achieved for most cases, high later age strength, comparable to that achieved with room temperature curing, is found only for a few cases. By examining cut sections of microwave cured specimens, the reduced long term strength is found to be associated with increased porosity and microcracking. It is postulated that the pores and microcracks are formed as a result of overheating. In Leung and Pheeraphan [4], fixed power is applied and the specimen temperature increases monotonically. With feedback power control which puts a limit on the maximum specimen temperature, the amount of overheating can be reduced. Also, by avoiding energy consumption in overheating the specimen, less total energy is required and the process can be more energy efficient.

The major purpose of the present investigation is to illustrate the optimization of microwave curing processes with the help of feedback temperature control. Here, an optimal process is loosely defined as a process which will provide high early and later age strength, with a reduced amount of required energy. Note that the optimal process obtained in this work is a relative optimum among the cases studied. With more experimental work following the framework presented in this paper, it is possible to obtain even better processes.

The experimental work starts with preliminary tests using mortar specimens with 0.5 w/c ratio. The best process identified in the preliminary tests, and some of its variations, are applied to concrete specimens of 0.4 w/c ratio to determine an optimal power history. The optimal history curve is approximated with discrete power levels which can be generated by low cost microwave generators (such as the kitchen oven). The discrete power is then applied to concrete specimens with w/c ratio from 0.4 to 0.325. With the discretized optimal power, very high early strength can be achieved with little deterioration in long term performance.

Experimental Program

To make mortar and concrete specimens, type III Portland cement is used with different sources of sand. For mortar specimens, the cement/mortar sand ratio is fixed at 1:2. Mortar sand with a fineness modulus of 2.28 is supplied locally by B. Vitalini, Inc. from Milford in Massachusetts. For concrete specimens, the cement/sand/gravel ratio is 1:1:1.5. Sand with 2.82 fineness modulus is obtained from Boston Sand and Gravel Co. while pea gravel is supplied from B. Vitalini, Inc.. Pea gravel is washed and dried in the conventional oven for one day. After 7 days in air, it is sieved to a size between 9.4 mm (0.371 in) and 2.36 mm (0.093 in) before use. For specimens with w/c ratio below 0.35, superplasticizer (WRDA-19 supplied by W.R. Grace & Co.) is used. 4 grams of WRDA-19 is used per 454 grams of cement. It is added to the water before mixing.

Nine 76.2 mm (3-in) by 152.4 mm (6-in) specimens are cast in each batch. Six of them (cast in polyethylene molds) are microwave cured while the rest are cured normally. The specimens in the oven are arranged in a ring on the turntable. In most cases, microwave energy is applied 30 minutes after water is added to the mix. To monitor the internal temperature, a temperature probe is inserted into one of the microwave cured specimens. After microwave curing, the specimens (except the one with the probe) are removed from the oven and covered with plastic sheets. At 3.5 hours after mixing, three microwave cured specimens are removed from the molds and capped for compression test at 4.5 hours. The rest of the microwave cured specimens, as well as the normal cured specimens, are then removed from the molds after one day. They are then cured in saturated-lime water at 22.8°C (or 73 F) for 6 more days until testing at 7 days.

To perform microwave curing, a microwave oven model fabricated by Cober Electronics, Inc. (LBM1.2A) is employed. It can generate power at any level from 0 to 1200 watts. To achieve uniform heating, there are a mode stirrer and a turntable. In addition, the oven is supplied with a temperature probe and an Analog Devices μMAC-1050 data acquisition card to monitor the internal temperature of the material and to facilitate feedback control of the process. The μMAC-1050 is installed with the RS-232 interface for data communication with a personal computer. Actual data recording and feedback control is carried out with the help of the Labtech "Notebook" software. The software has the capability for PID (Proportional-Integral-Derivative) control but for simplicity, only proportional control is employed. The output power is then proportional to the difference between the required temperature and the temperature at a particular moment. In our experiments, a proportional constant of 3 is employed. Besides the proportional constant, the power history is also affected by the maximum allowable power set in the experiments. By reducing the maximum allowable power, a limit is set on the power at the early stage of the process (when there is a large difference between target temperature and current temperature). It is therefore a means to limit the heating rate at the early stage.

Results and Discussions

Tests with Mortar Specimens. To obtain the optimal process, some 'trial and error' experiments were first carried out with mortar specimens. A w/c ratio of 0.5 was employed. In Leung and Pheeraphan [4], 0.5 w/c mortar specimens were microwave cured under constant power at various levels and for different duration. For six 76.2 mm × 152.4 mm specimens, the optimal process (for constant power) was found to be 400W for 45 minutes. In the present study, a new set of specimens were cured under such conditions and the temperature during curing was monitored. The temperature was found to increase monotonically during the curing process and reached a maximum of 85°C. Since it was postulated that the use of constant power may lead to unnecessary over-heating, feedback control processes were carried out to limit the temperature of the specimens to below 80°C. Including the case with constant power, five different curing processes are investigated and compared. The five cases are listed below:

Case M1: Constant power at 412 watts for 45 minutes.

Case M2: Feedback temperature control to limit maximum temperature to 60°C, with total heating time of 90 minutes. (Maximum power = 600W)

Case M3: Feedback temperature control to approach 50°C in the first 20 minutes and to approach 80°C in the next 25 minutes; total heating time is 45 minutes. (Maximum power = 1000W)
Case M4: Feedback temperature control to limit maximum temperature to 80°C; total heating time is 45 minutes. (Maximum power = 1,200W). In this case, the microwave is applied 35 minutes after mixing (rather than 30 minutes as in all other cases).
Case M5: Constant power at 800 watts for 20 minutes, followed by feedback temperature control to limit maximum temperature to 80°C; total heating time is 45 minutes. (Max. power = 800W)

It should be noted that the power reported in this paper is slightly different from that reported in Leung and Pheeraphan [4]. In the previous paper, power is read directly from the meter on the front of the oven. The numbers are therefore not very precise (within about ±20 W). In this paper, the more precise reading recorded by the computer through the data acquisition card is reported. For example, for Case M1 above, the power is reported to be 412W and it is equivalent to a meter reading of 400W, which is the number reported in Leung and Pheeraphan [4] for the best case with constant power.

The various curing processes are chosen in a rather arbitrary manner, but they do give rise to very different temperature variations during curing (Fig. 1). The early compressive strength (at 4.5 hours) and the later age strength (7 days) for microwave cured specimens are measured and compared with the 7 day strength of normal cured specimens. The results for the five different processes are shown in Fig. 2. In the figure (and in the following bar charts for other sets of results, the number above each bar shows the strength value in MPa and the number in parenthesis is the percentage of reference strength achieved. In all the figures, the reference strength is taken to be the 7 day strength of normal cured specimens of the same batch.

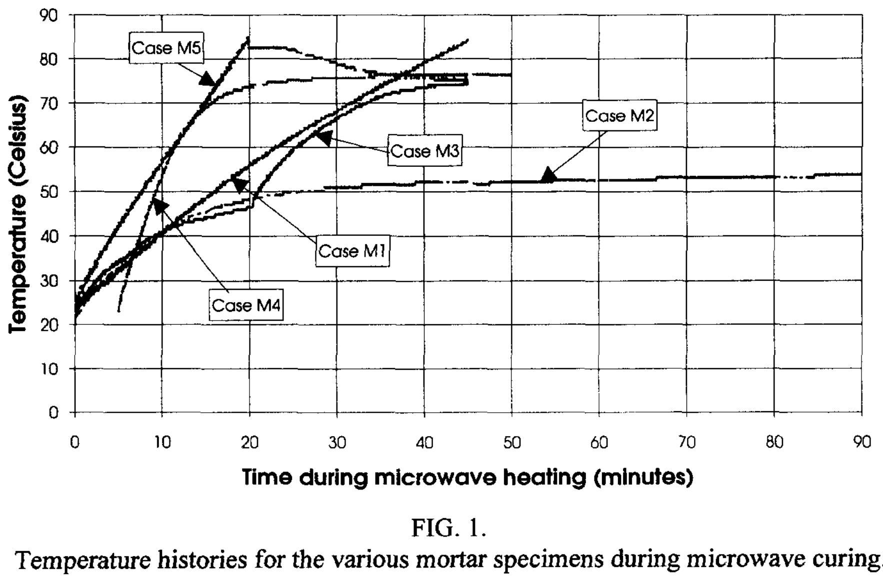

FIG. 1.
Temperature histories for the various mortar specimens during microwave curing.

To compare the results for different cases, it is most informative to consider the percentage of reference strength achieved, to minimize the effect of material variation from one batch to another. Results from Fig. 2 indicate that Case M1 and Case M4 provide the best combinations of early and later age strength. Examination of both Fig. 1 and Fig. 2 showed that the low heating rate of Case M2 is insufficient to provide high early age strength, while the high heating rate of Case M5 leads to early overheating and significant deterioration in later age strength. Case M3 provide reasonably good results but is inferior to Case M1 and Case M4. Indeed, by summing the percentage of reference strength achieved at 4.5 hr and 7 day, Case M4 seems to be slightly better than Case M1. Also, if we also record the power vs time curve for the two cases during curing and calculate the total energy consumption (as the area of the power vs time curve), it is found that the energy consumption for Case M1 is 0.309 kWhr while that for Case M4 is 0.302 kWhr. Case M4 therefore also turns out to be slightly more energy efficient.

With the use of feedback temperature control, the mortar specimens showed only marginal improvement over those cured with constant power. Leung and Pheeraphan [4] have shown for the case of fixed power that microwave cured concrete performs much better than microwave cured mortar specimens. Also, concrete with aggregates is more widely used than mortar in practical applications. Subsequent tests are therefore carried out with concrete specimens.

Concrete Specimens with 0.4 w/c Ratio. For concrete specimens, a w/c ratio of 0.4 was employed. Note that the grading of the sand used in this investigation is different from that used in our previous work [4]. With a better grading, we are able to remove mixing problems mentioned in Leung and Pheeraphan [4]. The first series of tests for concrete specimens investigates four different curing processes, which are similar to cases M1 and M4 above, which give good results for mortar:

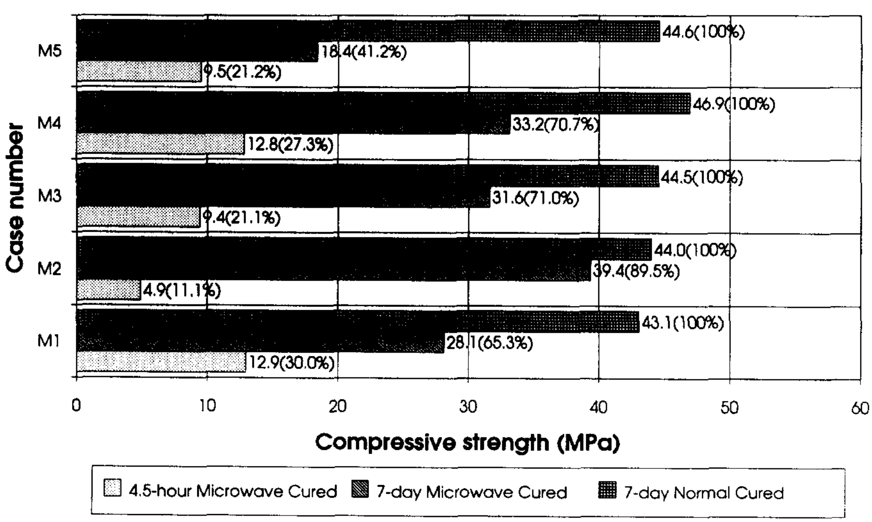

FIG. 2.
Compressive strength for microwave cured mortar specimens (0.5 w/c ratio).

Case C1: constant power at 412W for 45 minutes
Case C2: Feedback temperature control to limit maximum temperature to 80°C; total heating time is 45 minutes (maximum power = 750W)
Case C3: Feedback temperature control to limit maximum temperature to 85°C; total heating time is 45 minutes (maximum power = 1,200W)
Case C4: Obtain the power vs time for C2 and apply a 'reversed' history with Power at time t equal to Power at time (45 minutes -t) for case C2. Total heating time is 45 minutes.

Note that Case C4 requires the same amount of energy as C2 but would supply less energy to the specimens at the earlier stage of microwave heating and more energy at the later stage. Compared with cases C1 and C2, we expected less overheating. The power history as well as the temperature history for cases C1 to C4 are shown in Fig. 3a and 3b. The compression test results are shown in Fig. 4. In this figure (and subsequent figures that are similar) the number in parenthesis behind each case indicates the final w/c ratio after microwave curing. From Fig. 4, several important observations can be made. The high heating rate of case C3 lead to significant reduction in later age strength. For case C4, both the early and later age strength is lower than that for case C2. While the two cases reach similar final temperatures after microwave curing (Fig. 3b), the more rapid heating at the early stage for case C2 seems to be closer to the optimal process. Compared with case C2, case C1 has higher early age strength but do not perform as well at later age. This can be explained by the higher temperature reached by case C1 in the curing process. By summing the percentage of reference strength achieved at 4.5 hr and 7 day, case C2 is slightly better than case C1. However, if we calculate the total power consumption from the area under the power vs time curve (Fig. 3a), the energy consumption for case C1 is found to be 0.309 kWhr while that for case C2 is only 0.241 kWhr. With feedback temperature control, case C2 can provides similar early and later age strength to C1 with 20% less energy consumption.

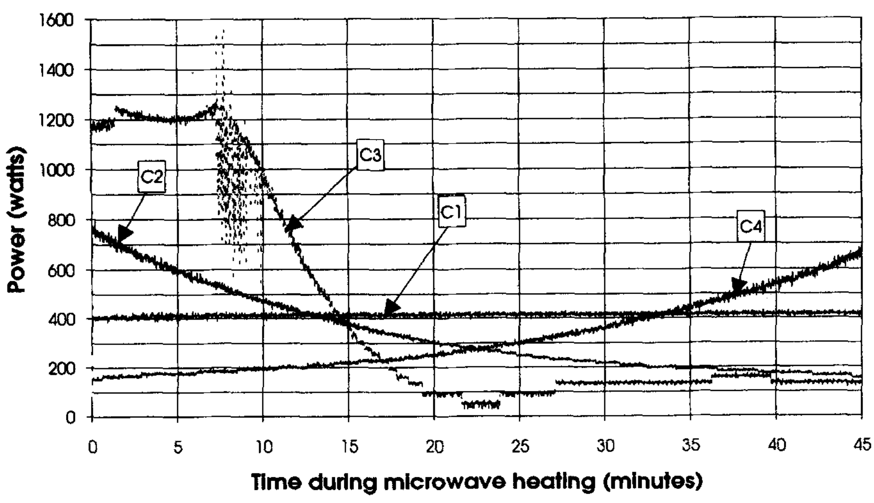

FIG. 3(a).
Power history during microwave curing for the various cases.

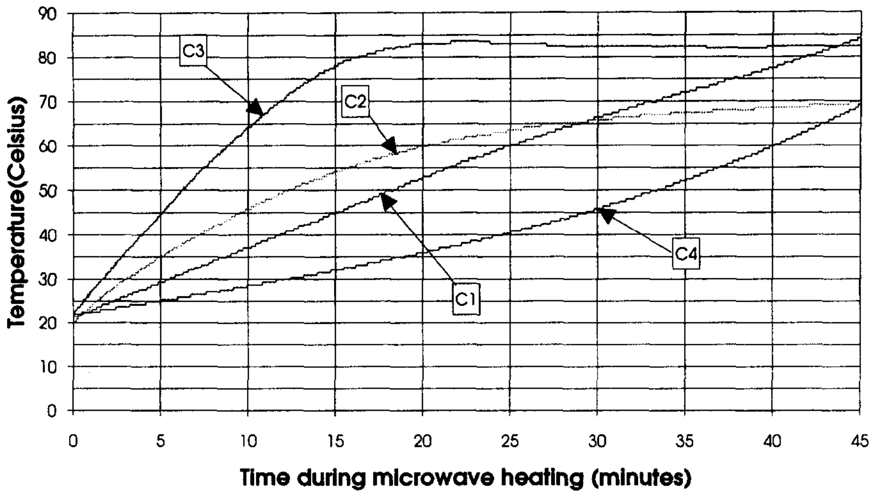

FIG. 3(b).
Temperature history during microwave heating for the various cases.

The above results indicate that it is advantageous to employ close loop temperature control for concrete specimens. To carry out feedback control, a microwave oven which allows continuous variation of power is required. A microwave generator which can produce continuously varying power (such as the one in our laboratory oven) is, however, very expensive. On the other hand, the fixed power generator in kitchen microwave ovens are inexpensive and suitable for practical engineering applications. For the fixed power generator, by using a switch to turn the power on and off for different fractions of time, discrete

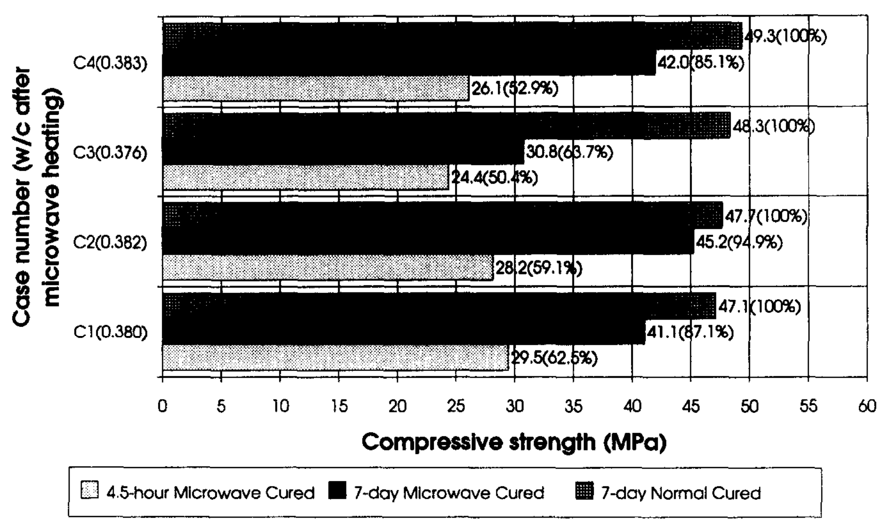

FIG. 4.
Compressive strength for the various Concrete specimens (0.40 w/c ratio).

power levels can be produced. Therefore, after an optimal power history is identified through feedback power control, one can approximate the power history with a number of discrete power levels. If the discrete power levels provide results comparable to the continuously varying power, low cost microwave generators can be used. The feasibility of microwave curing for practical applications is then greatly enhanced.

The power history for case C2 was discretized in two different manners (Fig. 5). Concrete specimens were then cured with these discrete power levels. For case C5, the power is discretized into 5 minutes intervals of 675W, 550W, 450W, 350W, 300W, 250W, 200W, 150W and 100W. For case C6, the discretized history is 800W (5 min), 412W (10 min), 300W (10 min) and 200W (20 min). For both cases, the total power for the discretized power is roughly equal to that of the continuously varying power. Compressive test results for case C5 and C6 are shown together with C2 in Fig. 6. While the use of discrete power leads to lower strength at 4.5 hours, the 7 day strength is comparable or higher to specimens cured with continuously varying power. With discrete power, the strength achievable at 4.5 hours (which are 25.2 MPa and 26.2 MPa for the two cases) are still very high. Also shown in Fig. 6 are results from two other cases, C7 and C8. These two cases are exactly the same as cases C5 and C6, only that the temperature probe is not inserted into the specimens to monitor the temperature during curing. Since no feedback control is required for the discrete power case, the temperature probe is not necessary. Originally, we assumed that the temperature probe has a negligible effect on the curing process. Cases C7 and C8 were carried out to verify such an assumption. To our surprise, cases C7 an C8 give results significantly different from cases C5 and C6, indicating that the probe does have a significant effect on the curing process. Removing the probe leads to better results. In particular, the later age strength showed no deterioration compared to normal cured specimens. Summing the percentage of reference strength achieved at 4.5 hr and 7 day indicates that the use of discrete power with no temperature probe (cases C7 and C8) produces better results than the original feedback control case with the temperature probe (case C2).

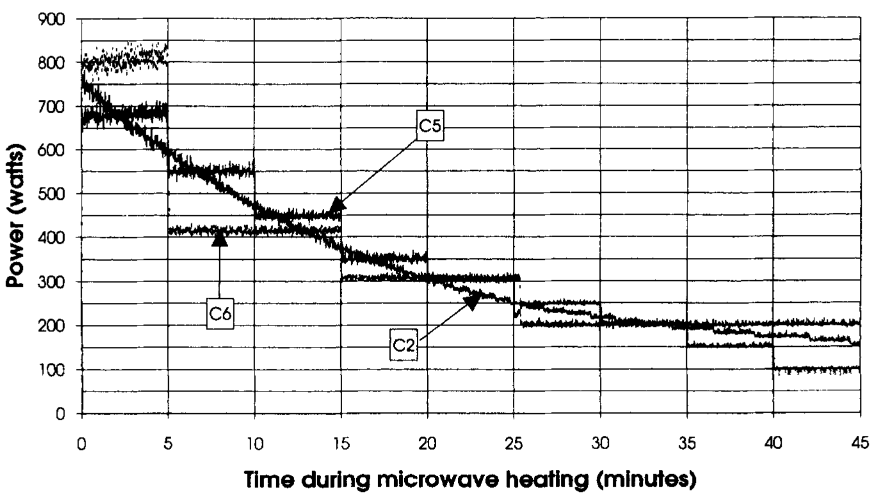

FIG. 5.
Discrete power histories as approximations for the optimal power history.

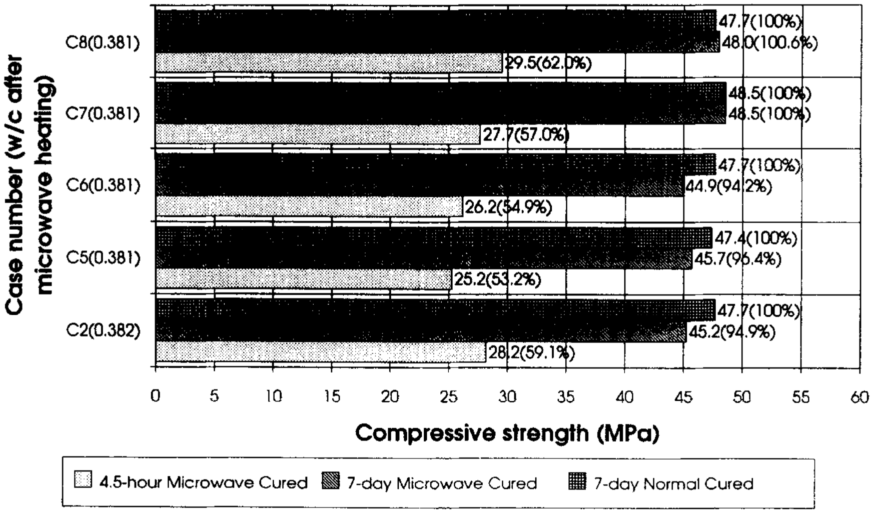

FIG. 6.
Compressive strength of 0.40 w/c concrete microwave cured with continuous and discrete power histories.

<u>Concrete Specimens with Low w/c Ratio and Superplasticizers</u>. With good results obtained from 0.4 w/c concrete specimens, microwave curing are carried out with lower w/c ratios to see if further improvements are possible. Specimens with 0.35 and 0.325 w/c ratios were cast with the use of superplasticizers. 0.35 w/c specimens were cured under the same power history of case C2 (feedback control with temperature probe), case C7 and case C8 (discrete power with no temperature probe). These experiments are referred to as cases C9, C10 and

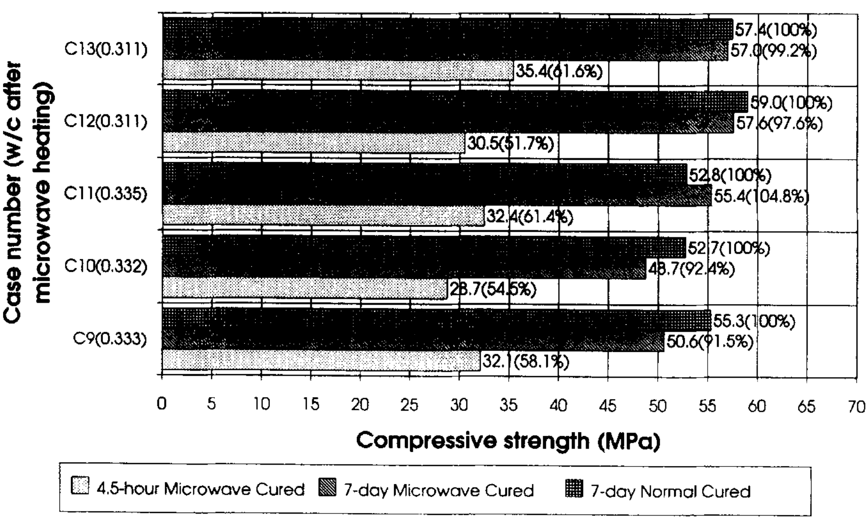

FIG. 7.
Compressive strength results for 0.35 w/c and 0.325 w/c concrete specimens.

C11 respectively. 0.325 w/c specimens were cured under the same power history of case C7 and C8. These cases were referred to as C12 and C13. All the results for concrete with superplasticizers are shown together in Fig. 7. For all cases, the 4.5 hr strength goes beyond half the reference strength while the 7 day strength exceed 90%. The results from cases C11 and C13 are particularly impressive. In these cases, the later age strength shows no deterioration compared to 7 day normal cured specimens. For w/c = 0.35, the 4.5 hr strength reaches 32.4 MPa while the 7 day strength is 55.4 MPa. For w/c = 0.325, the 4.5 hr strength reaches 35.4 MPa while the 7 day strength is 57.0 MPa. It should be noted that case C8 also gives rise to the best result for 0.4 w/c specimens. The 5-level discrete power used in cases C8, C11 and C13 can therefore be considered as the optimal process for concrete specimens of w/c ratio from 0.4 to 0.325.

Conclusions

Microwave curing of mortar and concrete specimens are carried out with feedback temperature control. For concrete of w/c = 0.4, we identify an optimal process which can provide good combination of early age (4.5 hr) and later age (7 day) strength with 20% less energy consumption than the case with constant power. To allow the use of low cost microwave sources, the optimal power (which is a continuous variation) is approximated by discrete power levels. Our experimental results indicate that the use of discrete power produces results similar to those obtained with the continuous varying power. The discrete optimal power is then applied to specimens with w/c of 0.35 and 0.325. Very high early age strength can again be obtained with no deterioration in later age performance. In summary, through an experimental approach, we have successfully developed an optimal process for concrete with w/c ratio from 0.4 to 0.325. For w/c = 0.4, the optimal process gives rise to a strength of 29.5 MPa at 4.5 hr and 48.0 MPa at 7 days. For w/c = 0.325, the 4.5 hr strength reaches 35.4 MPa while the 7 day strength is 57.0 MPa. The results clearly indicate the advantage of microwave curing over conventional thermal curing. Further research and developments to scale up the microwave curing process for practical applications should therefore be pursued.

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