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VERY HIGH EARLY STRENGTH OF MICROWAVE CURED CONCRETE

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ABSTRACT

A high rate of strength development in concrete can benefit a number of important operations in the construction industry, including concrete precasting and pavement repair. In this study, the acceleration of concrete curing with microwave energy is investigated. Type III Portland cement is employed and both mortar and concrete specimens are made and tested. By applying the microwave energy for only 45 minutes, the compressive strength of concrete at an early age of 4.5 hours can reach 19.2 MPa (2,785 psi) for w/c=0.55 and 27.2 MPa (3,947 psi) for w/c=0.40. For the 0.55 w/c composition, the 7-day compressive strength reaches 37.4 MPa (5,417 psi), which is higher than that of conventionally cured specimens. Such performance compares favorably with commercially available rapid hardening concrete as well as concrete containing accelerators, showing microwave curing to be a promising technique for practical applications.

Introduction

A higher rate of strength development in concrete can greatly facilitate several important processes in the construction industry. For example, in the development of precast concrete products, it is desirable to attain sufficient strength within a short period of time so the moulds can be re-used and the final products can be handled and delivered to the site as soon as possible. In the repair of localized damaged regions in concrete pavements (such as spalls, holes or severely cracked regions), rapid strength develepment in the new concrete can minimize disruption to the traffic flow.

Heating can accelerate the curing of concrete (1). Conventional heating techniques, such as steam curing, rely on the conduction of heat from the exterior to the interior of a sample. The heating is therefore non-uniform and a long heating period is required to attain the required temperature. Microwave heating, which is based on internal energy dissipation associated with the excitation of molecular dipoles in electromagnetic fields, allows faster and more uniform heating. A short process time is therefore sufficient to provide high early strength. Wu et al (2) reported that 15 to 30 minutes of microwave application can improve the 3 day compressive strength of concrete by around 39-47% and the flexural strength by 12-15%. Moreover, unlike steam cured specimens, the 28 day strength is also increased. This increase in later age strength is attibuted to the removal of water from the fresh concrete when microwave is applied, causing collapse of the capillary pores and densification of the concrete.

Hutchison et al (3) obtained the compressive strength of concrete specimens cured under various levels of microwave energy at ages of 1, 7 and 28 days. The strength of microwave cured specimens are found to be slightly higher than that of the conventionally cured control specimen. Also, the degree of hydration was measured at 1, 3 and 9 hours and 1, 7 and 42 days. The results indicate that microwave application can significantly increase the degree of hydration during the first day, after which the microwave cured specimens and the control specimen attain similar degrees of hydration.

In Hutchison et al (3) and Wu et al (2), the earliest age at which microwave cured specimens are tested is one and three days, respectively. In both precasting and pavement repair, it is desirable to develop significant strength at an age much earlier than one day, hopefully within several hours. The findings reported in (2) and (3) thus have little practical significance. Moreover, in (2) and (3), only mortar specimens have been studied. In this investigation, compressive strength values of microwave cured mortar and concrete specimens are measured at the very early age of 4.5 hours (with one series measured at 3 hours). To study the effect of microwave on long term strength development, the 7 day strength of microwave cured specimens is also obtained and compared with results for conventionally cured specimens. The performance of microwave cured specimens with the best combination of short and long term strength are then compared with commercial rapid curing concrete as well as concrete containing accelerators.

Experimental Program

Concrete cylinders of 76.2 mm diameter and 152.4 mm height (or 3"x6") are made with type III Portland cement. While both Wu et al (2) and Hutchison et al (3) used type I cement in their investigations, type III cement is used here to maximize early strength development. To make a mould that is transparent to microwave, 152.4 mm lengths were cut from polyethylene pipes of 76.2 mm inner diameter and fitted to a polyethylene plate at one of its ends. Both mortar and concrete specimens are made. For the mortar specimen, the cement/sand (c/s) ratio is fixed at 1:2. For concrete specimens, the cement/sand/aggregate (c/s/a) ratio is 1:1:1.5. As a reference, the compressive strength of conventionally cured mortar specimen reaches 21.9 MPa (3178 psi) after one day.

In the experiments, a microwave oven fabricated by Cober Electronics Inc. (Model LBM1.2V) is employed. The oven is capable of generating power at any level from 0 to 1,200W. Equiped with both a turntable and a mode stirrer, the oven allows uniform heating of the specimens. Also, the oven is supplied with thermo-probes and data communication hardware to allow the feedback control of microwave process. However, as a first investigation on the very early strength of microwave cured concrete, feedback control is not carried out and fixed forward power is employed for all of our tests.

Nine specimens are casted in each batch. Three of the specimens are cured by conventional methods while six of the specimens are microwave cured. The microwave cured specimens are weighed before they are transferred to the microwave oven and arranged in a circle on the turntable. After a certain delay time, microwave power is applied for a specified period of time. Specimens are then removed from the oven and weighed again to determine the water loss and the final w/c ratio. A plastic sheet is put on top of the mould to prevent further moisture loss. Half of the specimens are taken out of the mould at 3.5 hrs, capped and tested at 4.5 hrs. (Note: for specimens tested at 3 hrs, they are removed from the mould after 2 hrs.) The other three microwave cured specimens are removed after 24 hrs, and left in a water bath for 6 more days until they are tested. The conventionally cured specimens are covered with plastic sheets after casting, removed from the mould after one day, and placed in the water bath until testing at an age of 7 days. It should be noted that in this investigation, time (e.g. delay time before microwave application, age at which testing is done) is measured from the moment when water is added to cement and aggregates during the mixing procedure.

Various parameters, including heating rate, power level, water/cement ratio and delay time before microwave application, are first studied using mortar specimens. Then, concrete specimens made with various w/c ratio and subject to different microwave power levels are tested.

Results and Discussions

Mortar Specimens

Fig.1 shows the effect of heating rate on the early and long term strength of microwave cured mortar specimens. In Fig.1 and all other figures, the numbers in brackets along the x-axis indicate the final w/c ratio after microwave is applied. In this first series of experiment, the w/c ratio was kept at 0.5 and microwave was applied after a delay time of 30 minutes. A higher power level was accompanied by a shorter process time so that a fixed total forward energy of 1.08 MJ was applied to each batch of specimens. Cases with higher power levels therefore represent microwave curing with higher heating rates. From Fig.1, the 3 hr strength appears to reach a plateau at a power level of 500W while the 7 day strength exhibits significant drops for power levels beyond 400W. Also, in contrast to the findings of previous researchers (2,3), the 7 day strength of microwave cured specimens are lower than that for normal cured specimens for all cases. The results indicate that the long term strength is more sensitive to rapid heating at an early age when type III cement is used. Similar observations have been made for steam cured concrete (4). From the figures, the 3

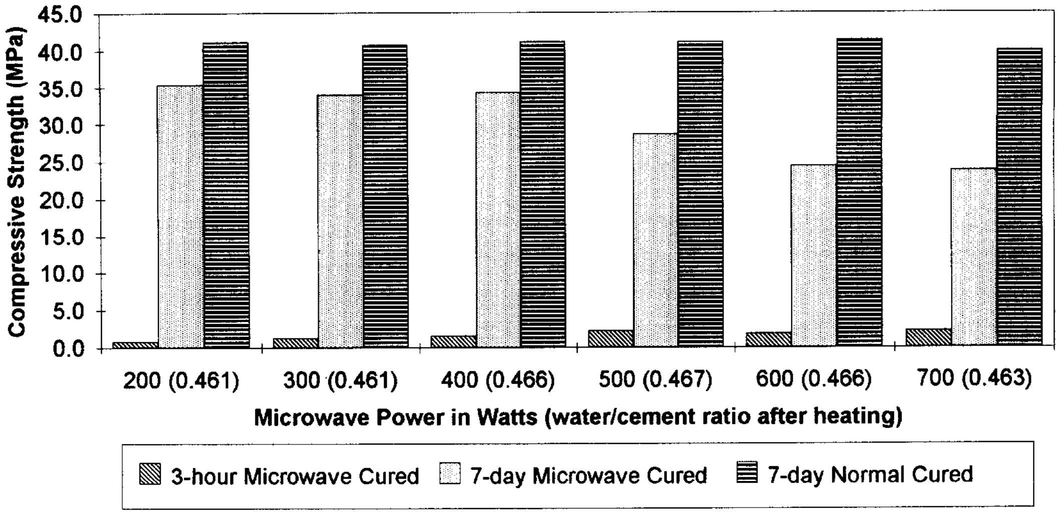


FIG.1
Effect of Microwave Power Application Rate on Mortar Specimens
(Delay Time = 30 min, w/c = 0.50, Total Power Applied = 1.08 MJ)

hour strength is still quite low, with a maximum value of only 2.23 MPa (323 psi) for the case with 500W power level. For further experiments, testing is carried out at 4.5 hrs instead.

Fig.2 shows the effect of power levels. Specimens of 0.5 w/c were microwave cured at various power levels for 45 minutes after 30 minutes of delay time. An increase of power level

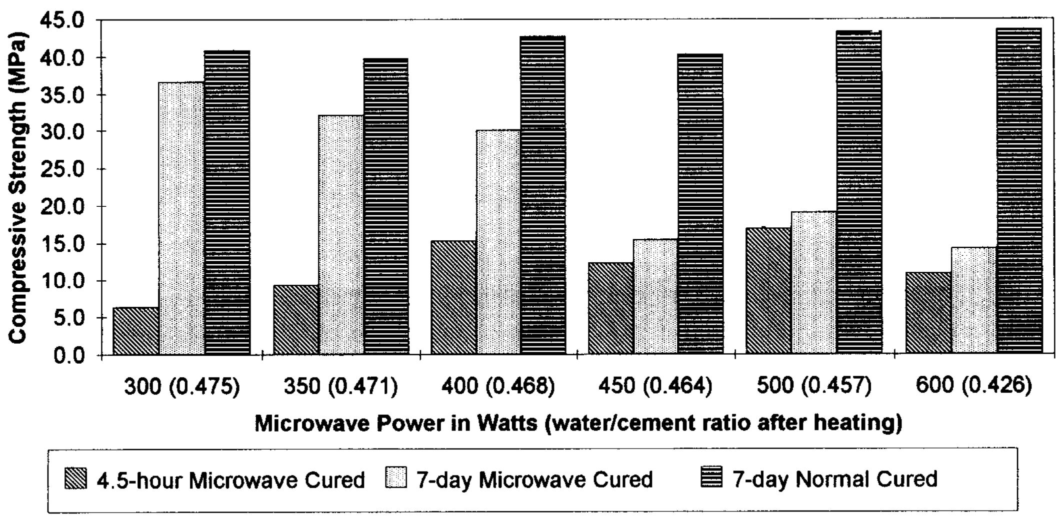


FIG.2
Effect of Microwave Power Level on Mortar Specimens
(Delay Time = 30 min, w/c = 0.50, Application Time = 45 min)

beyond 400W results in little further improvement in early strength but a significant drop in strength at 7 days. The power level of 400W thus appears to provide the best compromise between early and later age strength. For specimens microwave cured at 400W, the 4.5 hr strength is 15.3 MPa (2215 psi) while the 7 day strength is 30 MPa (4353 psi), reaching about 70% that of the conventionally cured specimen.

The effect of delay time is shown in Fig.3. For specimens of 0.5 w/c subject to 45 minutes of microwave application at 400W, the optimal delay time is found to be 30 minutes. Fig.4 shows the effect of w/c ratio. For specimens microwave cured at 400W for 45 minutes after 30 minutes of delay time, an increase of w/c ratio from 0.45 to 0.55 gives very similar strength values at 4.5 hrs (at around 15.5 MPa or 2250 psi). Surprisingly, the 7 day strength increases as the w/c ratio increases from 0.45 to 0.55 (with the final w/c increases from 0.419 to 0.516). For specimens with a higher w/c ratio, there is less heat liberated from the hydration reaction and hence a less severe deterioration of the long term strength. This argument is further supported by the 7 day strength measurements for 0.6 w/c specimens, which show very little difference between conventionally cured and microwave cured specimens. However, in the case with w/c=0.6, the heating rate (due to both applied power and heat liberated from hydration reactions) is not sufficient to give a 4.5 hr strength as high as that for lower w/c ratios. It thus appears that 400W is close to the optimal microwave power for a w/c ratio of 0.55.

Concrete Specimens

Fig.5 shows the effect of power level on microwave cured concrete specimens. For a fixed w/c ratio of 0.5 and a delay time of 30 minutes, when the power level increases from 300W to 450W, the strength at 4.5 hrs increases from 7.8 MPa (1132 psi) to 19.9 MPa (2890psi) while the 7 day strength goes from 39.0 MPa (5665 psi) to 33.3 MPa (4819psi). Several interesting points can be noticed. First, for the lower power levels, microwave cured specimens and conventionally cured specimens exhibit almost identical strength at 7 days. Compared with Fig.2 for mortar specimens, the concrete specimens subject to higher power levels of 400W and 450W show much less deterioration in 7 day strength than corresponding mortar specimens. Also, for all power levels, the 4.5 hr strength of concrete specimens are higher than that for corresponding mortar specimens.

Fig.6 shows the effect of microwave curing on concrete specimens of various w/c ratio. Again, as the w/c ratio goes from 0.45 to 0.55, there is little change in 4.5 hr strength values, which are 20.0 MPa (2,892 psi), 18.4 MPa (2,671 psi) and 19.2 MPa (2,786 psi), respectively, while the 7 day strength reaches a maximum of 37.3 MPa (5,400 psi) at 0.55 w/c. Also, for w/c=0.55 and 0.60, the 7 day strength of microwave cured and normal cured specimens are almost identical. For w/c=0.4, a very high strength of 27.2 MPa (3947 psi) can be achieved at 4.5 hrs, while the 7 day strength reaches 34.1 MPa (4944 psi). In this case, the mix is not very workable and the specimen is very porous. With the use of superplasticizers in the future, even better results can be expected. Again, by comparing Fig.6 and Fig.4, it is obvious that concrete specimens perform better than corresponding mortar specimens at both early and later age.

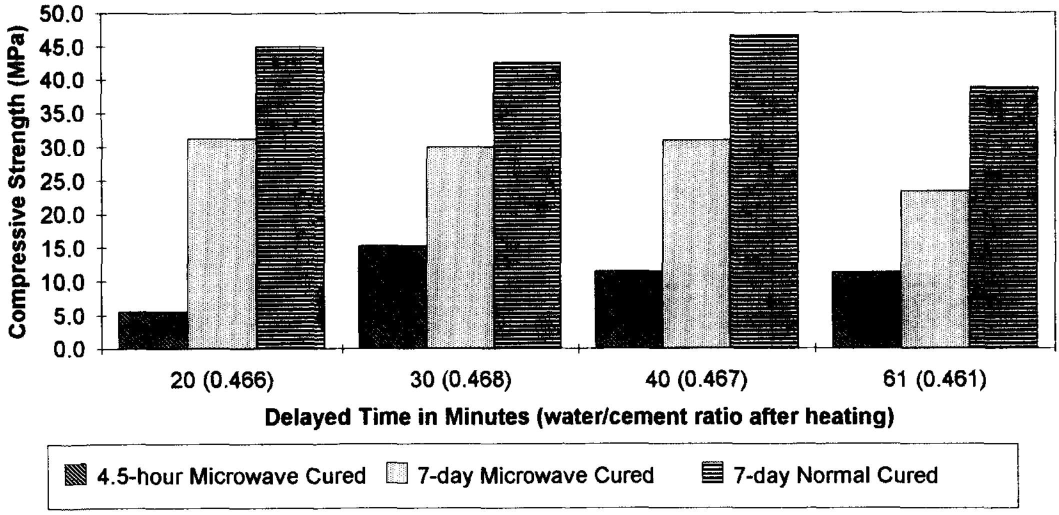


FIG.3
Effect of Delay Time on Mortar Specimens
(w/c = 0.50, Microwave Power = 400W, Application Time = 45 min)

To further investigate the effect of microwave on mortar and concrete specimens, sections are cut from various specimens (mortar, concrete, normal cured, microwave cured) and painted with a black paint. White zinc oxide powder is then spread onto the surface to reveal pores and microcracks. Pictures of various specimen surfaces are shown in Fig.7. By comparing the pictures for normal cured and microwave cured specimens, it is clear that microwave heating generate much more pores and microcracks in mortar specimens. One plausible explanation for the

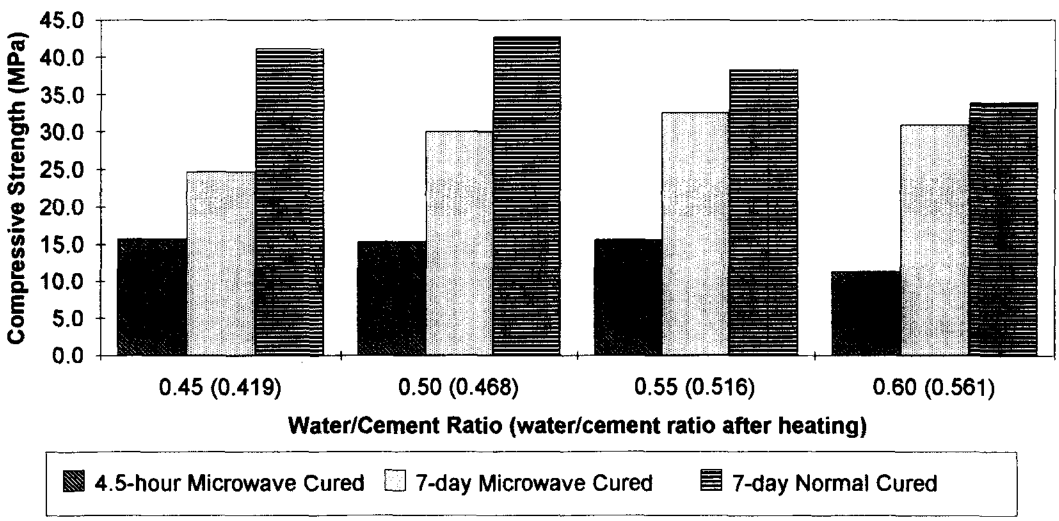


FIG.4
Effect of Water/Cement Ratio on Mortar Specimens
(Delay Time = 30 min, Microwave Power = 400W, Application Time = 45 min)

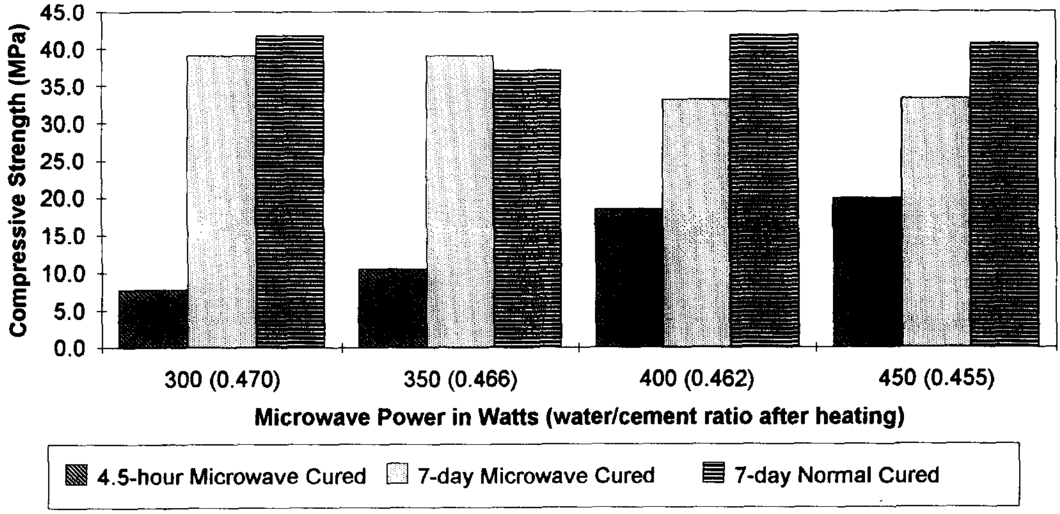


FIG.5

Effect of Microwave Power on Concrete Specimens

(Delay Time = 30 min, w/c = 0.50, Application Time = 45 min)

improved performance of microwave cured concrete over mortar specimens can then be given as follows. During microwave heating, expansion of the mortar phase and bubble formation due to local boiling can lead to the formation of microcracks and pores. In concrete, where the presence of aggregates restrains the expansion of the mortar, the amount of microcracks and pores is reduced and the strength is improved.

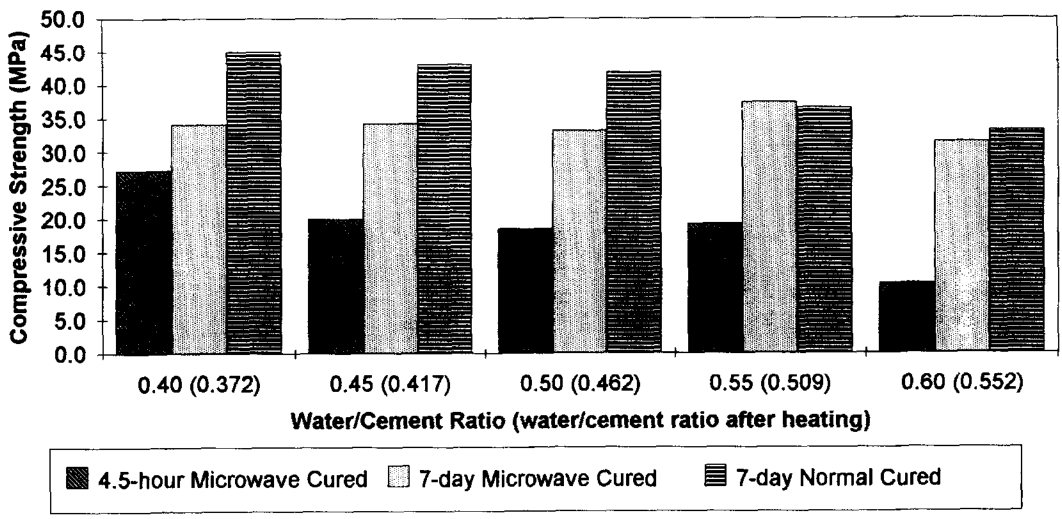
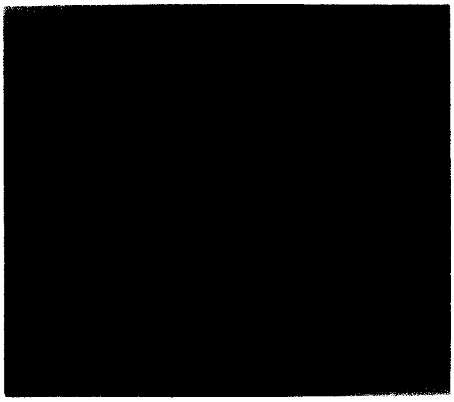


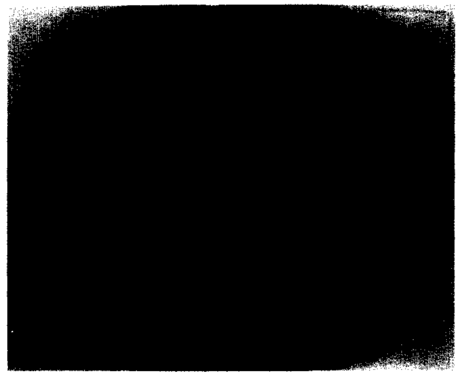
FIG.6

Effect of Water/Cement Ratio on Concrete Specimens

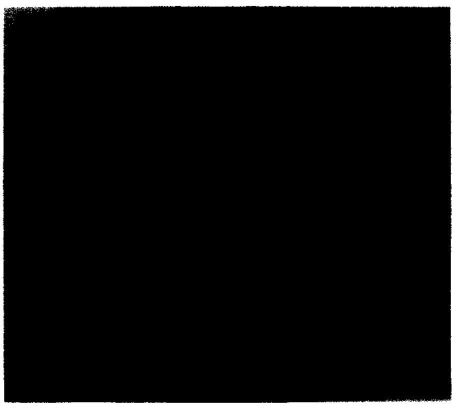
(Delay Time = 30 min, Microwave Power = 400W, Application Time = 45 min)



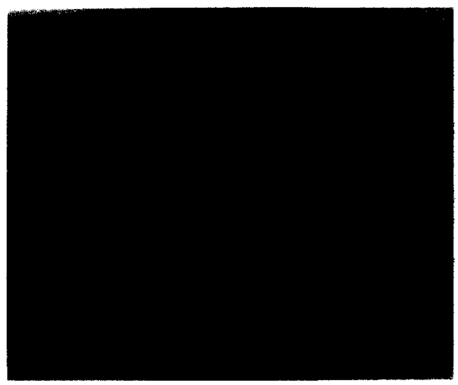
(a) Normal Cured Mortar



(b) Microwave Cured Mortar



(c) Normal Cured Concrete



(d) Microwave Cured Concrete

FIG.7
Photographs Showing Pores and Microcracks in Mortar and Concrete Specimens

Comparison with Other Rapid Curing Materials

In the repair of pavements, sufficient strength need to be developed within several hours. From the literature (5,6), the early and later age performance for (i) a concrete containing accelerators and (ii) a commercial rapid curing concrete are available. Since both of these materials have been employed in pavement repair in practice, it is informative to compare their performance with that achievable with microwave curing. For these comparisons, we took microwave cured concrete with 0.4 and 0.5 w/c ratio subject to 400W power for 45 minutes. Fig.8 compares microwave cured concrete (MCC) with a rapid setting portland cement concrete (PCC) containing accelerators (4). Additional tests are done for the 0.5 w/c concrete at 1 and 28 days. The results have been included in the comparison. From the figure, the early strength of microwave cured

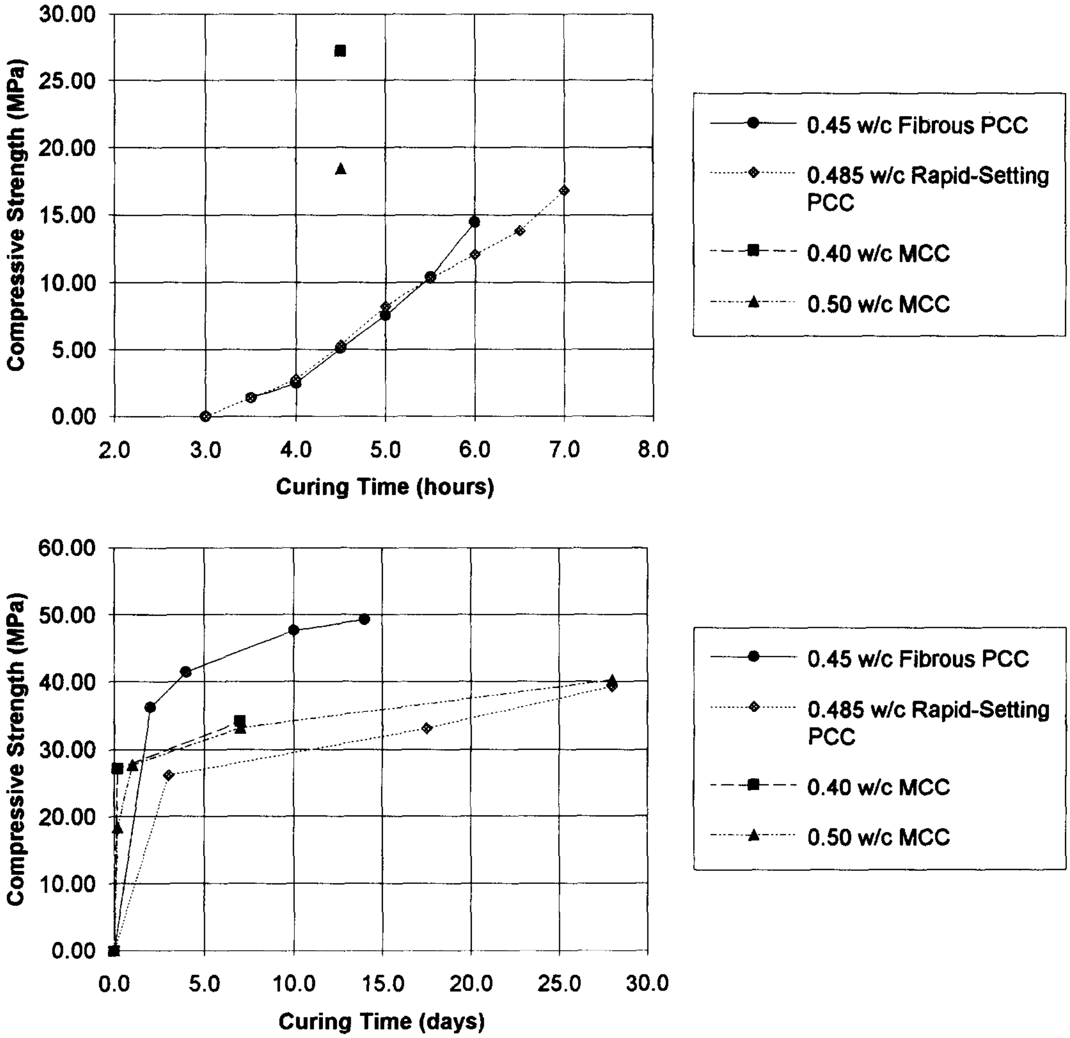


FIG.8
Comparison between Microwave Cured Concrete (MCC) and Rapid Setting Portland Cement Concrete (PCC) with w/c = 0.485

concrete is clearly superior. At 4.5 hrs, the rapid setting concrete can achieve only half to one-third the strength of the microwave cured concrete. Even up to 28 days, microwave cured concrete still possess higher strength than the rapid setting cement. Fiber reinforcement can significantly increase the later age strength of the rapid setting cement but the early strength is only slightly affected. It is expected that the microwave cured concrete can also be further improved through the incorporation of fibers. Table 1 compares microwave cured concrete (MCC) with a commercially available rapid curing concrete (RCC) (6). For similar w/c ratios, the values at both early and later age are comparable.

Additional Remarks

In this investigation, the possibility of developing very high early strength without significantly affecting the long term strength is illustrated (e.g. consider the case of 0.55 w/c concrete under 400W power for 45 minutes). To achieve optimal early and later age strength, the application of an appropriate temperature history to the specimen seems to be the key. Currently, experiments are being carried out with feedback temperature control of the process, with the objective to identify optimal temperature histories for good performance at both early and later age. Results of such investigations will be reported in subsequent papers.

TABLE 1
Comparison between Microwave Cured Concrete (MCC) and
a Commercially Available Rapid Curing Concrete (RCC)

	M. C. C. (Lab)	M. C. C. (Lab)	R. C. C. (Truck)	R. C. C. (Lab)
w/c Ratio	0.5	0.4	0.55	0.407
Strength, MPa (4.5 hrs)	18.4	27.2	17.7	24.0
Strength, MPa (7 days)	33.2	34.1	28.9	
Strength, MPa (28 days)	40.3		38.6	35.1

The use of microwave curing in precasting will require some modifications to present practice. For pavement repair, a special microwave applicator need to be designed. Issues related to the practical applications of microwave curing are discussed in a companion paper (7).

Conclusion

In conclusion, we want to highlight the following findings of our preliminary investigations: (i) very high early strength, almost 20 MPa (2,900 psi) for 0.55 w/c and 27.5 MPa (4,000 psi) for 0.40 w/c, is achievable with microwave curing in 4.5 hrs; (ii) for some compositions, the 7 day strength of microwave cured concrete can be as high as that for normally cured concrete; (iii) the preliminary results of microwave cured concrete compares favorably with currently used rapid setting or rapid curing materials. Our results, while preliminary, show that the microwave curing technique can potentially produce concrete with very high early strength and little deterioration in its long term performance.

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