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FREEZE-THAW DURABILITY OF MICROWAVE CURED AIR-ENTRAINED CONCRETE

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ABSTRACT

The strength development of concrete can be greatly accelerated by curing with microwave energy. Microwave curing can therefore be beneficial to construction operations such as concrete precasting and repair. To provide freeze-thaw durability for infrastructure applications, air entrainment has to be introduced. In this investigation, the freeze-thaw resistance of microwave cured air-entrained concrete is measured, and compared to that of air-entrained concrete under normal curing. Their compressive strength at 14 days and air-void characteristics are also measured and compared. The test results indicate that microwave curing can 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. © *1997 Elsevier Science Ltd*

Introduction

Microwave curing can lead to significant improvement in early age concrete strength compared to normal curing (1-5). At 4.5 hrs, strength from 19 to 35.4 MPa (2,750 to 5,130 psi) can be achieved for w/c ratio of 0.55 to 0.325. Also, for 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. This is because the early removal of water when concrete is still plastic allows a reduction in w/c ratio of the mix, which compensates for the strength reduction due to non-uniform hydration during heating. With advantages over conventional thermal heating in terms of both early and later age strength performance, microwave curing can potentially be applied to various construction operations such as concrete precasting and repair.

When concrete is used to construct roads and bridges subjected to freezing temperature, freeze-thaw durability is an important concern. To provide freeze-thaw resistance, air entrainment needs to be introduced. The application of microwave can densify the paste through water removal (1) but can also introduce more pores and microcracks in the specimen due to expansion of air during heating (4). Since microwave application can change the air-void system in concrete, it may affect the freeze-thaw durability of air-entrained concrete. Also, the expansion of entrained air may result in microcracking that affects the concrete strength. In this investigation, an experimental study is carried out to measure the strength and freeze-thaw resistance of microwave cured air-entrained concrete. Comparisons will be made with specimens under normal curing.

Experimental Program

To make concrete specimens, a cement/sand/gravel ratio of 1:1:1.5 is employed. 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. To provide freeze-thaw resistance, Duravair-1000, a liquid air-entraining admixture supplied by W.R. Grace & Co., is used to produce an air void system in concrete. As recommended by the supplier, air content should be in the range of 4-8% and can be produced with the typical addition rates range from 50-200 mL of Duravair-1000 per 100 kg of cement (or 0.75 to 3 fluid ounces per 100 lb). Addition rate within this range is used in the experiment and the admixture is added to the water before mixing.

To perform microwave curing, a microwave oven model fabricated by Cober Electronics, Inc. (LBM1.2A) is employed. The microwave cured specimens are cast in a polyethylene mold and arranged in a ring on the turntable in the oven. In all cases, 30 minutes after water is added to the mix, 375W microwave power is applied for a duration of 45 minutes. From our results on non air-entrained concrete, 412 W for 45 minutes (for six 76.2 mm × 152.4 mm or 3 in × 6 in specimens) gives the best results (4). (Note: in Ref.4, the power level is referred to as 400W. This is the power set on the oven but the actual power measured by the power meter is 412W). Such a power history, however, gives very low early and later age strength for air entrained concrete. 375W applied for 45 minutes is found to give much better results, and is therefore adopted in our experiments. For strength testing, nine 76.2 mm (3 in) by 203.2 mm (8 in) specimens are cast and five are microwave cured. 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 removed from the molds after one day. They are then cured in saturated-lime water at 22.8°C (73 F) for 6 more days until testing at 14 days.

For freeze/thaw testing, nine 76.2 mm (3 in) by 203.2 mm (8 in) and two 76.2 mm (3 in) by 279.4 mm (11 in) specimens are casted in each batch. Five 76.2 mm by 203.2 mm specimens are cured with the microwave energy while the rest are cured normally. The same power history as above is used. Three out of the five microwave-cured specimens and two 76.2 mm by 203.2 mm normal cured specimens are tested for compressive strength at 14 days. The rest are subject to freeze/thaw resistance test.

According to ASTM C666-92, the minimum length of specimen for freeze/thaw testing is 279.4 mm. However, the internal dimensions of our microwave oven limit the size of specimens to 203.2 mm. For qualitative comparison, we believe it is alright to use 203.2 mm specimens, which are shorter than that required by ASTM standards. Additional freeze/thaw tests on 279.4 mm normal cured specimens are carried out to compare results with shorter specimens.

In the freeze/thaw tests, specimens are frozen and thawed in water following Procedure A of ASTM C 666-92. Their weight and fundamental transverse frequency are measured for the computation of the relative dynamic modulus of elasticity after specific numbers of freeze-thaw cycles. In our experiment, each cycle takes about 7 hours and each specimen is subjected to freeze-thaw cycles until its relative dynamic modulus of elasticity reaches 60% of its initial value or the number of total cycles reaches 300, whichever occurs first.

To obtain the fundamental transverse frequency, the specimen is supported so that it may vibrate freely in the transverse mode. With the signal pickup device attached to the top surface near one end of the specimen, an impact is produced by small hammer at the other end. The vibration amplitude versus frequency is measured with a spectrum analyzer. The frequency with the highest amplitude gives the fundamental transverse frequency of the specimen.

Since freeze/thaw durability is governed by the air-void system in the concrete, the air contect in the fresh concrete, as well as the air void characteristics in the hardened concrete, are also measured. To determine the air content of freshly mixed concrete, the procedure in ASTM C 231-91b is followed. An air meter supplied by Forney, Inc., of type B according to ASTM C 231, is employed. To determine the air void characteristics of hardened concrete, including the air content, specific surface and spacing factor, longitudinal sections of the specimens are cut, polished, and examined in accordance with the requirements of Procedure B of ASTM C 457-90. By moving the cut sections under the microscope, examination can be carried out to see if a particular point on a grid system (Fig.1) falls in the solid matrix or in the air void. Based on the measurements, the various parameters can be calculated. To limit the uncertainty of the results, ASTM C 457 requires, for the maximum aggregate size of 9.5 mm (0.375 in), (i) the minimum length of traverse for examination to be 1905 mm (75 in), (ii) the minimum area to be traversed for examination to be 58 cm^2 (9 in^2) and (iii) the minimum number of points for examination to be 1125 points. In our experiment, the maximum size of aggregate is 9.4 mm (0.371 in). The length of traverse for each set of specimen is 2400 mm (94.5 in), the examined area is 60 cm^2 (9.3 in^2) and the number of total stops is 1200.

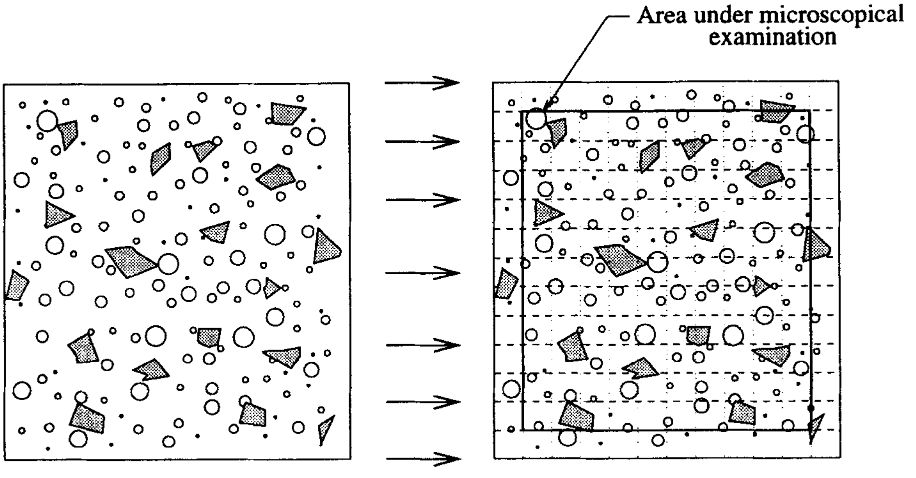

FIG. 1.
A regular grid system for the determination of air-void parameters.

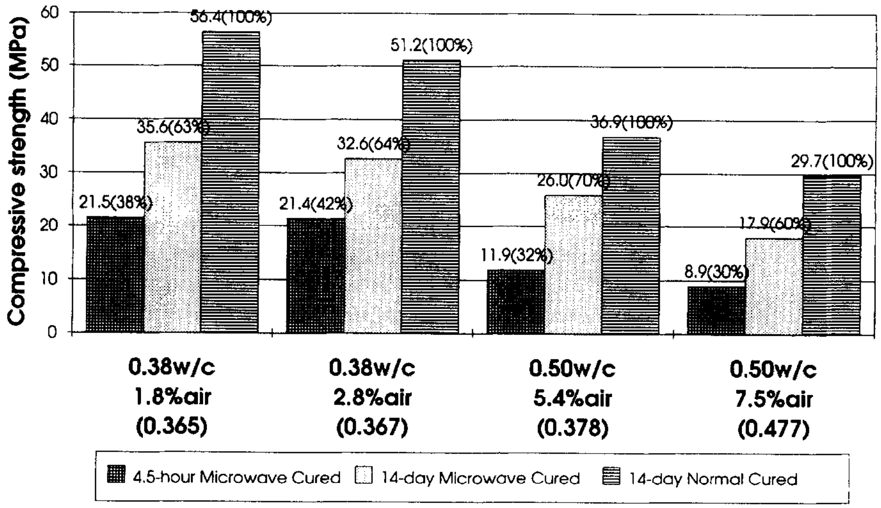

FIG. 2.
Early and later stage strength of air-entrained concrete.

For testing both strength (early and later age) and freeze/thaw durability, four types of specimens are prepared. They are made with 0.50 w/c (5.4% air content), 0.50 w/c (7.5% air content), 0.38 w/c (1.8% air content) and 0.38 w/c (2.8% air content). For freeze/thaw durability, specimens with 0.40 w/c but no air entrainment are also tested as a reference.

Results and Discussions

Strength at 4.5 Hrs and 14 Days. Figure 2 is a bar chart showing the compressive strength of air entrained concrete specimens at 4.5 hours and 14 days. On top of each bar are two numbers showing the strength in MPa as well as the strength as a percentage of the 14 day strength of normal cured specimens. The number in bracket below each case shows the w/c ratio after microwave curing. As for non air-entrained concrete, microwave curing is found to be effective in improving very early strength. In 4.5 hours, a strength of over 21.4 MPa (3,100 psi) is achievable with 0.38 w/c (with air content of 1.8% and 2.8%). In 14 days, the 0.38 w/c concrete can reach strength around 34.1 MPa (4,940 psi), which is good for most structural applications. For the 0.50 w/c concrete with 5.4% air content, the 4.5 hr strength reaches 11.9 MPa (1,719 psi) while the 14 day strength is 26.0 MPa (3,765 psi). The later age strength is still satisfactory for some structural applications. However, for the 0.50 w/c ratio with 7.5% air contect, the 14 day strength is only 17.9 MPa (2,596 psi) which is not too satisfactory. The current experimental results indicate that microwave curing together with air entrainment reduce the later age strength to only about 60 to 70% that of normal cured specimens. Therefore, to attain enough strength in the long term, a low w/c ratio should be employed. It should be noted that only one power history (375W for 45 minutes) has been employed in this investigation. Less reduction in later age strength may be possible with other power histories and this is an interesting topic for future investigation.

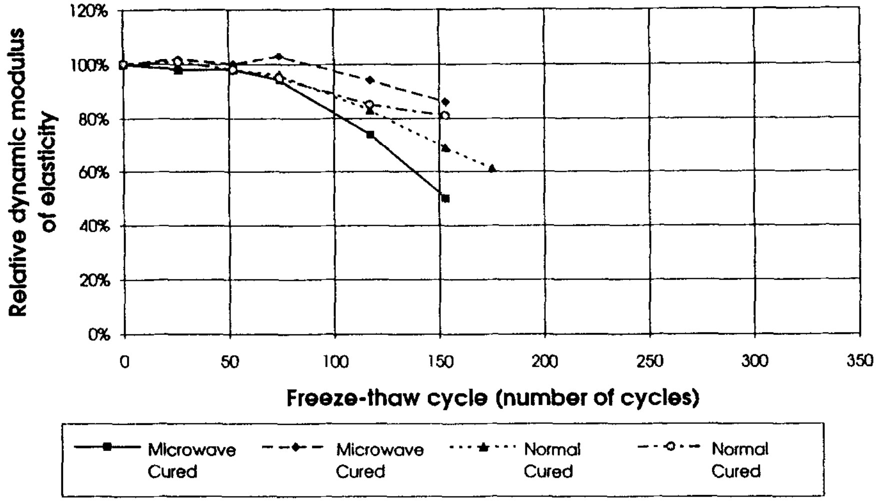

FIG. 3.
Relative dynamic modulus versus freeze/thaw cycle for 0.40 w/c ratio and no air entrainment.

Freeze/Thaw Durability. The freeze/thaw resistance for a non-air-entrained 0.4 w/c concrete, as well as that for the four types of air-entrained specimen, are shown graphically in terms of relative dynamic modulus in Figures 3 to 7 below. As a reference, one can see from Fig.3 that the non-air-entrained concrete specimens, whether normal or microwave cured, do not provide enough freeze/thaw resistance. After 175 to 225 cycles, the durability factor has

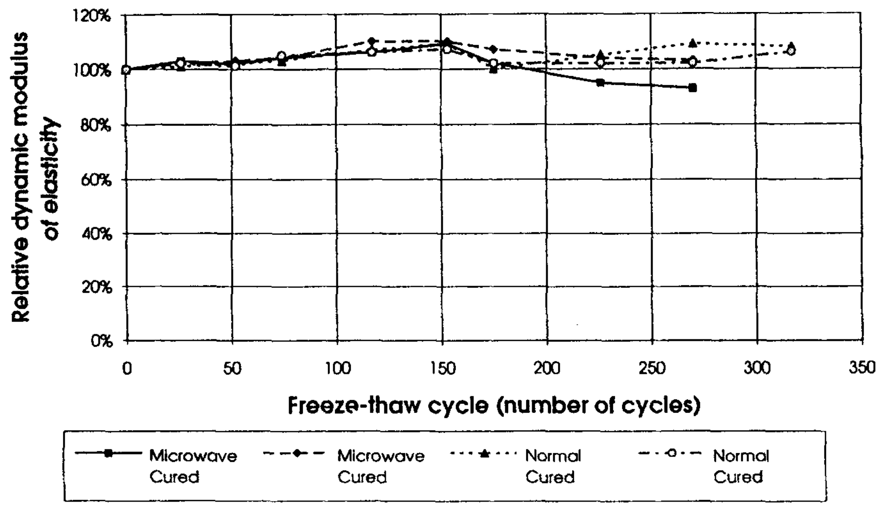

FIG. 4.
Relative dynamic modulus versus freeze/thaw cycle for 0.50 w/c ratio and 5.4% air entrainment.

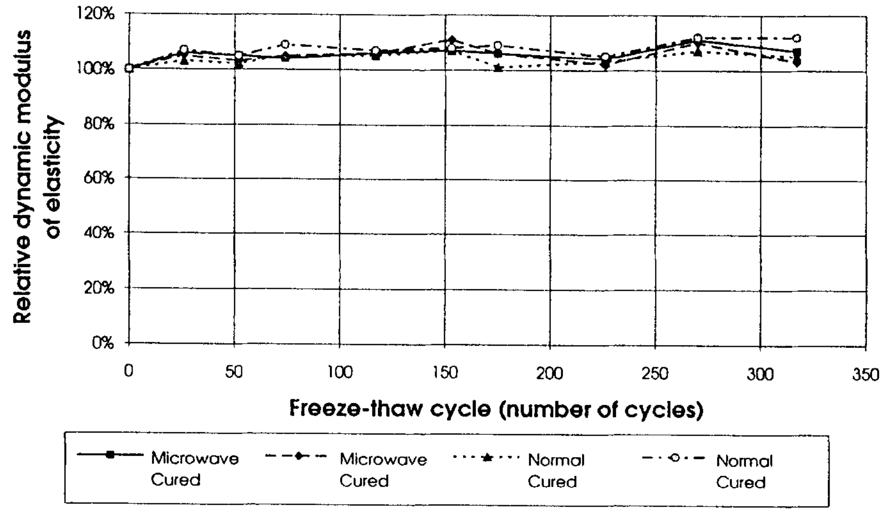

FIG. 5.
Relative dynamic modulus versus freeze/thaw cycle for 0.50 w/c ratio and 7.5% air entrainment.

become so low that the test is stopped. For the cases with air entrainment, all specimens except one case exhibit very good freeze/thaw durability with no reduction in relative dynamic modulus after 300 cycles. The only case which show significant deterioration is the microwave cured specimen with 0.50 w/c and 5.4% air content. In this case, the relative dynamic modulus remains high up to 270 cycles but drops significantly at 317 cycles. Based on the results, the durability factor calculated according to ASTM C666-92 gives an average

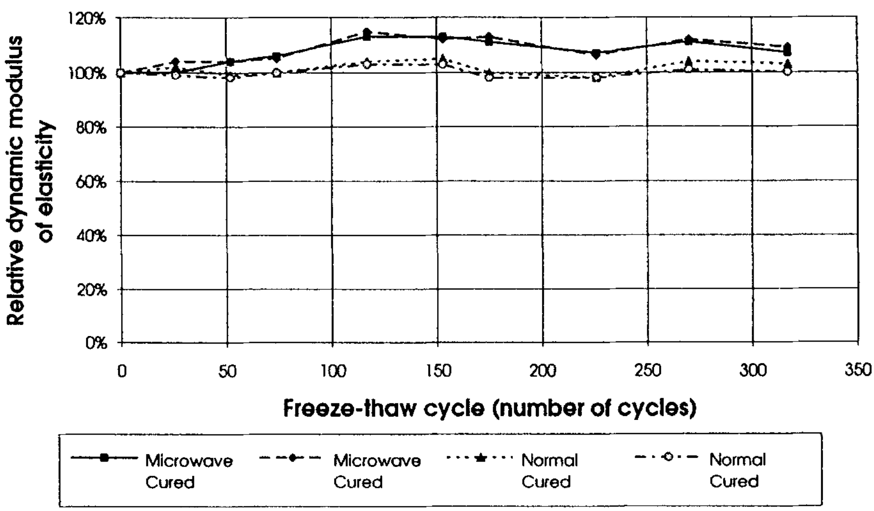

FIG. 6.
Relative dynamic modulus versus freeze/thaw cycle for 0.38 w/c ratio and 1.8% air entrainment.

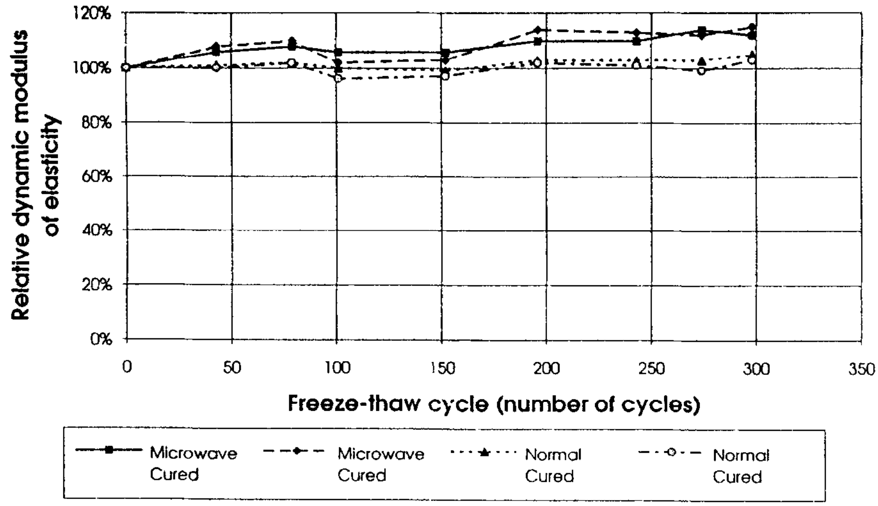

FIG. 7.
Relative dynamic modulus versus freeze/thaw cycle for 0.38 w/c ratio and 2.8% air entrainment.

value of 88.2 for the two specimens tested. According to Neville (6), a durability factor of 60 is satisfactory. However, some industrial companies require a durability factor of 90 to indicate enough resistance against freeze/thaw (7). The freeze/thaw resistance of this case is therefore considered marginal. For the 0.50 w/c specimens, the ones with 5.4% air entrainment offer marginal freeze/thaw resistance. 7.5% air entrainment provides good freeze/thaw resistance but low strength. Based on our experimental results, a low w/c ratio should be employed if microwave curing is applied to air entrained concrete.

Durability factors obtained from normal cured specimens of the standard size (76.2 mm by 279.4 mm) and a smaller size (76.2 mm by 203.4 mm) are compared in Table 1. The closeness of the two numbers validates our use of smaller size specimens to obtain the durability of microwave cured specimens.

TABLE 1

Durability Factor Obtained from Normal Cured Specimens of Different Sizes

	76.2 mm x 203.2 mm Specimen	76.2 mm x 279.4 mm Specimen
0.5 w/c (5.4% air)	107	105
0.5 w/c (7.5% air)	108.5	110
0.38 w/c (1.8% air)	101.5	100.5
0.38 w/c (2.8% air)	104	105

Air Void Characteristic Measurements. The air void chacteristics are shown in Table 2 below.

From the table, it can be observed that microwave curing will always lead to an increase in air content in the hardened concrete as well as an increase in spacing factor. A higher air content together with a higher spacing factor implies that the pore sizes are also increased. Two explanations can be proposed. During microwave heating, air pores can expand. On cooling, the expanded pores will not decrease in size because the surrounding matrix is no longer plastic. Also, during rapid heating, small pores may coalesce to become bigger ones. The increase in pore sizes lead to a decrease in compressive strength (as shown in Fig.2) as well as a reduced freeze/thaw durability in some cases (such as the 0.50 w/c concrete with 5.4% air).

The increase in spacing factor beyond the critical value of 0.2 mm recommended by ASTM and ACI does not impair the freeze/thaw durability of low w/c concrete. This is in agreement with many results reported in the literature (8-10) for normal cured concrete and silica-fume concrete. Since low w/c concrete has a denser paste and lower permeability, it contains a smaller amount of freezable water. Also, with a higher strength, the low w/c concrete can stand a higher pressure from water expansion. Low w/c concrete with a relatively large spacing factor can hence still possess good freeze/thaw durability.

Conclusions

Microwave curing can simultaneously increase air content, pore size and pore spacing in concrete specimens. In concrete with high w/c ratio, it may lead to a reduction in freeze/thaw durability as the pore spacing factor is increased. For low w/c ratio concrete with lower permeability, satisfactory freeze/thaw resistance can still be achieved with an increased spacing factor. Also, since microwave curing can reduce the strength of concrete specimens, low w/c concrete with high contents of air entrainment may not have enough strength for

TABLE 2

Air Void Characteristics for the Various Specimens

	Curing	AIR CONTENT Fresh Concrete (%)	Hardened Concrete (%)	Specific Surface (per mm)	Spacing Factor (mm)
0.5 w/c (5.4% air)	Normal	5.4	3.7	26.59	0.239
0.5 w/c (5.4% air)	Microwave	5.4	5.2	19.32	0.301
0.5 w/c (7.5% air)	Normal	7.5	7.9	25.18	0.181
0.5 w/c (7,5% air)	Microwave	7.5	9.5	21.60	0.197
0.38 w/c (2.8% air)	Normal	2.8	3.7	23.95	0.266
0.38 w/c (2.8% air)	Microwave	2.8	5.7	13.62	0.393

structural applications. In summary, based on both strength and durability considerations, low w/c ratio should be employed for microwave cured air-entrained concrete.

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