Microwave Curing of Cementitious Materials

by

Thanakorn Pheeraphan

Bachelor of Science
Virginia Military Institute
(1991)

Submitted to the Department of Civil and Environmental Engineering
in partial fulfillment of the requirements for the degree of Master of Science in Civil and Environmental Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

August 1993

©1993, Thanakorn Pheeraphan. All rights reserved.

The author hereby grants to MIT permission to reproduce and to distribute publicly paper and electronic copies of this thesis document in whole or in part.
Microwave Curing of Cementitious Materials

by

Thanakorn Pheeraphan

Submitted to the Department of Civil and Environmental Engineering on August 6, 1993, in partial fulfillment of the requirements for the degree of Master of Science in Civil and Environmental Engineering

Abstract

Microwave energy can accelerate the curing of cementitious materials, and can potentially be applied to pavement repair and precast concrete fabrication. In this work, the effects of microwave heating on the early and later strength (compressive, splitting tensile, and bond strength) of mortar and concrete specimens are studied. Several mix designs and microwave heating processes are investigated with the goal to obtain a compressive strength of at least 2,500 psi within about 5 hours, without significantly impairing the 7-day strength.

For the composition and size of specimen used in this experimental study, the optimal heating power at a 45-minute heating time is around 400 watts based on both compressive and splitting tensile strength. In particular, the optimal mix and process (among those studied in this work) for mortar is found to be 400 watts at 45 minutes for a w/c ratio of 0.55, which gives a compressive strength of 2255.5 psi at 4.5 hours and 4723.5 psi at 7 days. For concrete, the optimal mix and process is found to be 400 watts at 45 minutes for a w/c ratio of 0.40, resulting in a compressive strength of 3947.0 psi and 4944.4 psi at 4.5 hours and 7 days, respectively. Such performances are comparable to more expensive rapid hardening materials used in practice. The test on bond strength shows that the bond splitting tensile strength under microwave heating at 7 days decreases by 12.3% compared with normal-cured mortar, whereas the slant shear bond strength reaches only 50% of the slant shear bond strength under normal curing. Moreover, the pull-out test shows that 1-day bond strength between the steel bar and mortar paste under microwave heating is impaired by 23% compared to the case under normal curing.

In addition, the microstructures of these specimens are examined using the scanning electron microscopy technique. X-ray analysis is also used to determine the chemical components of the hydration products and hence to identify the products.

Thesis Supervisor: Christopher K. Y. Leung
Title: Assistant Professor
This thesis is dedicated to my family,
with all my love.
Acknowledgement

I would like to thank Prof. Christopher K.Y. Leung for his kindness, advice and all of his help throughout my study here. I am very happy to work with him. There would not have been this thesis without his valuable advice as well as his encouragement.

Thanks all of my friends in the 1-034 Lab and CEE department for their valuable discussion and suggestion: Yiping, Yoshi, Kwang Lee, Ira, and others. Also thanks Stephen and Arthur Rudolph for their help in preparing equipment and giving me some advice.

I am very grateful to all of my friends (P'Tom, Roong, Ittipon, Look-Tan, Bun, Nong Kung, Hi-Sun, Peter, and others) for their friendship and supports, especially to Roong for reading through parts of the draft and for her helpful comments, corrections, encouragement, and everything.

My academic study is all supported by the Royal Thai Air Force and all of the experimental works are funded by Prof. Leung.

Finally, this achievement would not have been possible without my previous education at Virginia Military Institute, Royal Thai Preparatory Armed Forces Academy, and Montfort College, as well as strong supports by my friends and family.
Contents

1 Introduction .................................................. 16
   1.1 Motivation ............................................... 17
   1.2 Objectives ................................................ 18
   1.3 Approach .................................................. 19
   1.4 Organization ............................................. 20

2 Literature Review .......................................... 23
   2.1 Introduction .............................................. 23
   2.2 Curing of Concrete ...................................... 23
      2.2.1 Curing at Ambient Temperatures ..................... 25
      2.2.2 Curing at Elevated Temperatures ................... 26
   2.3 Hydration of Cement ...................................... 28
      2.3.1 Calcium Silicates .................................... 29
      2.3.2 Tricalcium Aluminate ................................ 31
      2.3.3 Tetracalcium Aluminoferrite ....................... 32
      2.3.4 Summary .............................................. 32
   2.4 Water in Hardened Cement Paste ....................... 33
   2.5 Microwave-Material Interactions ...................... 33
   2.6 Pavement Repair Techniques ............................ 34
      2.6.1 Full-Depth Repair .................................... 35
      2.6.2 Partial-Depth Repair ................................. 36
   2.7 Precast Concrete Industry Review ..................... 37
   2.8 Review of Previous Studies on Microwave Curing in Concrete .... 40
3 Experimental Program

3.1 Introduction ........................................ 56
3.2 Parameters to be Studied .......................... 57
3.3 Scope of Experimental Work ....................... 57
3.4 Equipments and Machines .......................... 57
3.5 Mixing and Curing Processes ....................... 59
3.6 Sample Preparation of Microstructural Study .... 60
3.7 Testing Procedures ................................ 60
   3.7.1 Compressive Test ................................ 61
   3.7.2 Splitting Tensile Test .......................... 61
   3.7.3 Young's Modulus Test .......................... 63
   3.7.4 Slant Shear Test ................................ 64
   3.7.5 Direct Tensile Test ............................. 64
   3.7.6 Pull-Out Test ................................... 66

4 Test Results and Discussions ......................... 85

4.1 Introduction ....................................... 85
4.2 Normal-Cured Specimens ............................ 85
4.3 Microwave-Heated Specimens ....................... 86
   4.3.1 Mortar Specimens .............................. 87
   4.3.2 Concrete Specimens ............................. 101
4.4 Microstructural Characterization .................. 104
   4.4.1 Scanning Electron Microscope with an X-Ray Analyzer 104
   4.4.2 Environmental Scanning Electron Microscope .... 108
4.5 Comparison with Rapid Hardening Materials used in Practice 109

5 Conclusions and Recommendations ....................... 165

5.1 Research Summary .................................. 165
5.2 Conclusions ....................................... 165
5.3 Recommendations for Future Research ................ 167
## A Plausible Preliminary Designs of Microwave Applicators for Concrete Applications

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.1 Concrete Pavement Repair</td>
<td>169</td>
</tr>
<tr>
<td>A.2 Precast Concrete Fabrication</td>
<td>170</td>
</tr>
</tbody>
</table>
List of Figures


2-2 Effects of limited moisture curing on the compressive strength development of concrete with 0.50 w/c ratio [Neville, 1981] (from W.H. Price, "Factors influencing concrete strength," Journal of the American Concrete Institute, Vol. 47, No. 6, pp. 417-432, 1951.) .......................... 45

2-3 The typical scheme of low pressure steam curing [Mindess et al., 1981] .......................... 45

2-4 Compressive strength development in pastes of pure cement compounds [Mindess et al., 1981] ........................................... 46


2-6 Rate of heat evolution during the hydration of tricalcium silicate [Mindess et al., 1981] .......................... 47
2-7 Rate of heat evolution during the hydration of tricalcium aluminate with gypsum [Mindess et al., 1981] ........................................ 47
2-8 Rate of hydration of the cement compounds in paste of the pure compounds [Mindess et al., 1981] ........................................ 48
2-10 Interaction of microwaves with materials [Sutton, 1989] .............. 49
2-11 Comparison between heating in conventional oven and in microwave oven [Sutton, 1989] .................................................. 49
2-14 Results of flexural strength and compressive strength due to microwave heating at different heating rates by Xuequan et al. [1987] .............. 52
2-15 Results of flexural strength development and compressive strength development due to normal curing and microwave heating at different heating rates by Xuequan et al. [1987] (Note: x = normal curing; * = heating at power level 1 for 30 minutes, and the other one = heating at power level 2 for 15 minutes) ........................................ 53
2-16 Results of water permeability of mortar piles versus testing time by Xuequan et al. [1987] ........................................ 54
2-17 Results of percent hydration versus time by Hutchison et al. [1991] .... 54
2-18 Results of temperature versus time by Hutchison et al. [1991] ....... 55
2-19 Results of strength of mortars tested at 1, 7, and 28 days for normal curing and microwave curing by Hutchison et al. [1991] .............. 55
3-1 Experimental program for normal curing .............................................. 68
3-2 Experimental program for microwave heating ...................................... 69
3-3 Experimental program for microstructural examination .......................... 70
3-4 A 2450 MHz, 1200-watt microwave oven with PC to control .................... 71
3-5 A 22.4-kip Instron testing machine .................................................. 72
3-6 A 60-kip Baldwin testing machine .................................................... 73
3-7 A 200-kip Baldwin testing machine with PC to control .......................... 73
3-8 The SEM: (top) Control panel and (bottom) Chamber ........................... 74
3-9 An ordinary rotary mixer .................................................................... 75
3-10 An arrangement of polyethylene moulds in the microwave oven ................. 76
3-11 A 3 in. x 2 in. cylindrical plexiglass, a 3 in. x 6 in. specially-made plexiglass half-cylinder, and a 3-in. diameter specially-made plexiglass cylinder with an inclined interface plane (30 degree from the longitudinal axis) ......................................................... 76
3-12 Splitting tensile test setup for a regular specimen ................................. 77
3-13 A typical plot of load and LVDT reading from bond splitting tensile test .... 78
3-14 Bond splitting tensile test setup for a bimaterial specimen ....................... 79
3-15 Young’s modulus test setup .............................................................. 80
3-16 An “old” part of specimen with an embedded steel bar to prepare the whole specimen for direct tensile test .............................................. 80
3-17 The surface end of a specimen for direct tensile test ............................... 81
3-18 Direct tensile test setup ................................................................. 82
3-19 A steel bar with a 3-in. cylindrical plexiglass and a polyethylene mould to prepare a specimen for pull-out test ......................................................... 83
3-20 Pull-out test setup ................................................................. 84

4-1 The development of compressive strength, splitting tensile strength, and modulus of elasticity of mortar specimens under normal curing 121
4-2 Results of the effect of heating rates at the same energy input level on the compressive strength (at 3 hours and 7 days) of mortar specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing) ........................................... 122

4-3 Relative thermal expansion of water and air relative to that of solids [Soroka, 1979] (from Alexanderson, J., “Strength Loses in Heat Cured Concrete,” Proc. Swedish Cement Concrete Research Institute, 43, 1972.) 123

4-4 Results of the effect of power levels at a heating duration of 45 minutes on the compressive strength (at 3 hours and 7 days) of mortar specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing) ........................................... 124

4-5 Results of the effect of power levels at a heating duration of 45 minutes on the compressive strength (at 4.5 hours and 7 days) of mortar specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing) ........................................... 125

4-6 Results of the effect of delayed times for a heating rate of 400 watts at and 45 minutes on the compressive strength (at 4.5 hours and 7 days) of mortar specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing) ........................................... 126

4-7 Results of the effect of water/cement ratios for a heating rate of 400 watts and 45 minutes on the compressive strength (at 4.5 hours and 7 days) of mortar specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing) ........................................... 127

4-8 Results of the effect of power level at a heating duration of 45 minutes on the splitting tensile strength (at 4.5 hours and 7 days) of mortar specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing) ........................................... 128
4-9 Results of the effect of power levels at a heating duration of 45 minutes on the compressive strength (at 4.5 hours and 7 days) of concrete specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing) .................................................. 129

4-10 Results of the effect of water/cement ratios for a heating rate of 400 watts and 45 minutes on the compressive strength (at 4.5 hours and 7 days) of concrete specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing) .......... 130

4-11 SEM Micrographs of 0.50 w/c normal-cured mortar sample at 4 and 4.5 hours ............................................................... 131

4-12 SEM Micrographs of 0.50 w/c normal-cured mortar sample at 6 hours 134

4-13 SEM Micrographs of 0.50 w/c normal-cured mortar sample at 12 hours 135

4-14 SEM Micrographs of 0.40 w/c normal-cured concrete sample at 4.5 hours 139

4-15 SEM Micrographs of 0.40 w/c normal-cured concrete sample at 24 hours 143

4-16 SEM Micrographs of 0.50 w/c microwave-cured mortar sample at 4 hours 145

4-17 SEM Micrographs of 0.50 w/c microwave-cured mortar sample at 4.5 hours ................................................................. 148

4-18 SEM Micrographs of 0.50 w/c microwave-cured mortar sample at 6 hours 151

4-19 SEM Micrographs of 0.50 w/c microwave-cured mortar sample at 12 hours ................................................................. 152

4-20 SEM Micrographs of 0.40 w/c microwave-cured concrete sample at 4.5 hours ................................................................. 154

4-21 SEM Micrographs of 0.40 w/c microwave-cured concrete sample at 24 hours ................................................................. 158

4-22 ESEM Micrographs of 0.50 w/c normal-cured mortar sample ........ 160

4-23 ESEM Micrographs of 0.50 w/c microwave-cured mortar sample ... 162

4-24 Comparison of strength development [adapted from Parker et al., 1988] 164

A-1 Design system for pavement repairs by using microwave energy . . . 171

A-2 Design system for precast concrete fabrication by using microwave energy 172
# List of Tables

1.1 Service life of materials used in spall repairs (adapted from Smith et al. [1991]) ................................. 22

2.1 Chemical compounds of Portland cement (adapted from Mindess et al. [1981]) ........................................ 42

2.2 Characteristics of cement compounds during hydration (adapted from Mindess et al. [1981]) ..................... 42

2.3 Typical chemical composition of Portland cement (adapted from Mindess et al. [1981]) ............................. 43

2.4 Testing program by R.G. Hutchison et al. [1991] at different microwave power levels ............................... 43

4.1 The development of Modulus of elasticity of mortar specimens under normal curing .................................. 110

4.2 The development of compressive strength of mortar specimens under normal curing ............................... 110

4.3 The development of splitting tensile strength of mortar specimens under normal curing .......................... 111

4.4 The development of bond splitting tensile strength of mortar specimens under normal curing ..................... 111

4.5 The development of bond slant shear strength of mortar specimens under normal curing .......................... 112
4.6 Results of the effect of heating rates at the same energy input level on
the compressive strength (at 3 hours and 7 days) of mortar specimens
under microwave curing ........................................... 113

4.7 Results of the effect of power levels at a heating duration of 45 min-
utes on the compressive strength (at 3 hours and 7 days) of mortar
specimens under microwave curing ........................................... 113

4.8 Results of the effect of power levels at a heating duration of 45 min-
utes on the compressive strength (at 4.5 hours and 7 days) of mortar
specimens under microwave curing ........................................... 114

4.9 Results of the effect of delayed times for a heating rate of 400 watts
and 45 minutes on the compressive strength (at 4.5 hours and 7 days)
of mortar specimens under microwave curing ........................................... 114

4.10 Results of the effect of water/cement ratios for a heating rate of 400
watts and 45 minutes on the compressive strength (at 4.5 hours and 7
days) of mortar specimens under microwave curing ........................................... 115

4.11 Results of the effect of power levels at a heating duration of 45 minutes
on the splitting tensile strength (at 4.5 hours and 7 days) of mortar
specimens under microwave curing ........................................... 115

4.12 Results of the effect of microwave curing for a heating rate of 400 watts
and 45 minutes on the bond splitting tensile strength (at 4.5 hours and
7 days) of mortar specimens ........................................... 116

4.13 Results of the effect of microwave curing for a heating rate of 400 watts
and 45 minutes on the slant shear bond strength (at 4.5 hours and 7
days) of mortar specimens ........................................... 116

4.14 Results of the effect of microwave curing for a heating rate of 300 watts
and 45 minutes on the pull-out bond strength (at 1 day) of mortar
specimens ........................................... 117

4.15 Results of the effect of power levels at a heating duration of 45 minutes
on the compressive strength (at 4.5 hours and 7 days) of concrete
specimens under microwave curing ........................................... 117
4.16 Results of the effect of power levels for a heating rate of 400 watts at and 45 minutes on the compressive strength (at 1 and 28 days) of mortar and concrete specimens under microwave curing ............... 118

4.17 Results of the effect of water/cement ratios for a heating rate of 400 watts and 45 minutes on the compressive strength (at 4.5 hours and 7 days) of concrete specimens under microwave curing ............... 118

4.18 A mix proportion for concrete mix using Rapid Set Cement (by H.H. Holmes Testing Laboratories, Inc.) ......................... 119

4.19 Compressive strength comparison of MCWC cementitious materials and concrete mix using Rapid Set Cement ....................... 119

4.20 Mix Proportions for PCC, Fibrous PCC, and MCWC cementitious materials (adapted from Parker et al., 1988) ............... 120
Chapter 1

Introduction

It is believed that thermal energy can enhance the hydration of cementitious materials, leading to a gain in early strength. At present there are some curing methods which apply thermal energy to improve the early strength, such as, steam curing and traditional thermal curing technique in a conventional oven. Another potential way of applying thermal energy is the use of microwave energy in heating up the samples in a microwave oven. Compared with the conventional thermal process in the normal oven, microwave processing requires shorter curing period and also improve quality of the products [Xuequan 1987].

Microwave curing technique of concrete is first studied by Xuequan et al. [1987]. The microwave was employed as a new energy source to promote hydration of cement. They concluded that microwave desiccation could improve the strength and durability of concrete samples due to a decrease in porosity. Hutchison et al. [1991] studied the effects of microwave heating on the degree of hydration and on the compressive strength. They concluded that microwave energy could enhance the hydration process of mortar samples by shortening the induction period without decreasing their long term compressive strength.

From previous studies, it is obvious that there was no distinct objective in applying this new concrete curing technique to practice except for use in the precast concrete industry. In this research, the main objective is to employ this technique not only to precast concrete production, but also to concrete pavement repairs, because it is
believed that microwave energy has potentials in enhancing the degree of hydration, bringing about high strength as early as a few hours. However, a very high early strength would normally imply a reduced strength at a later age. This thesis thus explores the effects of microwave heating on the strength of the concrete, both at very early age (a few hours) and later ages, to identify optimal process and material design.

1.1 Motivation

The high early strength development is the focus of this work because the foremost advantage of microwave curing is the gain in strength in the early stage. At present, the only rapid curing technique which leads to high early strength in practice is steam curing at elevated temperatures with or without pressure. This technique is useful in the precast concrete industry because of (1) a reduction in manufacturing or production costs due to shortened processing time, and (2) a reduction in working area.

With the presence of microwave energy nowadays and the results of the previous studies on microwave desiccation of concrete, microwave curing technique is plausibly another curing technique which can be used in accelerating the strength development of concrete at the early age. If so, this technique can be used in (1) repairing a concrete pavement in the situation where reopening of the pavement to the traffic is critical, and (2) increasing efficiency in precast concrete manufacturing. With the use of microwave heating technique in pavement repairs, it can considerably save money loss due to delay of pavement's reopening. Also, in precast concrete industry, the energy cost can be decreased due to reduction in processing time.

There might be some arguments stated as to why another curing technique is needed for the repair of pavements. The advantage of microwave curing over the use of advanced materials (i.e., epoxy concrete, magnesium phosphate concrete, polymer cement concrete and other rapid hardening cements) lies in the fact that microwave curing requires less expensive materials (i.e., Portland cement), fewer skillful techni-
cians, and less severe quality control. In addition, there are many limitations and problems of using these advanced materials. For example, according to Smith et al. [1991], epoxy concrete is expensive and is not thermally compatible with Portland cement concrete; magnesium phosphate concrete cannot be used with limestones and is very sensitive to the amount of the water added to the mixture. More importantly, the great concern of using advanced materials in repairing is in the durability or service life problem. According to Smith et al. [1991], the durability of these materials is poorer than that of ordinary Portland cement. For example, the range of life expectancies of epoxy concrete and magnesium phosphate concrete, which are used in spall repairs, are between 1 and 8 years, and 0.5 to 5 years, respectively, while that of Portland cement is between 0.5 to 14 years. Table 1.1 shows the service life of these materials used in spall repairs. As a result, microwave heating is worth considering as another alternative technique to increase the strength at early age.

1.2 Objectives

The main objectives of this research are

1) to conduct a brief literature search and review on curing techniques, hydration process, and microwave heating technique.

2) to study the effects of microwave curing on the strength of mortars and normal strength concrete at very early age (4.5 hours) and later age (7 days).

3) to develop a microwave curing process and a mix design to achieve a concrete compressive strength of at least 2,500 psi within about 5 hours after the mixing of water and cement without significantly impairing the 7-day strength.

4) to study the effects of microwave heating on the bond strength between old and new concrete and on the bond strength between steel bar and cement paste.

5) to study the differences in morphology between normal-cured specimens and microwave-heated specimens via scanning electron microscope techniques.

6) to develop preliminary designs of microwave applicators in concrete pavement repairs and precast concrete fabrication.
1.3 Approach

Microwave energy can accelerate the hydration process, leading to a rapid gain in early strength. Due to uniform heating, the ultimate strength may not be significantly impaired under proper microwave heating rate and heating duration.

In the investigation, by controlling the input power and heating time of the microwave, as well as the age of concrete during microwave application, the rate of strength gain for various concrete mixes is determined. The optimal curing process and mix design, which provide the best compromise between early and later age strength, can then be developed.

This study illustrates the effects of microwave heating on the early and later strength properties including the compressive, splitting tensile, and bond strengths. Six major tests are performed: Young’s modulus test, compressive strength test, direct tensile test, splitting tensile test, slant shear test, and pull-out test.

The optimal heating power and duration are first obtained based on the compressive strength. Then the splitting tensile and bond strength are studied at the optimal heating rate.

Since this technique is expected to be applicable to precast concrete as well as concrete pavement repairs, the strength of interface between old and new concrete (cured by microwave) and between steel bar and cement paste have to be determined. Various tests on the interface, including the slant shear test, splitting tensile test, direct tensile test, and pull-out test are carried out.

To explain the results from the experiment, the scanning electron microscope technique is used to examine the microstructure of the samples. In addition, the X-ray analysis is used to analyze the chemical compositions of hydration products.

Besides the work on material and process development, the design of a microwave applicator to be used in the field is presented.
1.4 Organization

This thesis includes five chapters.

The first chapter, which is an introduction chapter, covers the history of the microwave curing technique, objectives, approach, and organization of this thesis.

Chapter 2 is the literature review. It first explains the curing methods of concrete which can be divided into two categories: curing at ambient temperature and curing at elevated temperature. Water curing and sealed curing are examples of curing methods at ambient temperature; curing with low and high pressure steam curing are examples of curing methods at elevated temperature. In addition, the hydration process of cement compounds is described in terms of hydration of the individual constituents, including calcium silicates, tricalcium aluminate, and ferrite phase. This part is followed by the interaction of the constituents inside materials caused by the microwave heating mechanism. The pavement repair and precast concrete manufacturing techniques are also reviewed in order to understand how the microwave heating technique can be applied. Then a review of existing studies on microwave curing of concrete is presented.

Chapter 3 explains the experimental program which includes the parameters to be studied, scope of experimental work, equipment and machines to be used, mixing and curing processes, sample preparation of microstructural study, and testing procedures.

Experimental results and discussions are then included in chapter 4 which covers the most important findings of this work. This chapter is divided into four parts. The first part deals with properties of normal-cured specimens which are used as the baseline for comparison with the results on the second part which determines the properties of microwave-cured specimens. The findings on the effects of microwave heating on compressive, tensile, and bond strengths are presented in the second part. Much effort is devoted to the investigation of the effects on compressive strength of mortar specimens due to microwave treatment where four parameters are concerned: (1) heating rates under the same energy input level, (2) power levels at 45 minutes heating time, (3) delayed time, and (4) water/cement ratio. For the effects on the
splitting tensile strength, power level at 45 minutes heating time is the only parameter studied. Moreover, the results on bond strength present how the microwave energy affects the bond at the interface between new and existing mortars, and the bond at the interface between steel bar and cement paste. The third part of chapter 4 complements the experimental results with the results from the scanning electron microscope examinations and the X-ray analyses. Micrographs are attached for better understanding. The final part compares the strength performances of microwave-cured cementitious materials to those of rapid hardening materials used in practice.

Chapter 5 summarizes the research and reports the main conclusions. Recommendations for future research are given.

Appendix A presents the plausible preliminary designs of microwave applicators for concrete pavement repairs and precast concrete fabrication.
Table 1.1: Service life of materials used in spall repairs (adapted from Smith et al. [1991])

<table>
<thead>
<tr>
<th>Repair Material Type</th>
<th>Experience (Years of Use)</th>
<th>Range</th>
<th>Range of Life Expectancy (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portland Cement Concrete</td>
<td>13.2</td>
<td>1 to 50</td>
<td>0.5 to 14</td>
</tr>
<tr>
<td>Magnesium Phosphate Concrete</td>
<td>8.3</td>
<td>3 to 15</td>
<td>0.5 to 5</td>
</tr>
<tr>
<td>Epoxy Concrete</td>
<td>14.9</td>
<td>1 to 35</td>
<td>1 to 8</td>
</tr>
<tr>
<td>Polymer Concrete</td>
<td>6</td>
<td>2 to 10</td>
<td>0.5 to 8</td>
</tr>
</tbody>
</table>
Chapter 2

Literature Review

2.1 Introduction

This chapter reviews basic knowledge on the curing and hydration of cement, the interaction of microwave with materials, pavement repair and precast concrete manufacturing (which are areas for the potential application of microwave-cured concrete), and the details of previous studies on the microwave curing technique. By reviewing these subjects, it should become clear that certain properties (such as, compressive, splitting tensile, and bond strengths) are of primary interest for the microwave-cured concrete. Therefore, these parameters will become the primary focuses of this research.

2.2 Curing of Concrete

In order to obtain good concrete, freshly placed concrete should be cured under suitable environment and temperature for a certain period of time. Curing process is defined by Neville [1981] as the procedure used to promote the hydration process by controlling the suitable temperature and movement of moisture from and into the concrete immediately after placing and finishing for a definite period of time to achieve the desired strength and durability level. Thus, the objectives of the curing process are (1) to keep the concrete under a favorable temperature, (2) to prevent
the loss of moisture content in the concrete, and (3) to give an additional moisture to the concrete or, in other words, to keep the concrete as saturated as possible. The significance of the curing process at an early age of the concrete is to improve the strength that changes more rapidly in the early stage than in the later stage. The curing temperature and humidity level are the two most important conditions which determine the rate of the hydration at the early stage and thus affect the rate of the strength development of concrete.

It is well known in the concrete study that curing temperature can significantly affect the early strength development of concrete. Figure 2.1(a) shows the effect of curing temperature on the 1-day and 28-day compressive strength development. The result shows that the higher the curing temperature, the higher is the early strength, but the lower is the later strength. Mindess et al. [1981] gives explanations for this observation: the increased early strength is due to the increased rate of cement hydration whilst the decreased later strength is probably due to the non-uniform distribution of hydration products, causing weak zones in the concrete. Figure 2.1(b) also shows the effect of curing temperature on the compressive strength at different ages up to 90 days. It is again clear that if the specimen is cured under high temperature, the early strength will increase whereas there is a decrease in later strength. In addition to the curing temperature, the placing temperature also affects the strength development. Figure 2.1(c) shows the compressive strength development of concrete specimens, which are placed at different temperatures and then cured at 21°C. It is obvious that the effect of the placing temperature on the strength development is the same as that of the curing temperature. Therefore, it can be summarized that the higher the initial temperature of concrete, the higher is the early strength, but the lower is the later strength.

Another factor of the strength development is the humidity level of the concrete. Loss of water can cause drying shrinkage, leading to the formation of concrete cracks due to the development of tensile stresses. Thus, the entrance of the water into the concrete has to be made possible to replenish the loss of water from self-desiccation.
and evaporation. Mindess et al. [1981] stated that if the internal relative humidity level dropped below 80 percent due to loss of moisture, the hydration and the strength would be arrested. Figure 2.2 shows the effect of limited moisture curing on the compressive strength development. It is obvious that the rate of strength development decreases as the water is lost from the specimens. As a result of water loss, further strength development begins to cease.

Based on the curing temperature, curing methods can be separated into two types [Mindess et al., 1981]:

1) Curing at ambient temperatures
2) Curing at elevated temperatures

2.2.1 Curing at Ambient Temperatures

There are two methods that can be categorized under curing at ambient temperatures, namely, water curing and sealed curing.

Water Curing

Water curing is a method that supplies additional moisture and maintains the present level of the water in the concrete. Examples of this method are ponding or immersion, spraying or sprinkling, and saturated wet coverings. This method is beneficial in hot-weather concreting since it can provide some cooling to the concrete.

Sealed Curing

Sealed curing is a method that only prevents the loss of water from the concrete. An example of this method is to use plastic sheets and waterproof paper in covering the surface of the concrete. Another example is to apply the membrane-forming curing compounds consisting of waxes, resins, chlorinated rubber, and solvents of high volatility to the surface of the concrete.
It is important to note that water curing is better than sealed curing because the availability of water in the hydration to the concrete can prevent self-desiccation and evaporation [Mindess et al., 1981].

2.2.2 Curing at Elevated Temperatures

In cold weather, hydration will be retarded; therefore, the curing temperature must be increased to protect the concrete from freezing and to raise the strength gain. The feasible curing methods for this purpose are live steam curing, curing with heating coils, and using electrically heated forms. This review is limited to steam curing only.

Steam curing can be separated into low-pressure and high-pressure steam curing. It is advantageous to use steam curing in the situation where the early strength gain is important and where additional heat is required to accomplish hydration, i.e., in cold weather. A steam-curing cycle is composed of

1) A period of presteaming (2 to 5 hrs),
2) A period of controlled heating (about 2.5 hrs),
3) A period of holding the maximum temperature (6 to 12 hrs), and
4) A period of controlled cooling (2 hrs).

Low Pressure Steam Curing

It is known that curing concrete under live steam at atmospheric pressure increases the rate of strength development. Therefore, this process can be used in the precast concrete industry to provide a faster turnover of products and a shorter curing period. The range of the maximum curing temperature is 40 to 100°C (104 to 212°F), but the optimal result is usually obtained at the curing temperature between 65 and 80°C (150 to 175°F) [Mindess et al., 1981].

The curing cycle of low pressure steam curing is as described above. The typical scheme of low pressure steam curing is shown in Figure 2.3. The presteaming period which allows for the initial hydration will help improve the later strength of the concrete. The rates of heating are approximately 33°C/hr (60°F/hr) and 11°C/hr
(20°F/hr) in the presence and absence of the presteaming period, respectively [Mindess et al., 1981]. It is suggested by Mindess et al. [1981] that high heating rates should be avoided. At high heating rates, the ultimate strength of concrete will decrease because of the nonuniform distribution of hydration products during the rapid initial hydration process. This leads to larger capillary pores in the paste and higher water permeability. If the presteaming period and the heating rates are optimized, the strength after 3 days can exceed that of 28 days under normal curing.

The rate of cooling is suggested to be about 22 to 33°C/hr (40-60°F/hr) [Mindess et al., 1981]; however, after the curing period, the hardened concrete is less sensitive to thermal shocks so the rate of controlled cooling will not significantly affect the properties of the concrete. Nevertheless, after the cooling period additional moisture curing at room temperature should be provided in order to let the hydration process continue, further filling up the capillary pores in the concrete.

Although the strength of the concrete under low pressure steam curing is not much different from those of concrete under normal curing at ambient condition, this curing process generally leads to lower creep and shrinkage strains [Mindess et al. 1981]. Compared with normal curing, the hydration process of this curing technique takes place more rapidly, but the reactions are basically the same [Mindess et al. 1981].

**High Pressure Steam Curing**

The range of curing temperature in high pressure steam curing is between 160 to 210°C (320-410°F) while the steam pressure is between 6 to 20 atm [Mindess et al., 1981]. High pressure steam curing is one of the techniques used in the precast concrete industry and in the production of special products such as asbestos-cement composites, lightweight cellular concrete and calcium silicate bricks.

The curing cycle of high pressure steam curing is the same as that of low pressure steam curing except that the rate of pressure release after the steaming period must be controlled. The pressure release should be done rapidly, completing within 20 to 30 minutes in order to accelerate the evaporation of water from the product to help
cooling it quickly.

The properties of the concrete under this curing process are significantly different from those of the concrete cured below 100°C because of the changes in the chemistry of hydration. The advantages are as follows [Mindess et al. 1981]:

1) The product is ready for use within 24 hours.
2) There are less creep and shrinkage.
3) The resistance to sulfate attack is promoted.
4) The elimination of efflorescence improves the appearance of the product.

The disadvantages of this curing process include the followings [Mindess et al. 1981]:

1) limited applicability to certain kinds of products,
2) high capital cost of the production plant,
3) low bond strength between the concrete and the reinforcement (50%), and
4) increased brittleness compared with ordinary concrete.

2.3 Hydration of Cement

Hydration of cement is simply defined as the chemical reaction between cement compounds and water. As soon as the water contacts the cement, each particle of the cement will grow in size and build up links with the adjacent particles, resulting in stiffening and hardening. Hydration continues under ambient temperature and suitable moisture as long as there are some spaces for hydration products.

The following subsections explain the reactions of the primary compounds of Portland cement, which is the most commonly used cement in the U.S., as they undergo the hydration process. Table 2.1 shows the main chemical compounds of Portland cement while their characteristics during hydration are given in Table 2.2. The chemical reaction of each compound is described independently for the sake of clarity; however, in reality these compounds hydrate together and the reactions occur simultaneously. The shortened notations to be used later on are given below:
\[ C = CaO \quad \text{(lime)} \]
\[ S = SiO_2 \quad \text{(silica)} \]
\[ A = Al_2O_3 \quad \text{(alumina)} \]
\[ F = Fe_2O_3 \quad \text{(ferric oxide)} \]
\[ H = H_2O \quad \text{(water)} \]
\[ \tilde{S} = SO_3 \quad \text{(sulfur trioxide)} \]

### 2.3.1 Calcium Silicates

Calcium silicates \((C_3S \text{ and } C_2S)\), constituting about 75% of the weight of cement, are the components which provide most of the strength to concrete (shown in Figure 2.4 and 2.5). The hydration reactions of calcium silicates can be written as follows:

\[ 2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH \quad (2.1) \]
\[ \text{and } 2C_2S + 4H \rightarrow C_3S_2H_3 + CH \quad (2.2) \]

where \(C_3S_2H_3\) (written briefly as C-S-H) is a poorly crystalline material called calcium silicate hydrate or tobermorite gel,

and \(CH\) is a crystalline material called calcium hydroxide.

Hydrated cements are composed of 25 percent of calcium hydroxide and 50 percent of tobermorite gel by weight; therefore, the strength and other properties of the hydrated cement depend primarily on tobermorite gel. To illustrate the hydration stages of calcium silicates, a heat evolution curve determined by conduction calorimetry is used. It plots the rate of heat evolution (unit in Calorie/gram hour) against time (unit in hour). Figure 2.6 shows this curve during the hydration process of \(C_3S\) (tricalcium silicate) which can be separated into five stages: the initial reaction period (or rapid heat evolution period), dormant period (or induction period), acceleration period, deceleration period, and steady state period (or continuing, slow
Upon mixing of water and cement, a large amount of heat is liberated by the reaction which involves the hydrolysis of calcium and hydroxide ions from the surface of the $C_3S$ grains into the solution. The reaction rate then declines quickly to a minimum level within fifteen minutes. This period is followed by the dormant period during which the cement paste still remains in the plastic state and there is very little hydration occurring since there might be some deposition of a protective layer on the $C_3S$ particles [Neville, 1981]. Hydrolysis also slows down and becomes stable in this period as the concentration of calcium and hydroxide ions increases. The end of the dormant period is marked by a rapid heat evolution of the curve and a growth of C-S-H and $CH$ [Scrivener, 1989]. The dormant period normally lasts 2-4 hours. Eventually, during the acceleration period, the protective layer of the $C_3S$ grains is ruptured due to the pressure of the hydrated products [Neville, 1981], allowing C-S-H to grow on the surface of the $C_3S$ grains at an increasing rate and form a new coating to cover the grains. This period is identified by a marked increase in heat liberation which lasts about 4-8 hours before the rate of heat evolution declines once again. During the deceleration period when the final setting has already passed and the cement paste is hardening, hydration still continues but the reaction is slow and the rate of heat evolution falls quickly because the hydrated products are forming heavier and thicker layers which prevent the movement of ions and water molecules into the unhydrated $C_3S$. This period lasts about 12-24 hours. At the end of the deceleration period, the rate of heat evolution drops to the minimum, followed by the steady state stage where the formation of hydration products is even slower. Hydration continues as long as there are spaces to be filled up and $C_3S$ to react.

$C_2S$ (dicalcium silicate) hydrates in a similar manner to $C_3S$; however, its reaction rate is much slower [Mindess et al., 1981]. Moreover, the calorimetric curve of the $C_2S$ cannot be easily established because the level of heat liberation is too low.
2.3.2 Tricalcium Aluminate

The hydration reaction of $C_3A$ (tricalcium aluminate) in Portland cement involves sulfate ion as shown below. Figures 2.4 and 2.5 indicate that the hardened paste of $C_3A$ provides rather low strength to the concrete compared with that of calcium silicates.

$$C_3A + 3C\tilde{S}H_2 + 26H \rightarrow C_6A\tilde{S}_3H_{32} \quad (2.3)$$

where $C\tilde{S}H_2$ is gypsum,

and $C_6A\tilde{S}_3H_{32}$ is ettringite.

However, if sulfate in gypsum is consumed all before the tricalcium aluminate, then ettringite will react with the remaining $C_3A$ and transform into monosulfoaluminate, which is another hydration product of $C_3A$ containing less sulfate. This reaction is shown below.

$$2C_3A + C_6A\tilde{S}_3H_{32} + 4H \rightarrow 3C_4A\tilde{S}H_{12} \quad (2.4)$$

where $C_4A\tilde{S}H_{12}$ is simply called the monosulfoaluminate.

Monosulfoaluminate is not desirable when concrete may be subjected to sulfate attack because it can react with the sulfate and transform back into ettringite whose density is lower (1730 kg/m$^3$) [Brooks, 1990]. The formation of ettringite can cause a large increase in volume of concrete, leading to cracking and failures in the concrete structure.

It is known that ettringite produced from adding gypsum or some other form of calcium sulphate into Portland cement will retard the rate of $C_3A$ hydration by forming a barrier around $C_3A$ [Mindess et al., 1981] [Soroka, 1979]. The barrier then ruptures and $C_3A$ will hydrate quickly again. The more gypsum is added, the more the $C_3A$ hydration is delayed and also the more stable ettringite is. Therefore, the amount of gypsum is controlling the early rate of $C_3A$ hydration. If gypsum is not added to the cement, flash set can occur because of rapid hydration of $C_3A$.

The calorimetric curve of this hydration looks similar to that of calcium silicates but the rate of heat evolution is much higher. The curve is shown in Figure 2.7.
2.3.3 Tetracalcium Aluminoferrite

The hydration products of $C_4AF$ (tetracalcium aluminoferrite) are the same as those of $C_3A$, but its reaction involves less heat liberation and is much slower [Mindess et al., 1981]. The provided strength of the set paste is doubtful. According to Figure 2.5, $C_4AF$ provides the same strength level as $C_3S$; on the other hand, $C_4AF$ gives much lower strength according to Figure 2.4. Due to the presence of gypsum, flash set will not occur easily. The reactions of this hydration are shown below:

$$C_4AF + 3C\bar{S}H_2 + 21H \rightarrow C_6(A, F)\bar{S}_3H_{32} + (A, F)H_3 \quad (2.5)$$

and

$$C_4AF + C_6(A, F)\bar{S}_3H_{32} + 7H \rightarrow 3C_4(A, F)\bar{S}H_{12} + (A, F)H_3 \quad (2.6)$$

It should be noted that iron oxide and alumina in the parentheses are interchangeable and can be combined in any A/F ratio.

2.3.4 Summary

The hydration rates of the cement compounds can be summarized from Table 2.2 and Figure 2.8 in the following order:

$$C_3A > C_3A + C\bar{S}H_2 > C_3S > C_4AF + C\bar{S}H_2 > C_2S$$

In addition, the rate of compressive strength development of each cement compound can be seen in Figures 2.4 and 2.5, from which, it can be concluded that the most important contribution to the early strength of cement is $C_3S$ (tricalcium silicate) while $C_2S$ (dicalcium silicate) will supply additional strength after the early period. However, according to Figure 2.5, $C_4AF$ also reaches the strength level of $C_3S$. Thus the strength provided by $C_4AF$ is still uncertain. Based on the result in Figure 2.4, calcium silicates will not only provide the early strength but also the ultimate strength of the cement paste because the strength supplied by $C_3A$, $C_4AF$, and $C\bar{S}H_2$ is rather low compared to those of calcium silicates.

Once the general roles of each cement compound have been understood, the properties of cement with different compositions can be explained. For example, the
purpose of having a large amount of $C_3S$ in type III Portland cement is to gain high early strength. Table 2.3 shows the typical chemical composition of Portland cement.

2.4 Water in Hardened Cement Paste

It is important to understand the classification of water in the hardened cement paste since water can absorb microwave energy more than the other constituents of concrete. Four types of water in the hardened cement paste are classified as follows [Mehta, 1991]:

1) *Capillary water* or *Free water* resides in the pores of the paste and is considered as "evaporable water", which means that it can be removed easily without any changes in volume. It is also free from the attractive force of the solid surface.

2) *Chemically combined water* is known as "non-evaporable water", which is a part of the solid paste due to hydration with the cement. It thus cannot be lost on drying.

3) *Adsorbed water* is held on the surface of the solid particles by the surface force. It can be lost by drying, and it is responsible for shrinkage drying.

4) *Interlayer water* resides between the layers of the C-S-H sheets. It can be dry out only under strong drying.

For more understanding, these four types of water can be illustrated by Figure 2.9.

2.5 Microwave-Material Interactions

Microwave is an electromagnetic wave with a wavelength of 1 mm - 1 m and a frequency range of 0.3 to 300 GHz. It is coherent and polarized. It obeys the laws of optics and, depending on the material, can either penetrate, reflect, or partially
penetrate through the material. For instance, microwave cannot penetrate metals. For better understanding, Figure 2.10 [Sutton, 1989] illustrates the interaction of microwave with the materials.

Microwave can be used as an energy source to heat dielectric materials composed of positive and negative poles. Water is an example of dielectric materials. When microwave transmits through a dielectric material, an internal electric field is generated inside the material, leading to a vibration or movement of the polar molecules to reduce the intensity of the electric field [Sutton, 1989]. These movements are resisted by frictions and inertial forces. Consequently, heat is generated and the temperature is elevated inside the material. To better understand how the microwave heats up a material, Figure 2.11 illustrates the comparison between heating materials in the conventional oven and in the microwave oven.

2.6 Pavement Repair Techniques

Pavement structure is generally composed of subgrade, subbase, and pavement. Subgrade is defined as the very bottom part or foundation of the pavement system. It is actually a layer of compacted and prepared soil. Subbase consists of layers of suitably compacted granular materials. Pavement is the top layer which is designed to resist and support the traffic loads. It is noted that the present UK Department of Transportation requirements of the cube compressive strength for concrete pavement are about 4,500 psi (31 N/mm²) and 6,400 psi (44 N/mm²) at 7 and 28 days, respectively [Croney et al., 1992]. In addition, Atkinson [1990] stated that Lilley [1973] had reported that a thin bond repair could be opened to the traffic once the strength of cubes, which made from the repaired materials, reached about 1,450 psi (10 N/mm²).

Pavements are divided into two types, namely, flexible and rigid pavements. Flexible pavement is one that uses all types of bituminous materials as binders. Asphalt and tars are examples of these materials. A typical flexible pavement is composed of subgrade, subbase, base, and surface course. Its surface course is made from the bituminous materials and the base course consists of the granular materials used with
or without the bituminous binders.

Rigid pavement is commonly known as concrete pavement since the major component of this pavement is concrete. It can be either plain concrete, lightly reinforced concrete, continuously reinforced, prestressed concrete, or fibrous concrete. In this type of pavement, there are subgrade, subbase, and surface course. Subbase may not be necessary because the concrete pavement can rest on the soil foundation itself. In this research, this type of pavement is being of interest.

Many concrete pavements on the interstate system and local streets are under deterioration because of the weather, heavy traffic, and lack of maintenance. Damage can easily occur everywhere on the pavements. It can be seen in forms of cracks (transverse, longitudinal, diagonal, corner cracks), disintegration, fault, pumping, etc. Disintegration means that some parts of the concrete pavement, especially on its surface, are falling out of place due to improper mixing, unsuitable aggregates, improper curing, or chemical attack. The examples of disintegration are spalling, blowups, and scaling. A fault refers to a difference in the levels of two adjacent slabs due to a shrinkage of the underlying layers or due to the pumping out of the base materials. Pumping is defined as the rejection of sand, water, and other particles through the opening spaces (i.e., joints or cracks) when vehicles pass the pavement.

In general, there are five pavement repair methods [Darter, 1988]: (1) full depth repair (full-depth patching), (2) spall repair (partial-depth patching), (3) slab jacking, (4) subsealing, and (5) diamond grinding of the surface. In this study, only small scale full-depth repair and partial-depth repair are of interest because one of the purposes of this research is to use microwave in accelerating the repair process.

2.6.1 Full-Depth Repair

This repair technique is used to replace a deteriorated concrete pavement entirely. It is suggested by Brown [1992] that the size of the repair patch should be at least one lane wide and 6-10 feet long. The boundaries of the patch must be cut full depth by a diamond saw. Then concrete inside the boundaries is to be removed with care not to cause any damage to the surrounding area. To avoid pavement repair failures, the
subbase must also be inspected whether it needs a repair or not. A poor subbase has
to be cut by at least 6 inches in depth, and the old subbase material should then be
replaced and compacted with the new material.

To provide mechanical load transfer at the joints between the patch and the ex-
sting pavement, the Federal Highway Administration (FHWA) [Brown, 1992] rec-
ommends the use of at least four dowel bars on each side of the lane width. Figure
2.12 shows an example of dowel bars layout in a full-depth repair. The surface at the
patch face should be chipped away to promote aggregate interlock. Before placing
the new concrete, dowel bars should be inserted into holes partially filled with grout
to bond the bars to the existing pavement.

For reinforced concrete pavement, the repair is the same as described above except
that there are reinforcements extending into the repair area.

According to Darter [1988], Portland cement is strongly recommended to use
instead of asphalt cement because asphalt patch performs poorly in a full-depth repair.
In particular, the asphalt patch can be pushed by the surrounding pavement, leading
to cracks at the joints, and a loss in load transfer.

2.6.2 Partial-Depth Repair

According to Brown [1992], a partial-depth repair is required when the deteriorated
part does not extend deeper than one-third of the pavement thickness. Darter [1988]
also suggests that it can be used for a repair which extends less than one-half of
the pavement thickness. However, according to Smith et al. [1991], a partial-depth
repair is limited to the pavement whose deteriorated part does not occur below the top
third of its thickness and does not extend more than half width of the lane. Sounding
technique, using a metal rod or hammer, is applied to discover the distressed area. A
sharp sound indicates sound concrete, and a dull sound indicates a distressed area.

Saw cutting is applied to located boundaries and a lightweight air hammer is used
to remove the deteriorated part to avoid cracking the sound concrete. The surface
then is cleaned and dried. A compressible filler must be infiltrated into the gaps
between the joints and the existing part to prevent the new concrete from entering
the joints. To ensure a good bond between new and old concrete, a bonding material must be applied to the surface before placing the new concrete. The patch can now be finished and cured to prevent moisture loss. Similar procedures reported by Darter [1988] are illustrated in Figure 2.13.

2.7 Precast Concrete Industry Review

Another useful application of microwave curing is in the manufacturing of precast concrete products whose strength development need to be high at the early period. With the use of microwave energy, the precast products can be demoulded and handled fast, resulting in a shorter processing time and a lower production cost. Two criteria for a precast concrete work are summarized by Levitt [1982] as follows:

1) Products should gain sufficient strength soon after placing such that demoulding, handling, and stacking are possible within 6-18 hours.

2) Besides strength and durability, shrinkage, exothermal reaction, and cost are also of concern.

Generally, heat curing (or accelerated curing) is used to accelerate cement hydration because heat promotes high early strength of concrete. Two factors under heat curing that must be known and controlled are temperature gradient and humidity within the system. Temperature gradient relates directly to the early strength development and the occurrence of cracking. An appropriate humidity level within the system is also important because the products will have low permeability and become weak at the surface under low humidity (since the water can evaporate quickly from the surface) and because efflorescence and flooding of water can occur under overly high humidity.

General considerations for heat-accelerated curing in a typical precast fabrication are listed below [Levitt, 1982].
1) Heat should be applied with an appropriate timing, i.e., when the concrete is still in a plastic state. If it has already begun to harden, thermal stresses can cause cracking.

2) Before the curing temperature reaches 5 – 15°C below the desired maximum curing temperature, the heating rate should be within the range of 10 – 20°C per hour.

3) The maximum curing temperature should not exceed 90°C.

4) The cooling rate should be within the range of 10 – 20°C per hour while the temperature gradient is suggested to be 50 – 150°C per meter.

5) Relative humidity should be controlled to a range of 75-90 % to prevent either an overly rapid heating or an overly wet condition.

Four methods of curing precast concrete are discussed below:

1) steam curing,
2) electrical curing,
3) cement addition, and
4) other methods such as microwave curing.

Steam curing is the cheapest and most widely used method. The production and recycling of steam determine whether this method is economical or not. For example, one technique to produce steam in practice is to pass hot oil to heat up the water under the concrete.

Two electrical curing methods are described by Levitt [1982]. In the first, the current is passed directly through the rebars or prestressing tendons in order to heat up the surrounding concrete and accelerate its hydration. The problems with this method are that heat will not be distributed uniformly and that overheating can cause a loss of tensile properties in the wires. However, the advantage of this technique is in enhancing the strength gain of some particular part of the concrete products. This can be done by casting disposable wires to that part. In the second method, the current
is passed through the concrete between opposite steel plates of a semi-electrically-insulated mould. The supply switch must also be controlled to prevent overheating. Both methods require heavy duty transformers to supply the current with low voltage to the system. It is important to note that there are other electrical methods which are more economical and practical but they require more skillful workers to operate.

Cement reaction is an exothermal reaction which can provide heat to the system. In precast production, the most commonly used cement are ordinary Portland cement, rapid-hardening Portland cement, sulphate resisting Portland cement, and high alumina cement. Using more amount of cement will release more heat to the system resulting in an acceleration of the hydration process. However, the cost of production will certainly increase and workability will decrease. This method is more efficient if the mould is well insulated and the product is covered by an insulator such as polystyrene.

There were some efforts made to use infrared and microwave energy in curing concrete. According to Levitt [1982], the method of applying infrared energy is not desirable because it can heat up just the surface and the method of microwave curing is difficult to control and its plant can be very expensive. Moreover, using infrared and microwave energy to produce large units of precast concrete is inconvenient.

Besides the use of heat-accelerated curing as described above, there are other feasible methods to achieve high early strength (e.g., using of hot water and adding of water-reducing admixtures or accelerators) but they are rarely used in the production. According to Levitt [1982], precast concrete members, produced in an experiment by mixing cement, water at 80°C and heated aggregates to reach the final temperature of 95°C, can be demoulded at the age of three hours. Accelerators can be used to accelerate the setting and hardening rates of cement. Calcium chloride is the most common and the cheapest accelerator; others include calcium formate and sodium nitrite, but they are not as effective as calcium chloride [Levitt, 1982]. The performance of these accelerators is very sensitive to the chemical composition of Portland cement (especially tricalcium aluminate). Moreover, an accelerator can behave in a certain
way only when the temperature is between 5 and 25°C. Therefore, if the temperature increases due to an exothermal reaction of cement with water, the behavior of the accelerator is no longer predictable.

2.8 Review of Previous Studies on Microwave Curing in Concrete

The paper on microwave curing in concrete by Xuequan et al. [1987] discussed the mechanism of microwave curing, the optimum process test conditions, and the effects of microwave curing on compressive strength, flexural strength, and permeability.

The mechanism of microwave curing in concrete can be explained briefly as follows: while the concrete is heated by the microwave energy, its internal temperature rises and thus cement hydration is enhanced. Some water is desiccated at this stage, and the so-called "plastic shrinkage" occurs to decrease porosity. These effects can improve the strength and durability of the concrete.

In their experiment, a 2450 MHz and 1250-watt automatic cooking microwave oven was used. The maximum power level output was fixed at 650 watts. The range of the curing time was 15-120 minutes. The polyethylene moulds with 4x4x16 cm internal dimension were used to cast mortars whose mix ratios were 2.5 sand/cement and 0.44 water/cement. Portland cement grade 525 and silica sand were used in the mixing. Flexural and compressive tests were conducted. They concluded that the optimal conditions for microwave treatment were 30 minutes under the 150-watt power level and 15 minutes under level 2 which was not indicated clearly in the paper. (It is believed that power level 2 was greater than 150 watts.) The internal temperature of the specimens treated under level 1 for 30 minutes and level 2 for 15 minutes were 54 – 56°C and 57 – 58°C, respectively. These temperature ranges were considered to be favorable for the cement hydration. The authors explained further that the use of a high power level would cause splashing out of the cement paste due to a rapid evaporation of the water. In addition, an extended treatment would reduce the strength due to a water shortage for the hydration process and an increase in the

40
amount of the capillary voids in the concrete.

The results indicated that (1) the increase in the compressive strength was greater than the increase in the flexural strength (see Fig. 2.14), (2) the increase in strength during the early age was greater than that in the later age (see Fig. 2.15), (3) the microstructure of the microwave-treated specimen was denser than that of the untreated one (see Fig. 2.16), and (4) the delay of putting the specimen into the microwave oven could affect the strength of the specimen. The authors finally suggested that a new equipment should be designed to distribute microwave energy uniformly to the specimen so the optimum operating condition could be obtained.

There was another work of microwave curing in concrete done by R.G. Hutchison et al. [1991]. Basically, they wanted to investigate the use of microwave energy in accelerating cement hydration and in shortening the curing period of mortar specimens. The paper focused on the effects of microwave heating on the degree of hydration and on the compressive strength at various timings after casting.

In this work type I Portland cement was used to cast mortars with a 0.44 water/cement ratio in the 4x4x16 cm polystyrene moulds. The GE (model # JE 2851H) microwave oven was used and the power level output was set at 50 watts. The presence of different water loads in the oven was used to control the power levels of the experiment; thus, the power discharged to the specimens was inversely proportional to the amount of the water. Three different loads of water (600, 800, and 1000 ml) and three different durations in the oven (15, 22, and 40 minutes) were tried. Table 2.4 shows their testing program.

Three types of test were carried out to measure the degree of hydration, the internal temperature of the specimen, and the compressive strength. The results showed that (1) the microwave energy accelerated the hydration process in the first 24 hours and caused no difference after that period (see Fig. 2.17), (2) the induction period was reduced for the treated specimen (see Fig. 2.18), and (3) microwave energy did not affect the compressive strength at 1, 7, and 28 days of the treated specimens (see Fig. 2.19).
Table 2.1: Chemical compounds of Portland cement (adapted from Mindess et al. [1981])

<table>
<thead>
<tr>
<th>Chemical Name</th>
<th>Chemical Formula</th>
<th>Shortened Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tricalcium silicate</td>
<td>$3CaOSiO_2$</td>
<td>$C_3S$</td>
</tr>
<tr>
<td>Dicalcium silicate</td>
<td>$2CaOSiO_2$</td>
<td>$C_2S$</td>
</tr>
<tr>
<td>Tricalcium aluminate</td>
<td>$3CaOAl_2O_3$</td>
<td>$C_3A$</td>
</tr>
<tr>
<td>Tetracalcium aluminoferrite</td>
<td>$4CaOAl_2O_3Fe_2O_3$</td>
<td>$C_4AF$</td>
</tr>
<tr>
<td>Calcium sulfate dihydrate</td>
<td>$CaSO_42H_2O$</td>
<td>$CSH_2$</td>
</tr>
</tbody>
</table>

Table 2.2: Characteristics of cement compounds during hydration (adapted from Mindess et al. [1981])

<table>
<thead>
<tr>
<th>Chemical Compounds</th>
<th>Rate of Hydration</th>
<th>Amount of Heat Liberated</th>
<th>Contribution to Cement</th>
<th>Heat Liberation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tricalcium silicate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Dicalcium silicate</td>
<td>Slow</td>
<td>Low</td>
<td>Low Initially, high later</td>
<td>Low</td>
</tr>
<tr>
<td>Tricalcium aluminate plus gypsum</td>
<td>Fast</td>
<td>Very High</td>
<td>Low</td>
<td>Very High</td>
</tr>
<tr>
<td>Tetracalcium aluminoferrite plus gypsum</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Table 2.3: Typical chemical composition of Portland cement (adapted from Mindess et al. [1981])

<table>
<thead>
<tr>
<th>Chemical Compounds</th>
<th>Type of Portland Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td>Tricalcium silicate</td>
<td>50</td>
</tr>
<tr>
<td>Dicalcium silicate</td>
<td>25</td>
</tr>
<tr>
<td>Tricalcium aluminate</td>
<td>12</td>
</tr>
<tr>
<td>Tetracalcium aluminoferrite</td>
<td>8</td>
</tr>
<tr>
<td>Calcium sulfate dihydrate (gypsum)</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2.4: Testing program by R.G. Hutchison et al. [1991] at different microwave power levels

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Water Load (ml)</th>
<th>Time in Oven (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P1 + 600</td>
<td>600</td>
<td>15</td>
</tr>
<tr>
<td>P1 + 800</td>
<td>800</td>
<td>22</td>
</tr>
<tr>
<td>P1 + 1000</td>
<td>1000</td>
<td>40</td>
</tr>
</tbody>
</table>
Figure 2-1: Effects of temperature on the compressive strength development of concrete [Mindess et al., 1981]): (a) Comparison of 1-day and 28-day strengths (constant curing temperature). (Adapted from G.J. Verbeck and R.A. Helmuth, *Proceedings, Fifth International Symposium on the Chemistry of Cement, Tokyo, 1968*), Vol. 3, pp. 1-32.) (b) Curing temperature maintained continuously. (c) Initial Concrete temperature, curing temperature maintained at 21 C. (Adapted from W.H. Price, *Journal of the American Concrete Institute*, Vol. 47, No. 6., 1951, pp. 417-432.)
Figure 2-2: Effects of limited moisture curing on the compressive strength development of concrete with 0.50 w/c ratio [Neville, 1981] (from W.H. Price, "Factors influencing concrete strength," Journal of the American Concrete Institute, Vol. 47, No. 6, pp. 417-432, 1951.)

Figure 2-3: The typical scheme of low pressure steam curing [Mindess et al., 1981]
Figure 2-4: Compressive strength development in pastes of pure cement compounds [Mindess et al., 1981]

Figure 2-5: Compressive strength development of the major constituents of Portland cement [Soroka, 1979] (After Mironov and Malinina from Butt, Yu. M., V.M. Kolbasov, and V.V. Timashev, "High Temperature Curing of Concrete under Atmospheric Pressure," Proc. Symp. Chem. Cement Tokyo, 3, 437-476 (1968))
Figure 2-6: Rate of heat evolution during the hydration of tricalcium silicate [Mindess et al., 1981]

Figure 2-7: Rate of heat evolution during the hydration of tricalcium aluminate with gypsum [Mindess et al., 1981]
Figure 2-8: Rate of hydration of the cement compounds in paste of the pure compounds [Mindess et al., 1981]

Figure 2-9: Types of water in hardened cement paste [Mehta, 1936] (Based on R. F. Feldman and P.J. Sereda, Eng. J. (Canada), Vol. 53, No. 8/9, 1970)
Figure 2.10: Interaction of microwaves with materials [Sutton, 1989]

Figure 2.11: Comparison between heating in conventional oven and in microwave oven [Sutton, 1989]
(a) and (b) Results at Power Level 1

(c) and (d) Results at Power Level 2

Figure 2-14: Results of flexural strength and compressive strength due to microwave heating at different heating rates by Xuequan et al. [1987]
Figure 2-15: Results of flexural strength development and compressive strength development due to normal curing and microwave heating at different heating rates by Xuequan et al. [1987] (Note: x = normal curing; * = heating at power level 1 for 30 minutes, and the other one = heating at power level 2 for 15 minutes)
Figure 2-16: Results of water permeability of mortar piles versus testing time by Xuequan et al. [1987]

Figure 2-17: Results of percent hydration versus time by Hutchison et al. [1991]
Figure 2-18: Results of temperature versus time by Hutchison et al. [1991]

Figure 2-19: Results of strength of mortars tested at 1, 7, and 28 days for normal curing and microwave curing by Hutchison et al. [1991]
Chapter 3

Experimental Program

3.1 Introduction

This research is primarily interested in the application of microwave treatment to concrete in order to develop sufficient strength within a short period of time after heating so that it can be used both in pavement repair and in the precast concrete industry. Therefore, strength measurement is the focus of this experimental program.

In studying the strength for different applications, three types of specimens are used, namely, regular specimens, specimens with an interface, and specimens with an embedded steel bar. Regular specimens are used in compressive test and splitting tensile test to measure the compressive and tensile strength, respectively; specimens with an interface are used in bond splitting tensile test and slant shear test to measure the bond strength between new and old concrete while specimens with an embedded steel bar are used in direct tensile test and pull-out test to measure the bond strength between a steel bar and the cement paste. To cope with the availability of testing machines, equipments, and facilities, testing procedures and size of specimens are slightly different from the American Society for Testing and Materials (ASTM) standard.

The following sections describe the parameters of interest, the scope of experimental work, the equipments and machines, the mixing and curing processes, the sample preparation procedure for microstructural study, and the testing methods.
3.2 Parameters to be Studied

Due to limited research time, it is not possible to study all parameters that are likely to affect the strength of concrete under microwave curing. The parameters examined in this research are thus restricted to the following:

1) Microwave heating rate
2) Age after microwave heating
3) Microwave power level
4) Water/cement ratio
5) Presence of aggregates (mortar versus concrete)
6) Delayed time after the placing process

To isolate the effect of a particular parameter, it is varied while the others are kept constant.

3.3 Scope of Experimental Work

This research divides the experimental program into three parts, namely, the normal curing part, the microwave heating part, and the microstructural characterization part; the three parts of this experimental program are illustrated in Figures 3.1, 3.2, and 3.3, respectively. Since the focus of this research is to study the effects of microwave curing on concrete strength, the results under microwave heating are compared with those under normal curing. The microstructural study is used to help explain the differing results.

3.4 Equipments and Machines

This section describes the equipments and machines used in this work.

There are two kinds of moulds used in this study: plastic mould and polyethylene mould. The plastic mould is widely used in laboratories because it is easy to remove and can be reused. The polyethylene mould is also used but only when the specimen
is cured in the microwave oven. Polyethylene is a transparent material with respect to microwave which means that it does not absorb microwave energy; hence, the microwave energy can penetrate easily through the polyethylene mould and heat the cement paste without any loss of energy to the mould.

A 2450 MHz, 1200-watt microwave oven (see Figure 3.4), which is specifically designed by Cober Electronics, Inc. for research application in the laboratories, is used. Its interior size is 10.75 in. high x 15.5 in. wide x 16.75 in. deep. The range of the applied power level is 0 to 1200 watts. The oven is equipped with a turntable and a stirrer which are necessary to provide uniform heating to the specimens. It also has a temperature probe to measure the temperature of the heated products. It can be controlled either manually or by a computer with the use of Labtech Notebook software, which is a data acquisition and control program. The data, which include applied power, reflected power, and temperature of the specimens, can then be transmitted to the computer through a data acquisition card installed in the oven.

Tests in this study are carried out on three testing machines: (1) a 1331 servo-hydraulic Instron testing machine with the maximum tension and compression capacity of 22.4 kips (see Figure 3.5), (2) a 60-kip, manually controlled Baldwin testing machine (see Figure 3.6), and (3) a 200-kip Baldwin testing machine controlled by a computer (see Figure 3.7). The 22.4-kip Instron machine is used to perform Young's Modulus test and direct tension test. The 60-kip and 200-kip Baldwin machines serve the rest of the tests. Data obtained in tests are transmitted to a computer through a data acquisition/control unit of Hewlett Packard model HP 3497 A.

The microstructural studies are performed under the scanning electron microscope (SEM) model STEREOSCAN 240 manufactured by Cambridge Instruments Ltd., England (see Figures 3.8) and the environmental scanning electron microscope (ESEM) manufactured by ElectroScan. The AN 10000 X-ray analyzer used with the SEM was manufactured by Link Analytical Limited, England.
3.5 Mixing and Curing Processes

Since this study is a comparative study, the raw materials and the procedures must be kept controlled. In particular, the mixing and curing processes, which can affect the results easily, must be done consistently.

Type III Portland cement used in this study is manufactured by Dragon Products Company in Maine. Mortar sand and pea gravel are packed by B. Vitalini, Inc. from Milford in Massachusetts. These materials are easily obtained from local suppliers. Although each particle of type III Portland cement is already finer in size than that of other cement types, the cement still needs to be sieved through a sieve having 0.011-in. openings (Tyler equivalent = 30 mesh) to obtain a uniform quality of cement paste and to remove large cement crumbs. The gravel is also sieved through a sieve having 0.312-in. (or 7.925 mm) openings (US. Series Equivalent No. 2½), allowing the maximum size of coarse aggregate to be only 0.312 inch in diameter.

An example of mix proportion, by weight, of water : cement : sand, for normal strength mortars having 0.50 w/c ratio, is 1 : 2 : 4. For 0.50 water/cement concrete mixing, the weight ratio of water : cement : sand : gravel is 1 : 2 : 2 : 3. Each mixing is done in an ordinary rotary mixer (see Figure 3.9) for 7 minutes and the cement paste is then placed into the moulds. After that, the moulds are put on a vibrating table for 7 minutes and during this period they are tamped uniformly 25 times by a steel rod with a 0.20-inch diameter to reduce the voids or air bubbles, which are trapped in the paste.

After the mixing and placing processes, specimens are either covered immediately by plastic sheets or heated in the microwave oven and then covered by plastic sheets after the heating. In each microwave heating, six moulds are arranged as shown in Figure 3.10 to allow uniform heating. The curing age in this research is counted from the time that water is mixed with the cement. After 24 hours, the specimens are immersed in water until tested. Since the amount of water can affect the strength development, each specimen is weighed before and after microwave heating to determine the amount of water which is lost during the heating.
3.6 Sample Preparation of Microstructural Study

In studying the microstructure of mortar and concrete samples at several ages, a scanning electron microscope (SEM) is used. The environmental scanning electron microscope (ESEM) is also used but only when the samples are in an early stage. The major difference between SEM samples and ESEM samples is the condition of the specimens, i.e., a sample for the SEM has to be dry and coated with a conductive material (i.e., gold or carbon), whereas a sample for the ESEM can be either dry or wet.

Sample preparation procedure for the scanning electron microscope study is summarized as follows:

1) obtain a fractured sample at a desired age,
2) flood it with isopropanol to stop hydration,
3) wait for 15 minutes; dry it in a conventional oven for at least 2 hours; and then leave it in a desiccator until it is coated,
4) coat it with gold, and
5) store it in the desiccator until the SEM examination.

The steps basically follow the procedure used in the study of Portland cement at the early age by Pratt et al. [1983], with only slight changes. The samples to be examined under the ESEM do not need to be treated at all.

3.7 Testing Procedures

Six tests are carried out in this research: compressive test, splitting tensile test, Young’s modulus test, slant shear test, direct tensile test, and pull-out test. Compressive test and splitting tensile test are used to measure the compressive strength and tensile strength of specimens, respectively. Young’s modulus test is conducted to obtain the modulus of elasticity. In measuring the bond strength between new and old cement paste, bond splitting tensile test and slant shear test are performed. It is important to note that the procedure of bond splitting tensile test is similar to that
of splitting tensile test except that more devices and additional measurements are required in the former. The bond strength between the steel bar and cement paste is measured from the direct tensile test and pull-out test. The following sections describe each of the tests in more details.

3.7.1 Compressive Test

In this test, the size of each specimen is 3 inches in diameter and 6 inches high. It is loaded compressively at the rate of 4,000 lbs/min (until it breaks) by using either the 60-kip Baldwin or 200-kip Baldwin machine to measure its early strength. At the later age, the displacement loading rate of 0.010 in/min is used instead, and the test is carried out with the 200-kip Baldwin machine.

Each specimen is capped at both ends with hydrostone for about an hour prior to testing. Each end should take about half an hour to harden. The specimen is ready to be tested after the hydrostone at both ends has become hard. The compressive strength will then be obtained.

3.7.2 Splitting Tensile Test

Splitting tensile test is used to obtain the tensile strength of the specimen because it gives more consistent results and is simpler to carry out than other tensile tests (e.g., direct tensile test, etc.). It is known that the splitting tensile strength is usually about 5 to 15 percent higher than the direct tensile strength.

In this test, a 3 in. x 6 in. cylindrical specimen is tested along its sides in compression to obtain the tensile strength. The load is applied through two pieces of \( \frac{1}{2} \)-in. wide and \( \frac{1}{8} \)-in. thick plywood placed on the top and at the bottom of the specimen’s surface in order (1) to reduce high compressive stresses at the points of load application which might lead to local crushing and also (2) to reduce the loading effect of the non-uniform surface of the specimen. The load is applied by either the 200-kip or 60-kip Baldwin machine at the rate of 4000 lbs/min.

Special specimen preparation is needed only when the specimen is used in measur-
ing the tensile bond strength between old and new cement paste (called the bimaterial specimen). It is prepared by first casting the paste into the 3 in. x 6 in. cylindrical mould with a specially-made plexiglass half-cylinder (see Figure 3.11) placed inside. After 24 hours, the half-specimen is removed from the mould and separated from the plexiglass. The bonding surface is then sand-blasted to become rough. The first half of the bimaterial specimen is then ready to be cast to make a complete cylindrical specimen.

In case of a regular specimen, failure usually occurs in a splitting tensile manner and in a local crushing manner simultaneously. Therefore, the maximum load can be used to calculate the splitting tensile strength. The test results of regular specimens include both the load magnitude and the actuator displacement. According to ASTM C496-90 [1992], which is a standard test for splitting tensile strength of cylindrical concrete specimens, the splitting tensile strength, $T$, is therefore calculated from

$$T = \frac{2P}{\pi ld}$$  \hspace{1cm} (3.1)

where $P$ is load at failure,

$l$ is the length of a specimen, and

$d$ is the diameter of a specimen.

Figure 3.12 shows the splitting tensile setup for a regular specimen.

However, in the case of a bimaterial specimen, failure in the bond between two materials occurs before the final failure of the specimen due to local crushing. To calculate the bond strength, it is important to detect the load at bond failure between materials. The suggested method is to use a linear-variable-differential-transducer (or LVDT) to detect the bond failure. Both ends of the specimen are cut and ground smoothly to display the bonded line and to get rid of the overlapping part of the cement paste. Then a LVDT holder is glued by the 5-minute epoxy at one side of the material surface along the line, which is perpendicular to the bonded line and also is in the center of the specimen, while another small piece (0.25 in. x 0.5
in. x 1.0 in.) of aluminum is glued onto the other side of the material to act as a target. After the epoxy becomes hardened, insert the LVDT and the test can begin. The horizontal displacement between the bonded material during loading can then be detected. Load is applied until crushing failure occurs. The test results of the bimaterial specimens also include both the load magnitude and the actuator displacement. In addition, LVDT reading is obtained so the true bond tensile strength of the bimaterial specimen can be calculated from the load magnitude where the kink (i.e., a large horizontal movement due to bond failure) occurs on the plot of load versus LVDT reading. An example of this plot is shown in Figure 3.13. Hence, to calculate the bond splitting tensile strength, equation (3.1) is used again, but P is the load where the kink occurs. This calculation is just an approximated value of bond splitting tensile strength assumed that material properties is homogeneous throughout the specimen. The setup of the bond splitting tensile test is shown in Figure 3.14.

3.7.3 Young’s Modulus Test

Young’s Modulus test procedure is exactly the same as that of the compressive test except that two LVDT’s are used in this test to measure the vertical displacements, which finally change to strains, between two points of the specimen. The LVDT’s are tightened to a yoke, which is connected to the sides of the specimen by screws (see Figure 3.15).

The load and LVDT readings are transmitted through the data acquisition system into the computer. The specimen in the Young’s Modulus Test should not be loaded to failure because it might cause damages to the LVDT’s and the yoke. Therefore, the specimen is loaded by the 22.4-kip Instron machine to about 50 percent of its maximum compressive strength, which is obtained by testing the first specimen in the compressive test. The specimen from this test is then reloaded to obtain the compressive strength.
3.7.4 Slant Shear Test

The purpose of this test is to obtain the bond strength in the compressive shear between new and old cement paste at various ages. The geometry of each specimen is a 3 in. x 8 in. cylinder with an inclined interface plane (30 degree from the longitudinal axis) between the new and old cement paste. The test is performed in the same way as the compressive test at the loading rate of 0.010 in/min applied by the 200-kip Baldwin machine. However, due to the breakdown of the 200-kip Baldwin machine, some slant shear test has to be conducted at the loading rate of 4000 lbs/min under the 60-kip Baldwin machine.

Half of the specimen is prepared first by placing a specially-made plexiglass (see Fig. 3.11) in a polyethylene mould and then casting the paste into the mould. After 24 hours, the composite cylinder (composed of half plexiglass and half new concrete) is removed from the mould. The paste part is then separated from the plexiglass. After 6 days of curing in a water tank, the half-specimen is let dry in the air for about an hour. Then the sloping surface is sand-blasted to roughen the bonding surface. The half-specimen is then put back into the original mould for the complete casting into a cylindrical form.

Each specimen is also capped at both ends with hydrostone. After about an hour, the specimen is ready to be tested. According to ASTM C1042-91 [1992], which is a standard test method for bond strength of latex systems used with concrete by slant shear, the bond strength in the compressive shear test \( \sigma_{ss} \) is obtained from

\[
\sigma_{ss} = \frac{P}{A_{bs}}
\]

where \( P \) is the load at failure, and

\( A_{bs} \) is the area of bonded surface, which is about 14.137 \( in^2 \).

3.7.5 Direct Tensile Test

At present, there is no standard direct tensile test. The procedure in this research is based on the doctoral thesis of Wang at M.I.T. [1989]. The 22.4-kip Instron machine
is used in this test. The specimen used here is a 3 in. x 6 in. cylinder.

This test is intended both to measure the direct tensile bond strength between steel bars and the cement paste of specimen under normal curing and of specimen under microwave heating. Each specimen used for this purpose is prepared in a special way. The "old" cement paste with a steel bar of 5 inches long embedded inside is prepared by first placing the paste into a 3 in. x 6 in. cylindrical mould to reach the depth of about 3.5 inches. The steel bar, which is tightened with a 3 in. x 2 in. cylindrical plexiglass (see Fig. 3.11), is then immersed in the mould to ensure that the bar is 0.5 inches away from the bottom. This "old" specimen embedded with a bar (see Fig. 3.16) is removed from the mould after 24 hours and then cured in a water tank for many days. The whole specimen is finally formed by casting a fresh cement paste into the mould that has the "old" cement paste with a steel bar. Microwave energy can then be applied.

The specimen is ground at both ends by a grinding machine. The surface at each end is then grooved with four or five cuts in two perpendicular directions at the depth of about 0.15 inch to increase the surface area of the ends (see Figure 3.17). Four pieces of steel wires (with a length of 0.1 inch and a diameter of 0.02 inch) are glued onto each end of the specimen to control the thickness of the glue. The specimen is then glued onto a 4 in. x 4 in. x 0.5 in. steel plate by using the 5-minute epoxy.

The specimen is taken to the testing machine after the epoxy has set for 15 minutes. The plate attached to the specimen is then fixed to the actuator by tightening four screws to the plate that is connected to the actuator. Epoxy is then applied to the top surface of the specimen and the specimen is preloaded until it touches the top steel plate, which is already connected to another steel plate fixed to the load cell. A small compressive force is applied to the specimen at this stage. The specimen is left for an hour to obtain the full strength of the epoxy before testing. Figure 3.18 illustrates setup of the direct tensile test.

The test is run by the general test program on the Instron 1331 machine. To obtain a stable loading and to avoid machine oscillation, the machine parameters are set as follows: gain = 41, time constant = 14, and mass compensation = 10. The
loading rate is 0.0001 in/min.

It should also be noted that the Young's Modulus setup (with a yoke and two LVDT's) can be used in this test to measure the vertical displacements of the specimen in order to see whether the specimen is loaded uniformly or not.

3.7.6 Pull-Out Test

In addition to direct tensile test, pull-out test is used to measure the bond strength between the steel bar and the cement paste. It involves pulling a steel bar out of the hardened cement paste. In this study, the paste is either cured normally or cured by the microwave. The result from the microwave-heated paste is compared with that from the normal-cured paste.

Each specimen is prepared by first securing a steel bar in a hole in the middle of a 3 in. x 2 in. cylindrical plexiglass piece (see Figure 3.19). The cement paste is then placed into a 3 in. x 8 in. cylindrical polyethylene mould until a height of 3.5 inches is reached. The steel bar is then immersed between 1 and 2 inches into the paste. The specimens are now ready to be either cured in the microwave or cured normally.

Test is performed on the 60-kip Baldwin machine at the rate of approximately 500 lbs/min. The test setup is shown in Figure 3.20. Each specimen is placed in the holder, which is connected to the top part of the testing machine, with the embedded bar pointing downwards. The bar is then gripped by a pair of gripper, which is locked to the bottom part of the machine. A piece of 1/8 in. rubber sheet is inserted between the holder and the contacted surface of the cement paste to reduce the high local compressive stress on the paste during testing. The test results include the load at failure and the embedded length of steel bar. The pull-out bond strength ($\sigma_{po}$) is simply calculated from

$$\sigma_{po} = \frac{P}{\pi dl}$$  \hspace{1cm} (3.3)
where $P$ is the load at failure,

d is the diameter of the steel bar, and

l is the embedded length of the steel bar.
Normal Curing

Mortar

* Compressive Strength
* Splitting Tensile Strength
- Bond Strength
  * Modulus of Elasticity

New&Old Mortar

Splitting Tensile Strength
Slant Shear Strength

Note: * These specimens are tested at 8.5, 12.5, 24.5 hours, 3, 7, and 14 days

- For bond strength test, the old part is 14 days old while the new part is either 8.5, 13.5, 25.5 hours, 3, or 7 days old.

Figure 3-1: Experimental program for normal curing
Note: These specimens are generally tested at 4.5 hours and 7 days.

Figure 3-2: Experimental program for microwave heating
Figure 3-3: Experimental program for microstructural examination
Figure 3-4: A 2450 MHz, 1200-watt microwave oven with PC to control
Figure 3-5: A 22.4-kip Instron testing machine
Figure 3-6: A 60-kip Baldwin testing machine

Figure 3-7: A 200-kip Baldwin testing machine with PC to control
Figure 3.8: The SEM: (top) Control panel and (bottom) Chamber
Figure 3-9: An ordinary rotary mixer
Figure 3-10: An arrangement of polyethylene moulds in the microwave oven

Figure 3-11: A 3 in. x 2 in. cylindrical plexiglass, a 3 in. x 6 in. specially-made plexiglass half-cylinder, and a 3-in. diameter specially-made plexiglass cylinder with an inclined interface plane (30 degree from the longitudinal axis)
Figure 3-12: Splitting tensile test setup for a regular specimen
Figure 3.13: A typical plot of load and LVDT reading from bond splitting tensile test
Figure 3-14: Bond splitting tensile test setup for a bimaterial specimen
Figure 3-15: Young's modulus test setup

Figure 3-16: An "old" part of specimen with an embedded steel bar to prepare the whole specimen for direct tensile test
Figure 3-17: The surface end of a specimen for direct tensile test
Figure 3-18: Direct tensile test setup
Figure 3-19: A steel bar with a 3-in. cylindrical plexiglass and a polyethylene mould to prepare a specimen for pull-out test
Figure 3-20: Pull-out test setup
Chapter 4

Test Results and Discussions

4.1 Introduction

This chapter reports the results of the experiments. In this study, three parts of experimental works are involved:

1) testing the normal-cured specimens,
2) testing the microwave-treated specimens, and
3) studying the microstructure by the scanning electron microscope.

The results of the regular-cured specimens are used to compare with those of the microwave-heated specimens to determine whether or not microwave curing significantly improves the early strength and impairs the later strength of mortar and concrete. Microstructural characterization is carried out to help explain the results. Moreover, the results of the microwave-cured cementitious materials are compared with those of rapid hardening materials used in practice.

4.2 Normal-Cured Specimens

The measured properties of normal-cured specimens, which include the modulus of elasticity, the compressive strength, the splitting tensile strength, and the bond strength between the old and new parts of mortar, are measured at several ages, i.e.,
at 8.5, 12.5, 24 hours, 3, 7, and 14 days. Tables 4.1, 4.2, 4.3, 4.4, and 4.5 show the experimental results of Young's modulus test, compressive test, splitting tensile test, bond splitting tensile test, and slant shear test, respectively. In addition, the development of compressive strength, splitting tensile strength, and modulus of elasticity at various ages after mixing are shown in Figure 4.1.

Based on the 14-day strength, the splitting tensile strength develops much faster than the compressive strength at the early age (i.e., within 12 hours). From Table 4.3, at 8.5 and 12.5 hours the tensile strengths gain up to 15.9% and 64.3% of the 14-day strengths, respectively, while from Table 4.2, the compressive strengths at the same age gain only 4.1% and 17.6% of the 14-day strengths, respectively. On the contrary, after 12 hours the tensile strength develops much slower than the compressive strength. As the age of specimen increases, the compressive strength gradually increases as long as there are moisture and spaces left for hydration products to grow.

In pavement repair, bond strength between the new and old parts is important. Bond splitting tensile test and slant shear test are the two tests carried out to obtain the bond strength. The age here refers to the age of the new part only because the age of old part is 14 days old. Based on the 7-day bond strength, the bond splitting tensile strength develops much faster than the slant shear strength at the early age (i.e., within 12 hours). From Table 4.4, at 8.5 and 13.5 hours the bond tensile strengths gain 4.0 and 23.3% of the 7-day strength, respectively, whereas from Table 4.5, the slant shear strengths gain only 2.2% of the 7-day strength at 8.5 hours and 9.0% at 13.5 hours. However, both types of strength development are comparable at the later age, i.e., both are around 40, 70, and 100% at 1, 3, and 7 days, respectively.

### 4.3 Microwave-Heated Specimens

This section is the most important part of the research and the experimental work is carried out in the following order. Firstly, the effects of heating rates on mortar under the same energy input level on the compressive strength are examined. The heating time is then selected arbitrarily at 45 minutes, which seems to allow the
hydration to proceed in a suitable way, i.e., not to cause rapid heating. Under the 45-minute microwave heating duration, the power level is varied to study its effects on the compressive and tensile strength of the mortar. From the preliminary result, the optimal power level is around 400 watts. Therefore, in subsequent tests, to study the effects of delayed time and w/c ratio and to determine the bond strength, the heating rate is kept constant at 400 watts for 45 minutes.

The next parameters to be studied are the delayed time and the w/c ratio. Thus far, the delayed time (defined as the time after water is mixed with the cement) is kept at 30 minutes and the w/c ratio is 0.50. The compressive strength of mortar at 3 delayed times (i.e., at 20, 30, and 40 minutes) and four w/c ratios (i.e., 0.45, 0.50, 0.55, and 0.60) are examined. The next step is to investigate the bond strengths between new and old mortar, and between mortar and a steel bar. Results at the 45-minute heating time under the power level of 300 and watts are reported.

Finally, concrete, instead of mortar, is tested to study the effects of heating rate and the w/c ratio (i.e., at 0.45, 0.50, 0.55, and 0.60) on the development of compressive strength. As before, the microwave heating power is kept at 400 watts and the heating duration is 45 minutes.

Most of the results are measured at 4.5 hours (early age) and 7 days (later age). Only one set is tested at 3 hours instead of 4.5 hours. In addition, testing the specimens at 1 and 28 days is also conducted to study the long term effects of the microwave heating on the compressive strength.

In summary, two types of specimens are used in this part of the research, namely, mortar and concrete specimens. Mortar is studied more extensively and after the results from mortar are obtained, concrete is used to study further effects.

4.3.1 Mortar Specimens

Three properties of mortar specimens are investigated:

1) Compressive strength
2) Splitting tensile strength

3) Bond strength

The delayed time and the w/c ratio are 30 minutes and 0.50, respectively, unless indicated otherwise.

**Effects on the Compressive Strength**

Since the compressive strength, which relates to the tensile strength, is easier to measure, most efforts go into determining the compressive strength. Nevertheless, tensile strength is also measured and reported. The effects of microwave heating on the compressive strength are studied through four parameters as follows:

1) heating rate under the same energy input level,
2) power level at 45-minute heating time,
3) delayed time, and
4) water/cement ratio.

**Heating Rate under the Same Energy Input Level**  The energy input level is arbitrarily selected to be 1,080,000 joules. The purpose of keeping it constant is to study just the effect of heating rate on the compressive strength at the early and later ages. Therefore, each set of specimens is heated in the microwave oven at different power levels and for different heating durations. For example, the combinations of power level and heating time for the input energy at 1,080,000 joules are 200 watts at 90 minutes, 300 watts at 60 minutes, 400 watts at 45 minutes, 500 watts at 36 minutes, 600 watts at 30 minutes, and 700 watts at 25.71 minutes. (Note: It is assumed that each set of specimen absorbs the same amount of energy.) The compressive strength is then measured at the ages of 3 hours and 7 days for the microwave-heated specimens and just at 7 days for normal-cured specimens. The strength of normal-cured specimens is used as the baseline for comparison.
The result of this parameter is shown in Table 4.6, and Figures 4.2(a) and (b) show plots of this result, which is compared to the result of 7-day normal-cured specimens. At the early age, Table 4.6 shows that the range of 3-hour strength of specimens under microwave heating is between 117.8 and 323.4 psi, which is comparable to the strength of specimens under normal curing at 8.5 hours that has a 262.5 psi compressive strength (see Table 4.2). For the later age, using the strength of normal-cured specimens as the baseline (100%), the range of the strength of microwave-cured specimens at different heating rates is between 58.8% (or 3530.4 psi) and 86.0% (or 5130 psi). It is obvious that the 7-day strengths of specimens under 500 watts microwave heating and above gain up to only 60 to 70% of the 7-day strengths of specimens under normal curing.

It is believed that the development of compressive strength due to microwave heating depends on two distinct effects:

1) The effect of increased cement hydration

2) The effect of increased porosity and microcracks

While the microwave energy is being applied to the specimens, the rate of cement hydration is increased (referred to the result by R.G. Hutchison et al. [1991] which concluded that the microwave energy can accelerate hydration and reduce the induction period) because of the increased curing temperature, which can promote hydration process. As a result, the early strength of specimens under microwave heating can be higher than that of specimens under normal curing. However, it becomes that at the later age, the strength of specimens under microwave treatment is lower than that of specimens under normal curing. This can be explained by the effect of increased porosity and microcracks which dominates the results at later age. During heating and maybe a short while afterwards, due to the difference in the thermal expansion coefficients of the concrete constituents (see Figure 4.3), the greater expansion of water and air inside the specimen can result in an increase in both the porosity and the internal pressure, leading to the formation of microcracks inside the specimens. The strength at the later age of the treated specimens can therefore be
less than the untreated ones.

In addition, it is believed that the use of high microwave power (i.e., 500 watts and above, which are considered to be high powers in this study) can take away water so quickly that there is not enough water left to complete or to proceed the hydration process after heating. It may also raise the temperature to the level that is unfavorable to hydration process, leading to the formation of improper hydration products and cause strength reduction in the long term. In other words, the hydration products have not formed properly and uniformly yet since the water has been drying out too fast.

To conclude, the effect of increased cement hydration improves the early strength, but in the long term the adverse effect of increased porosity and internal microcracks becomes dominant and thus reduces the later strength.

**Power Level at 45-Minute Heating Time**  As mentioned earlier, the heating time is set to 45 minutes and the power level is changed to study its effect on the compressive strength. Four power levels 300, 400, 500, and 600 watts are employed initially. Later on the power level at 350 and 450 watts are employed for additional tests.

From the result shown in Tables 4.7, the compressive strengths obtained at three hours period are quite low, i.e., between 88.5 and 807.6 psi. Using the 7-day strength of normal-cured specimens as the baseline (100%), the 3-hour strengths and the 7-day strength of microwave-heated specimens range between 1.5 and 13.2% and between 30.3 and 91.2%, respectively. The result is also shown in Figures 4.4(a) and (b), which can be concluded that the higher the heating power, the higher is the early strength, but the lower is the later strength. For instance, the 3-hour strengths of specimens under 300 watts and 600 watts are 88.5 and 807.6 psi whereas their 7-day strength are 5561.8 and 1854.3 psi, respectively.

It is noted that one of the objectives of this research is to obtain a compressive strength of at least 2,500 psi within 5 hours and it is clear that the 3-hour compressive
strengths of specimens under different heating powers cannot reach even 1,000 psi. Therefore, the early time to test the strength of specimens is changed from 3 hours to 4.5 hours instead to allow the strength to develop further.

The result of the compressive strengths at 4.5 hours is shown in Table 4.8 and Figures 4.5(a) and (b). At early age, the 4.5-hour strengths of the specimens under the microwave heating at 400 and 500 watts are 2,215.4 and 2,449.2 psi, respectively, whereas at later age (i.e., 7 days), the strengths of specimens heated under 400 and 500 watts are 4,353.1 and 2,762.2 psi, respectively. Compared to the 7-day strength of specimens under normal curing (100%), the 7-day strength of specimens under 500 watts heating is only 43.9% while that of specimens under 400 watts heating is 70.3%. Hence, it agrees well with the results, for specimens tested at 3 hours, that the higher the heating power, the higher is the early strength, but the lower is the later strength. However, although the 4.5-hour strength has surpassed the 3-hour strength considerably, the obtained strengths are still lower than 2,500 psi, which is the goal of this process development. Therefore, other parameters such as delayed time, w/c ratio, and presence of aggregates, which can affect the strength of the specimens, need to be changed. Results of such studies will be reported.

Another important thing in this study is that under the same microwave heating time (i.e., 45 minutes), but different heating powers, each set of specimens will lose different amount of water. From Table 4.8, each specimen under 300, 400, 500, and 600 watts microwave heating loses the water in an amount of 10.67, 13.83, 18.17, and 31.33 grams, respectively. Therefore, it is clear that the higher the microwave energy input, the more is the loss of water. If the water loses in small amount, the specimen will not gain any advantage at the very early age (such as early strength), but excessive loss of water can impair its later strength.

In summary, from the result of testing the microwave-treated specimens at 4.5 hours, it is clear that with a 45-minute microwave heating duration, the most desirable power level is 400 watts. For instance, the strength of treated specimens at 4.5 hours and 7 days are 35.8% (2215.4 psi) and 70.3% (4353.1 psi), respectively, based on the 100% (6193.1 psi) of the strength of untreated specimens at 7 days.
The explanation for the effect of different microwave power levels on the compressive strength is actually the same as in the previous section, but it can be explained further as follows. It is believed that due to the microwave energy the hydration rate of $C_3S$, which is responsible for the strength of the cement paste, can be accelerated and therefore provide the early strength. It is important to note that the large amount of $C_3S$ in type III Portland cement also provides the high early strength. However, due to loss of water and high temperature, the growth of C-S-H, which usually contributes most of the strength of the paste, is probably non-uniform. For this reason, its later strength (i.e., at 7 days) cannot be developed to even out the strength of the normal-cured specimens whose hydration is in a more suitable environment, i.e., enough water and proper temperature.

**Delayed Time**  The objective of studying this parameter is to examine the effect of the delayed time in microwave energy application on the compressive strength. It is worth mentioning again that the delayed time is the time after the water is mixed with the cement. Since it is believed that the age of cement paste before microwave applying is one of the important factors, which can affect the strength of the cementitious specimens; hence, it is important to study how the delayed time (or age of cement paste after mixing) can affect the strength. This study can be compared to the situation in practice where the delays of the transfer of concrete to the repair site is a concern. Mortar specimens with 0.50 w/c ratio are used instead of concrete specimens to study this parameter; the heating rate is set at 400 watts and 45 minutes because it is the most satisfactory heating rate from the result in the previous section. Since it usually takes about 20 minutes in preparing and mixing the specimens before microwave curing, three delayed times are examined: 20, 30, and 40 minutes.

Figures 4.6(a) and (b) and Table 4.9 illustrate the result of the effect of the microwave curing on the compressive strength of mortar specimens due to the delayed times. It is obvious that by heating the specimens after different delayed times, there
are only slightly differences in the w/c ratio after heating. For instance, the w/c ratios after the heating of the cases with 20, 30, and 40 minutes delayed times are 0.466, 0.468, and 0.467, respectively. In other words, the amount of water, which loses during microwave heating, is about the same. Under 20, 30, and 40 minutes delayed times, the water loses in the amount of 14.33, 13.83, and 14.17 grams, respectively. However, the strengths at 4.5 hours are different significantly while those at 7 days are about the same. The strengths at 4.5 hours of specimens with 20, 30, and 40 minutes delayed times are 814.4, 2215.4, and 1670.1 psi, respectively, whereas those at 7 days are 4537.5, 4353.1, and 4496.6 psi. Using the 7-day strengths of normal-cured specimens as the baseline (100%), the 4.5-hour strengths of the cases with 20, 30, and 40 minutes delayed times are 12.5, 35.8, and 24.7%, respectively, whereas 69.5, 70.3, and 66.4% are the 7-day strengths, respectively.

In cement hydration, $C_3S$ and $C_3A$ will react first [Neville, 1981], but gypsum, which is added to the cement, will retard the reaction of $C_3A$; therefore, $C_3S$ reaction becomes more dominant even at early age. If $C_3A$ is allowed to react first, it will form the porous structure and then the remaining cement constituents will hydrate and fill in this porous structure, giving an adverse effect on the strength. On the other hand, $C_3S$, whose reaction with water gives out the C-S-H, will construct properly the framework of the paste, leading to gain in strength. This knowledge can be applied to explain the results of this section. The only difference of each set of specimens examined in this section is the delayed time. Therefore, the possible factors, which can cause the differing in the early strength, are

1) the structure of the paste before heating
2) type of water, which evaporates during heating

It is believed that if the microwave energy is applied while the cement paste is in a plastic state (i.e., at the very early age), the water in the mix proportion can be removed easily. At this stage, the structure of C-S-H can form improperly because of the rising temperature, quick precipitation of hydration products, and rapid evaporation of water. As a result, the strength at early age (i.e., 4.5 hours) is
reduced. However, if the microwave heating is applied after the specimen has begun to harden (for instance, 40 minutes), it is suspected that the type of water, which can lose during heating, most likely is the free water that resides in the pores because it is easier to remove than other types of water in the hardened paste. Consequently, the structure of the paste will be more porous, resulting in reduced strength at the early age. Nevertheless, after 24 hours, all of specimens are cured in the water tank so additional water can be supplied to them, leading to further hydration. Thus, their strengths at 7 days can be approximately the same.

The above explanation can be proved easily by extending the delayed time to above 40 minutes and then measuring the strength at early and later ages. The result of the case, whose delayed time is 61 minutes, is also shown in Table 4.9. The result of 61-minute delayed time proves that under microwave heating, its early strength is the same as the strength from the result of 40-minute delayed time, but its later strength is a little less than that of 40-minute delayed time. This is probably due to water bleeding of the specimen, resulting in the ease of water evaporation at the top surface due to microwave heating. As a result, the specimen becomes weaker and the microstructure becomes more porous compared to the specimen with 40-minute delayed time. The strength at the later age therefore reduces.

In this particular heating rate, it is obvious that the most favorable delayed time is 30 minutes. Therefore, it can be concluded that the differences in delayed time can lead to differing in strength at early age (such as, 4.5 hours) due to the developed microstructure of the paste and the types of evaporated water.

**Water/Cement Ratio** It is well known that the amount of water (or w/c ratio), which is one of the parameters, determines the strength of mortar samples. According to Xuequen et al. [1987], water is a dielectric material, which can absorb the microwave energy more than the other constituents of concrete, i.e., cement and sand, because it has higher dielectric constant and higher loss tangent. Consequently, it can evaporate rapidly. For these reasons, it is essential to study the effects of microwave
energy on the compressive strength of mortars due to differing in w/c ratios. In this section mortars, which are heated at 400 watts for 45 minutes, are examined under four w/c ratios: 0.45, 0.50, 0.55, and 0.60.

Table 4.10 and Figures 4.7(a) and (b) show the results of the effects of the microwave heating on the compressive strength of mortar specimens due to different w/c ratios. It is obvious that there is only slight difference in the 4.5-hour strength of specimens with 0.45, 0.50 and 0.55 w/c ratios whereas that of specimens with 0.60 w/c ratio is a little lower. For instance, the 4.5-hour strengths are 2275.3, 2215.4, 2255.5, and 1635.4 psi for 0.45, 0.50, 0.55, and 0.60 w/c ratios, respectively. At later age, it can be seen that the higher the w/c ratio, the higher is the percent of 7-day strength of microwave-heated specimens, which is based on the 7-day strength of normal-cured specimens. For example, using the 7-day strength of normal-cured specimens as the baseline (100%), the 7-day strength of microwave-heated specimens at 0.45, 0.50, 0.55, and 0.60 w/c ratios are 60.1, 70.3, 85.0, and 91.1%, respectively. However, when these 7-day strengths of microwave-heated specimens are expressed in terms of stress, they are only slightly different. They are, for example, 3581.5, 4353.1, 4723.5, and 4481.4 psi for 0.45, 0.50, 0.55, and 0.60 w/c ratios, respectively. It can be explained that for normal-cured specimens, the 7-day strength of higher w/c ratio is less than that of lower w/c ratio because more water results in higher porosity and therefore less strength.

In the study of this parameter, the amount of water (or w/c ratio) is the only factor that affects the strength of the cement paste. From the result in Table 4.8, it is obvious that the optimum w/c ratio of mortar specimens under this heating rate is between 0.50 and 0.55. It can be seen that although the 4.5-hour strengths of specimens with 0.45, 0.50, and 0.55 w/c ratios are in the same range, their 7-day strengths are quite different. This can be explained that the favorable w/c ratio for the early strength (4.5 hours) is between 0.45 and 0.55, but if the initial w/c ratio is low, after heating, there will be less amount of water for specimens to continue further hydration until their water immersion, leaving improper microstructure. It is believed that the microstructure development of cement paste is essentially important
in the early period; therefore, the water immersion of specimens after 24 hours will not significantly help improving the strength. On the other hand, if the initial w/c ratio is high, the early strength will be low whereas the later strength will be high.

It is important to note that under normal curing, the 7-day strength of specimens with 0.45 w/c ratio should not be lower than that of specimens with 0.50 w/c ratio. The reason for this result is that since the workability of 0.45 w/c mortar mixing is worse than that of 0.50 w/c mortar mixing, the structure of the former is therefore more porous, leading to lower strength at later age.

**Effects on the Splitting Tensile Strength**

Besides the compressive strength, the splitting tensile strength is also measured. A limited number of tests are carried out to study the effect of varying power levels at 45 minutes heating time.

**Power Level at 45-Minute Heating Time**  The heating time is fixed at 45 minutes and three different power levels (300, 400, and 500 watts) are used.

Table 4.11, Figures 4.8(a) and (b) illustrate the results of splitting tensile test. At the power level of 300 watts, the splitting tensile strength, compared to the results at the other power levels, is the lowest at the early age (4.5 hours) but becomes the strongest at the later age (7 days). It is actually about 17% higher than the strength at 7 days of normal-cured mortar specimens. At the 400-watt power level, the strength at the early age reaches about 50% of the 7-day normal-cured strength, while at the later age it is not significantly impaired, i.e., it is only 15% less than the 7-day normal-cured strength. For the heating power of 500 watts, the early age strength is about the same as that under 400 watts, but the later age strength is more significantly impaired than that of 400-watt heating, i.e., the strength is as much as 24 percent lower than the normal-cured strength at 7 days.

Although the later age strength at 300-watt heating is the highest among the power levels tested, 300 watts is still not the most desirable power for heating because
of its lowest strength at the early age. Therefore, the most satisfactory power level evaluated at both the early and later ages is 400 watts.

The results are very interesting when compared to the previous results on the compressive strength tested at the same heating rates. For instance, at the 300-watt power level, the results on the splitting tensile strength show improvement in the 7-day strength of the microwave-heated specimens, whereas those on the compressive strength show reduction in the 7-day strength. These can be explained as follows. Unlike conventional heating, where heat transfers through a surface of a material, a microwave heating involves a transfer of microwave energy throughout the body of the wet solid, called volumetric heating [Metaxas, 1991]. This volumetric heating can raise the temperature inside the wet solid to reach the boiling point of the liquid. Consequently, the liquid begins to evaporate by moving from the interior to the surface with a help of the internal pressure built up from the evaporation of the moisture inside the pores of the solid. Therefore, in microwaving of mortar specimens, the inside water tends to move toward the surfaces, but the outside water will evaporate first, leaving the exterior drier and more porous than the interior. The interior of the specimens hence becomes stronger than the exterior. The trend of splitting tensile strength with increasing pores can be explained as follows. Under a suitable heating rate, the interior is cured most effectively and therefore becomes very strong; whereas under an excessive heating rate, the internal pressure can lead to the formation of cracks and pores, leaving both the interior and exterior weak. Since the compressive strength is measured as the strength of the whole specimen, whereas the splitting tensile strength is measured as the tensile-resisted capacity in the middle part of the specimen, the part which provides most of the splitting tensile strength is the middle part, not the exterior. In other words, the exterior plays a minor role in tensile resistance. Therefore, the splitting tensile strength is reduced by a small percentage compared to the compressive strength at the same heating rate.
Effects on the Bond Strength

In pavement repairs, the bond strength between the new and old parts, and the bond strength between the steel bar and the cement paste are both important. Therefore, in this research both types of bond strength are studied.

New and Old Mortars  As mentioned earlier, two tests are used to measure the bond strength: bond splitting tensile test and slant shear test. The surfaces of the specimens used in these experiments are sand-blasted to increase the roughness. The heating rate is set again at 400 watts for 45 minutes. The old part is cured normally and is 14-day old at the testing time; the new part which is heated by microwave is tested at 4.5 hours (early age) and 7 days (later age).

Bond Splitting Tensile Test  The bond splitting tensile testing techniques are developed in this research to compare its results with another bond strength test, i.e., the slant shear test. See chapter 3 for more details.

Table 4.12 compares the bond splitting tensile strength under microwave heating with the result under normal curing. Since the bond strength at the early age is very sensitive to age, two sets of early strength test (at 4.5 hours for the new part) are carried out while the bond strength at the early age for the first set is 50.1 psi or 18.2% of the strength for a normal-cured part at 7-day old (274.8 psi from Table 4.4), and the early strength of the second set is 75.5 psi or 27.5%. At the later age, the strength at 7 days of the new part under microwave heating is 241.2 psi or 87.8% of that under normal curing.

Comparing the microwave heating result in Table 4.12 to the result under normal curing in Table 4.4, it is obvious that microwave heating enhances the bond strength at the early age but only impairs the bond strength at the later age slightly. For instance, with microwave heating, the average 4.5-hour bond strength is 62.8 psi, comparable to the bond strength of specimens under normal curing at 13.5 hours with the strength of 63.9 psi. At the age of 7 days, the bond strength of specimens
under microwave heating is 241.2 psi which is 87.8% of the bond strength under normal curing at the same age (274.8 psi).

**Slant Shear Test** According to Alexander et al. [1968] and Wall et al [1986], the slant shear test is more sensitive and more reliable than other bond strength tests (i.e., flexural tests with bond planes at 45° and 60° relative to the horizontal, and indirect tensile test). Thus, it is also used in this research to measure the bond strength of mortars.

Table 4.13 shows the slant shear bond strength of mortar specimens under microwave heating in comparison with the strength of normal-cured specimens at 7 days. At the early age of 4.5 hours, the results show similar trend to those from the bond splitting tensile test; that is the microwave energy enhances the bond strength. However, the measured bond strength under microwave heating at the later age (7 days) is much more severely impaired than that from the bond splitting tensile test. At 4.5 hours the average slant shear bond strength under microwave heating is 596.7 psi, which is nearly twice the strength under normal curing at 13.5 hours (265.1 psi from Table 4.5). However, at 7 days, the bond strength under the microwave heating (1462.4 psi) is only 50% of that under normal curing (2943.3 psi). This indicates that the later bond strength is substantially reduced by the microwave energy. It is important to note that since slant shear specimens and bond splitting tensile specimens are heated at the same time, the effect of larger sizes of the slant shear specimens results in higher absorption of microwave energy, causing bond strength reduce significantly.

**Mortar and Steel Bar** One of the major concerns in pavement repairs using the microwave energy is the interaction of microwave with reinforcing steel (i.e., Would it absorb the microwave energy and become hot? Would it spark and damage the bond between itself and the paste?). It is definitely necessary to test the effect of microwave heating on steel. According to Martin Yannone, a research and development manager at Cober Electronics Inc., the company which built the microwave oven used in this study, a steel bar can absorb the microwave energy and gets heated up easily if its
diameter is roughly less than 1/8 inch. With a small bar, microwave can induce a high voltage on its surface and ultimately heat it up. However, the size of the steel bar in pavements is usually larger than 1/8 inch in diameter.

In this research, to measure how well the cement paste in a specimen is bonded to an embedded steel bar, the direct tensile test and the pull-out test are used. Although the direct tensile test has no standard procedure, it can still be used here to compare the results under microwave heating with those under normal curing.

**Direct Tensile Test** In this test, the heating power is 400 watts and the heating duration is 45 minutes.

It is noted that bond strength between steel bar and the mortar paste from this test cannot be achieved since failure does not occur at the interface of the steel bar and the paste, but at the interface of the mortar paste and the epoxy. This is probably due to the fact that each end of specimen is weak, especially the end of the microwave-cured part. It can be explained further that during microwave heating, the exterior or the top surface of the microwave-cured part is the weakest part of the specimen so the failure is at the interface of mortar and epoxy.

**Pull-Out Test** In this test, the bond strength (or the pull-out strength) between the steel bar and the mortar paste is of interest. In the direct tensile test, failure at the mortar and epoxy interface may also be due to a weak mortar phase produced by too high a microwave power. Therefore, the heating rate used in this test is reduced to 300-watt heating for 45 minutes.

Table 4.14 shows the results of the pull-out test. At 1 day, the bond strength between the steel bar and the microwave-heated mortar paste is only 77% of that between the steel bar and the normal-cured mortar paste. Therefore, it is clear that under accelerated curing by the microwave curing method, the early (1 day) bond strength between the bar and the paste is reduced by as high as 23% compared with the bond strength at normal curing.

With high pressure steam curing [Mindess et al., 1981], the bond strength between
the steel bar can be reduced by as much as 50%, it is therefore clear that the microwave
curing method is better than the steam curing method as far as bond strength is
concerned.

4.3.2 Concrete Specimens

After the effects of the microwave energy on the compressive strength of mortar have
been studied, it is useful to examine further how microwaved-cured concrete specimens
perform as concrete is used more widely than mortar in practice.

Effects on the Compressive Strength

The effects of microwave heating on the compressive strength of concrete are studied
through two parameters, namely, the power level at 45-minute heating time and the
w/c ratio.

Power Level at 45-Minute Heating Time  In this study, the heating duration is
fixed at 45 minutes so that the results can be compared to those of mortar specimens.
The power levels, however, are limited to be between 300 and 450 watts, which is
the optimal range of mortar results based on the performances of the early and later
strength. Four power levels are examined: 300, 350, 400, and 450 watts.

Table 4.15 and Figures 4.9(a) and (b) show the results of the effects of different
microwave power levels at a 45-minute heating duration on the compressive strength
of concrete specimens. It is clear that as the power level is increased between 300 and
450 watts, the 4.5-hour strength also increases, whereas the 7-day strength decreases.
However, comparing with the 7-day strength of specimens under normal curing, the
7-day strength of specimens heated at 300, 350, 400, and 450 watts is as high as 93.5,
105.3, 79.2, and 81.6%, respectively. From the results both at 4.5 hours and 7 days, it
is obvious that the 450-watt microwave heating is the most desirable power level for a
45-minute heating duration for concrete with 0.50 w/c ratio. For example, using the
7-day strength of specimens under normal curing as the baseline (100%), the 4.5-hour strength and 7-day strength of specimens heated at 450 watts are 2889.6 psi (49.0%) and 4819.4 psi (81.6%), respectively.

The explanation for the effects of different microwave power levels at a 45-minute heating duration on the compressive strength of concrete specimens is the same as that given in the earlier section of this chapter for the mortar specimens. Nevertheless, from the results in Tables 4.8 and 4.15, the overall performances of concrete specimens (i.e., both the early and later strength) under microwave curing is much better than those of mortar specimens. At a 400-watt heating, for example, the 4.5-hour strength and the 7-day strength of 0.50 w/c concrete specimens are 2671.2 and 4806.7 psi, respectively, and they are 2215.4 and 4353.1 psi for 0.50 w/c mortar specimens. It is believed that the difference in their performances is due to the presence of aggregates. On heating, the expansion of water vapor in mortar may lead to the formations of pores and cracks, while in concrete, the aggregates restrain the expansion of water and may reduce the number and size of cracks and pores.

The measured 1-day and 28-day strength of concrete and mortar specimens heated at 400 watts for 45 minutes (shown in Table 4.16) is used to support the above explanation. Using the 28-day strength of normal-cured mortar specimens as the baseline (100%), the 1-day and 28-day strength of the microwave-heated mortar specimens are 47.56% (3218.5 psi) and 61.11% (413\text{F}.7 psi), respectively. For the concrete specimens, under the heating the 1-day and 28-day strength are 60.64% (4031.9 psi) and 87.80% (5838.0 psi), respectively, based on the 7-day strength of normal-cured specimens as 100%. It is obvious that although the mortar specimen is immersed in the water tank after 24 hours until tested, the strength development is very slow because it is believed that its microstructure is porous. Therefore, it can be concluded that with the presence of aggregates, the strength performance is improved due to the action of aggregate which may restrain the expansions of air and water due to the heating, resulting in reduction of the number and size of cracks and pores.
**Water/Cement Ratio** Five w/c ratios are used: 0.40, 0.45, 0.50, 0.55, and 0.60. The heating rate is 400 watts for 45 minutes, exactly the same as before.

Table 4.17 and Figures 4.10(a) and (b) show the compressive strength at both the early and later ages of the concrete specimens with different w/c ratios under microwave heating and normal curing. From the results, the optimal w/c ratio of a 400-watt microwave heating with a 45-minute heating duration of concrete specimens is at 0.40. For example, at 4.5 hours, the strength is as high as 3947.0 psi and the 7-day strength is 4944.4 psi. In addition, from the results of the cases with 0.45 and 0.50 w/c ratios, there are only minor differences in the strength both at the early and later ages. For example, while the early-age strength with 0.45 w/c is 2891.9 psi, the early-age strength with 0.50 w/c is 2671.2 psi. At the later age, the strength with 0.45 w/c is 4958.8 psi, compared with 4806.7 psi for 0.50 w/c. However, for the 0.55 w/c case, the early strength is about the same as in the 0.45 and 0.50 w/c cases, i.e., 2785.9 psi, but the later strength is somewhat higher, i.e., 5416.7 psi.

The strength at 7 days under normal curing for the 0.40 w/c ratio is 6536.0 psi. For the 0.45, 0.50, 0.55 and 0.60 w/c ratios, they are 6241.8, 6067.9, 5302.4, and 4812.4 psi, respectively. It is obvious that in the 0.55 w/c case, the later strength under microwave curing is greater than that under normal curing and if the w/c ratio is increased to 0.60, the later strength under microwave curing is again lower than that under normal curing. Therefore, it can be concluded that the maximum w/c ratio that provides high both early and later strength is 0.55 while its maximum can be as low as 0.40. In other words, the range of optimum w/c ratio to gain high early and later strength is between 0.40 and 0.55.

The explanation for the effects of the microwave energy on the compressive strength of concrete specimens with different w/c ratio is the same as that for the case of mortar specimens and will not be reported here.
4.4 Microstructural Characterization

A simple way to study the dimensional arrangement of the hydration products is to examine the fractured surface of the specimens. For young samples, the fractured path is intergranular so the fractured surface represents the outer surface of the grains of hydration products. In contrast, the fractured surface of the old paste is along the weak plane of the specimens, which appears to be along the surface of massive calcium hydroxide crystals and then transgranular into the other hydration products. Therefore, this surface does not represent the actual microstructure of the whole paste [Scrivener, 1989]. With this problem, it becomes very difficult to interpret the electron micrographs of the cement paste. Nevertheless, the microstructural study is still important in comparing the development of microstructure under microwave heating to that under normal curing at several ages.

Electron microscopes are used as tools to examine the microstructure of the samples during the hydration of the cement paste. Two types of electron microscopes are used: the scanning electron microscope (SEM) and the environmental scanning electron microscope (ESEM). The major difference between samples for the SEM and those for ESEM is the allowable state of the samples. A sample for the SEM has to be free of water and coated with conductive materials (e.g., gold or carbon), whereas a sample for the ESEM is permitted to be in either wet or dry state. For this reason, the ESEM is very valuable in studying early cement hydration; however, the images are not as sharp at higher magnification powers in comparison to those viewed by the SEM. Therefore, in this study the SEM is mainly used to examine the microstructure, but some ESEM micrographs are also included.

4.4.1 Scanning Electron Microscope with an X-Ray Analyzer

In this work, with the help of the scanning electron microscope and X-ray analyzer, the differences in microstructures of specimens cured normally and of specimens heated by the microwave at several ages can be obtained. It is important to note that the
age of each specimen is counted from the time at which the water is mixed with the
cement and ends at the point when it is allowed to dry in a conventional oven. Each
specimen is examined through its fractured surface.

Observations of Normal-cured Specimens:

In this study, the samples are examined at the ages between 4 hours and 24 hours.
Mortar specimens with 0.50 w/c and concrete specimens with 0.40 w/c are used to
prepare samples for the examination.

The scanning electron micrographs of mortar samples with 0.50 w/c ratio at 4
and 4.5 hours shows that there is little formation of C-S-H, which has a fibrillar
morphology, on the surface of the cement grains (Figures 4.11(a) and (b)); therefore,
little bonding of the cement grains has occurred at this stage. Some short rods of AFt
(etrtringite or calcium aluminum trisulfate) and some large plates of AFm (calcium
aluminum monosulfate) can be seen on the fractured surface (Figure 4.11(c)). In
addition, due to drying, small crystals of gypsum (or calcium sulfate) can be seen as
small white crystals on the surface of larger anhydrous cement grains (Figures 4.11(d)
and (e)). These micrographs agree well with the experimental work that due to low
bonding between the cement grains and highly porous microstructure, the compressive
strength cannot be measured at this age. However, the overall microstructure of the
samples at 6 hours seems to have developed more bonding (less porous) than that
of the samples at 4.5 hours. There are a lot of needlelike AFt and platelike crystals
of AFm formed on the fractured surface (Figures 4.12(a) and (b)). At 12 hours, the
microstructure tends to be denser, but develops to be an essentially layered structure
(Figures 4.13 (a), (b), (c), and (d)). This is due to the rapid growth of both C-S-H
and AFt on the surface of the cement grains (Figures 4.13 (e), (f), and (g)).

For the case of 0.40 w/c ratio concrete samples, the micrographs show that at
4.5 hours, the gelatinous layer and some short rods of AFt are collapsed back to the
surface of the cement grains due to drying (see Figure 4.14(a)) as also indicated by
Scrivener (1989). The C-S-H products, AFt rods, and AFm plates can be seen easily
on the fractured surface (Figures 4.14(b), (c), and (d). Comparing the micrographs
at 4.5 hours of the concrete with 0.40 w/c (Figure 4.14(e) and (f)) to those at 4.5 hours of the mortar with 0.50 w/c (Figure 4.11(d) and (e)), it becomes clear that the microstructure of the former is denser than the latter; hence, the compressive strength of the former can be obtained (i.e., 101.2 psi) whereas the compressive strength of the latter cannot be measured since it is still in a half solid and plastic state. Although the layered structure of the concrete sample at 4.5 hours (Figure 4.14(g)) looks similar to that of the mortar sample at 12 hours (Figure 4.13(b), (c), and (d)), the structure in the latter has more bondings and is probably more well developed. Therefore, the strength of the latter is greater than that of the former. At the age of 24 hours, the growth of C-S-H and AFt rods increase to fill up the spaces (Figure 4.15(a)); hence, the strength at this age increases significantly compared to the strength at 4.5 hours. Figures 4.15(b) and (c) show the formation of C-S-H along with some AFt rods, covered by the unknown massive crystals, which are believed to be crystals of calcium hydroxide, which usually form at the interface zone between aggregates and the paste.

Observations of Microwave-heated specimens:

Under microwave heating, the microstructures of mortar with 0.50 w/c and concrete with 0.40 w/c are examined at the ages between 4 and 24 hours. These samples are heated at 400 watts for 45 minutes.

For the case of mortar sample, at 4 hours, some AFm plates are clearly distinguishable from the paste (Figures 4.16(a) and (b)) and massive crystals of calcium hydroxide can also be seen easily on the fractured surface (Figures 4.16(c) and (d)). The growth of C-S-H is rapid as it can be seen from Figures 4.16(c) and (f), resulting in a high gain of early strength. At 4.5 hours, the structure becomes denser and crystals of AFt, AFm, and calcium hydroxide can be seen around the C-S-H (Figures 4.17(a) and (b)). The growth of C-S-H can be seen again in Figures 4.17(c) and (d). From Figures 4.17(e) and (f), the hydration products begin to fill up the pore spaces. At the age of 6 hours, there is more bonding of C-S-H between cement grains (Figures 4.18(a) and (b)); the C-S-H and small AFt rods are filling up more of the pore.
spaces. Furthermore, the micrographs at 12-hour age show that the microstructure has developed even more as shown in Figures 4.19(a), (b), and (c). The AFm plates can also be seen in Figure 4.19(a).

At the age of 4.5 hours, the microstructure for the concrete sample with 0.40 w/c is denser than that of mortar with 0.50 w/c at the same age. Some AFt rods can also be seen on the fractured surface (Figures 4.20(a)). In addition, Figures 4.20(b) and (c) show that there are formations of large AFm plates on the fractured surface. It is again believed that some AFt and AFm crystals shrink back to the surface of the grains due to drying as seen in Figures 4.20(d) and (e). From Figures 4.20(f) and (g), the fibrillar C-S-H can be seen. At 24 hours, small rods of AFt appear on the surface of the grain (Figure 4.21(a)). The microstructure looks quite porous in Figures 4.21(b) and (c). Figure 4.21(d) illustrates a big pore with some anhydrous cement grain inside. It may be the case that upon the heating, the internal vapor pressure is built up and rupture the bond of the materials, and water then evaporates away. This may explain the decrease in later strength of microwave-cured concrete compared with normal-cured concrete. Such pores are likely to be also parts in mortar specimens although they are not observed in this investigation.

Summary:

To conclude, at the early age, the microstructure of samples under microwave curing is clearly distinct from that of the samples under normal curing. The former has denser structure than the latter due to the effect of microwave energy in accelerating the cement hydration; therefore, the C-S-H forms more rapidly, resulting in more bonding between cement grains and higher early strength. For samples at the later age, it is very difficult to compare their microstructures. However, it is believed that the effect of porosity and non-uniform hydration products dominates the later strength.
4.4.2 Environmental Scanning Electron Microscope

The observations of mortar samples with 0.50 w/c under normal curing and microwave curing are carried out at the ages between 0.5 and 3.5 hours. The microwave power is kept at 400 watts for 45 minutes. The microstructure of samples under microwave curing is examined to compare with that of samples under normal curing.

For normal-cured sample, at 30 and 60 minutes, many short rods of AFt are seen clearly on the cement grains (Figures 4.22(a) and (b)). It becomes clear that at 2 and 2.5 hours, there is little formation of C-S-H, and the microstructure looks porous (Figures 4.22(c) and (d)).

For sample under microwave heating, at the age between 2.5 and 3.5 hours, there are many long rods of AFt formed on the fractured surface (Figures 4.23(a), (b), (c) and (d)). This observation agrees well with the result of the microwave cured sample examined under the SEM. Additionally, the microstructure of sample under microwave curing is denser than that of sample under normal curing at the same age.

To compare the microstructure at the early age of the samples under microwave curing and that of samples under normal curing, it is obvious that the microstructure of the former has developed more rapidly than the latter, and many long rods of AFt appear on the fractured surface of the former, but many short rods of AFt on the surface of the latter. Under normal curing, short rods of AFt form due to the first reaction of some $C_3A$ and calcium sulfate at the very early time after mixing (i.e., 10 minutes), whereas long rods of AFt form at about 18 hours due to the secondary hydration of $C_3A$ [Scrivener, 1989]. Therefore, from the appearance of long rods of AFt at an age of 4.5 hours as well as a denser microstructure of the sample, it can be concluded that the microwave energy enhances the cement hydration.
4.5 Comparison with Rapid Hardening Materials used in Practice

This section compares both early and later strength obtained in this study to those obtained by using more expensive rapid hardening material (i.e., Rapid Set Cement) and to those obtained by adding an accelerator to Type III Portland cement to enhance the rate of strength gain.

Firstly, Rapid Set Cement is manufactured by Rapid Set Products company. The company has claimed that the product can reach a compressive strength of 2,000 psi or more in one hour and is ready for use. In this comparison, tests on compressive strength of Rapid Set concrete were carried out by H.H. Holmes Testing Laboratories, Inc. in Illinois. The mix proportion is shown in Table 4.18. Their results and the results from this research are compared in Table 4.19. It is obvious that our results are comparable to their results at both early and later age. It is noted that their strength development at later age is quite low when compared to ours.

Secondly, our results are compared with the results obtained by using a "nonchloride" accelerator with Type III Portland cement called "rapid-setting Portland Cement Concrete." The mix proportions are compared and illustrated in Table 4.20. Figures 4.24(a) and (b) compare their strength at early and later ages, respectively. It is obvious that our result on 0.40 w/c microwave-cured concrete at early age is superior to their results at the same age. Moreover, at later age, the strength development trends of 0.50 w/c microwave-cured concrete and rapid-setting PCC are similar.

To conclude, the performances (i.e., compressive strength at various ages) of microwave-cured concrete are comparable to those of rapid set concrete and concrete mixed with the accelerator.
Table 4.1: The development of Modulus of elasticity of mortar specimens under normal curing

<table>
<thead>
<tr>
<th>Age (hrs)</th>
<th>Young's Modulus (ksi)</th>
<th>14-day Young's Modulus (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5</td>
<td>415.5</td>
<td>11.5</td>
</tr>
<tr>
<td>12.5</td>
<td>1206.9</td>
<td>33.5</td>
</tr>
<tr>
<td>24.5</td>
<td>2281.6</td>
<td>63.4</td>
</tr>
<tr>
<td>72.0</td>
<td>3121.5</td>
<td>86.7</td>
</tr>
<tr>
<td>168.0</td>
<td>3478.5</td>
<td>96.6</td>
</tr>
<tr>
<td>336.0</td>
<td>3600.2</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table 4.2: The development of compressive strength of mortar specimens under normal curing

<table>
<thead>
<tr>
<th>Age (hrs)</th>
<th>Compressive Strength (psi)</th>
<th>14-day Compressive Strength (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5</td>
<td>282.8</td>
<td>4.1</td>
</tr>
<tr>
<td>12.5</td>
<td>1139.1</td>
<td>17.6</td>
</tr>
<tr>
<td>24.5</td>
<td>3178.2</td>
<td>49.1</td>
</tr>
<tr>
<td>72.0</td>
<td>4988.3</td>
<td>76.8</td>
</tr>
<tr>
<td>168.0</td>
<td>5809.5</td>
<td>89.8</td>
</tr>
<tr>
<td>336.0</td>
<td>6487.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Table 4.3: The development of splitting tensile strength of mortar specimens under normal curing

<table>
<thead>
<tr>
<th>Age (hrs)</th>
<th>Splitting Tensile Strength (psi)</th>
<th>14-day Tensile Strength (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5</td>
<td>34.6</td>
<td>16.9</td>
</tr>
<tr>
<td>12.5</td>
<td>343.0</td>
<td>64.3</td>
</tr>
<tr>
<td>24.5</td>
<td>373.2</td>
<td>69.9</td>
</tr>
<tr>
<td>72.0</td>
<td>409.2</td>
<td>76.7</td>
</tr>
<tr>
<td>168.0</td>
<td>522.6</td>
<td>97.9</td>
</tr>
<tr>
<td>336.0</td>
<td>533.6</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table 4.4: The development of bond splitting tensile strength of mortar specimens under normal curing

<table>
<thead>
<tr>
<th>Age of NC New Part (hour)</th>
<th>Bond Splitting Tensile Strength (psi)</th>
<th>7-day NC Bond Tensile Strength (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5</td>
<td>11.1</td>
<td>4.0</td>
</tr>
<tr>
<td>13.5</td>
<td>63.9</td>
<td>23.3</td>
</tr>
<tr>
<td>25.5</td>
<td>109.9</td>
<td>40.0</td>
</tr>
<tr>
<td>72.0</td>
<td>202.8</td>
<td>73.8</td>
</tr>
<tr>
<td>168.0</td>
<td>274.8</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Note: NC represents normal curing.
Table 4.5: The development of bond slant shear strength of mortar specimens under normal curing

<table>
<thead>
<tr>
<th>Age of NC New Part (hour)</th>
<th>Bond Slant Shear Strength (psi)</th>
<th>7-day NC Bond Shear Strength (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5</td>
<td>65.6</td>
<td>2.2</td>
</tr>
<tr>
<td>13.5</td>
<td>265.1</td>
<td>9.0</td>
</tr>
<tr>
<td>25.5</td>
<td>1153.9</td>
<td>39.2</td>
</tr>
<tr>
<td>72.0</td>
<td>2072.6</td>
<td>70.4</td>
</tr>
<tr>
<td>168.0</td>
<td>2943.3</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Note: NC represents normal curing.
Table 4.6: Results of the effect of heating rates at the same energy input level on the compressive strength (at 3 hours and 7 days) of mortar specimens under microwave curing

<table>
<thead>
<tr>
<th>Power Level (watt)</th>
<th>Heating Time (minute)</th>
<th>Loss of Water during MCWH (g)</th>
<th>W/C Ratio after MCWH by Wt</th>
<th>Microwave Heating</th>
<th>Normal Curing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 Hours After Mixing</td>
<td>7 Days After Mixing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Compr. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
</tr>
<tr>
<td>200</td>
<td>90.00</td>
<td>16.83</td>
<td>0.461</td>
<td>117.8</td>
<td>2.0</td>
</tr>
<tr>
<td>300</td>
<td>60.00</td>
<td>16.50</td>
<td>0.461</td>
<td>181.8</td>
<td>3.1</td>
</tr>
<tr>
<td>400</td>
<td>45.00</td>
<td>14.50</td>
<td>0.466</td>
<td>222.9</td>
<td>3.7</td>
</tr>
<tr>
<td>500</td>
<td>36.00</td>
<td>14.17</td>
<td>0.467</td>
<td>323.4</td>
<td>6.4</td>
</tr>
<tr>
<td>600</td>
<td>30.00</td>
<td>14.50</td>
<td>0.466</td>
<td>267.8</td>
<td>4.5</td>
</tr>
<tr>
<td>700</td>
<td>25.71</td>
<td>15.67</td>
<td>0.463</td>
<td>318.5</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Note: MCWH represents microwave heating. NC represents normal curing.

Table 4.7: Results of the effect of power levels at a heating duration of 45 minutes on the compressive strength (at 3 hours and 7 days) of mortar specimens under microwave curing

<table>
<thead>
<tr>
<th>Power Level (watt)</th>
<th>Wt of Spec. before MCWH (g)</th>
<th>Loss of Water during MCWH (g)</th>
<th>W/C Ratio after MCWH by Wt</th>
<th>Microwave Heating</th>
<th>Normal Curing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 Hours After Mixing</td>
<td>7 Days After Mixing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Compr. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
</tr>
<tr>
<td>300*</td>
<td>1476.8</td>
<td>10.17</td>
<td>0.466</td>
<td>88.5</td>
<td>1.5</td>
</tr>
<tr>
<td>400</td>
<td>1483.3</td>
<td>14.50</td>
<td>0.466</td>
<td>222.9</td>
<td>3.7</td>
</tr>
<tr>
<td>500</td>
<td>1460.3</td>
<td>19.83</td>
<td>0.453</td>
<td>442.0</td>
<td>7.2</td>
</tr>
<tr>
<td>600</td>
<td>1460.3</td>
<td>30.00</td>
<td>0.428</td>
<td>807.8</td>
<td>13.2</td>
</tr>
</tbody>
</table>

Note: * no records on weights of specimens before and after microwave heating. MCWH represents microwave heating. NC represents normal curing.
Table 4.8: Results of the effect of power levels at a heating duration of 45 minutes on the compressive strength (at 4.5 hours and 7 days) of mortar specimens under microwave curing

<table>
<thead>
<tr>
<th>Power Level (watt)</th>
<th>Wt of Spec Before MCWH (g)</th>
<th>Loss of Water during MCWH (g)</th>
<th>W/C Ratio after MCWH by Wt</th>
<th>Microwave Heating 4.5 Hrs After Mixing</th>
<th>7 Days After Mixing</th>
<th>Normal Curing 7 Days After Mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compr. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
<td>Compr. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
<td>Compr. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
</tr>
<tr>
<td>300</td>
<td>919.1</td>
<td>15.5</td>
<td>5330.9</td>
<td>89.9</td>
<td>5928.6</td>
<td>100.0</td>
</tr>
<tr>
<td>350</td>
<td>1357.2</td>
<td>23.5</td>
<td>4660.9</td>
<td>80.7</td>
<td>5772.2</td>
<td>100.0</td>
</tr>
<tr>
<td>400</td>
<td>2215.4</td>
<td>36.8</td>
<td>4353.1</td>
<td>70.3</td>
<td>6193.1</td>
<td>100.0</td>
</tr>
<tr>
<td>450</td>
<td>1782.5</td>
<td>30.5</td>
<td>2235.2</td>
<td>38.3</td>
<td>5842.8</td>
<td>100.0</td>
</tr>
<tr>
<td>500</td>
<td>2449.2</td>
<td>39.0</td>
<td>2762.2</td>
<td>43.9</td>
<td>6286.4</td>
<td>100.0</td>
</tr>
<tr>
<td>600</td>
<td>1572.2</td>
<td>24.9</td>
<td>2063.8</td>
<td>32.7</td>
<td>6320.9</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Note: MCWH represents microwave heating. NC represents normal curing.

Table 4.9: Results of the effect of delayed times for a heating rate of 400 watts and 45 minutes on the compressive strength (at 4.5 hours and 7 days) of mortar specimens under microwave curing

<table>
<thead>
<tr>
<th>Delay Time (min)</th>
<th>Wt of Spec Before MCWH (g)</th>
<th>Loss of Water during MCWH (g)</th>
<th>W/C Ratio after MCWH by Wt</th>
<th>Microwave Heating 4.5 Hrs After Mixing</th>
<th>7 Days After Mixing</th>
<th>Normal Curing 7 Days After Mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compr. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
<td>Compr. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
<td>Compr. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
</tr>
<tr>
<td>20</td>
<td>814.4</td>
<td>12.5</td>
<td>4537.5</td>
<td>69.5</td>
<td>6525.9</td>
<td>100.0</td>
</tr>
<tr>
<td>30</td>
<td>2215.4</td>
<td>35.8</td>
<td>4353.1</td>
<td>70.3</td>
<td>6193.1</td>
<td>100.0</td>
</tr>
<tr>
<td>40</td>
<td>1870.1</td>
<td>24.7</td>
<td>4496.8</td>
<td>66.4</td>
<td>6789.2</td>
<td>100.0</td>
</tr>
<tr>
<td>61</td>
<td>1645.8</td>
<td>29.3</td>
<td>3400.3</td>
<td>60.5</td>
<td>5621.7</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Note: MCWH represents microwave heating. NC represents normal curing.
Table 4.10: Results of the effect of water/cement ratios for a heating rate of 400 watts and 45 minutes on the compressive strength (at 4.5 hours and 7 days) of mortar specimens under microwave curing

<table>
<thead>
<tr>
<th>W/C Ratio before MCWH by Wt</th>
<th>Wt of Spec before MCWH (g)</th>
<th>Loss of Water during MCWH (g)</th>
<th>W/C Ratio after MCWH by Wt</th>
<th>Microwave Heating</th>
<th>Normal Curing</th>
<th>7 Days After Mixing</th>
<th>7-day NC Comp. Str (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>1478.8</td>
<td>13.40</td>
<td>0.419</td>
<td>2275.3</td>
<td>38.2</td>
<td>3581.5</td>
<td>60.1</td>
</tr>
<tr>
<td>0.50</td>
<td>1500.0</td>
<td>13.83</td>
<td>0.468</td>
<td>2215.4</td>
<td>36.8</td>
<td>4353.1</td>
<td>70.3</td>
</tr>
<tr>
<td>0.55</td>
<td>1481.2</td>
<td>14.17</td>
<td>0.516</td>
<td>2255.5</td>
<td>40.8</td>
<td>4723.5</td>
<td>85.0</td>
</tr>
<tr>
<td>0.60</td>
<td>1476.7</td>
<td>16.00</td>
<td>0.561</td>
<td>1635.4</td>
<td>33.2</td>
<td>4481.4</td>
<td>91.1</td>
</tr>
</tbody>
</table>

Note: MCWH represents microwave heating. NC represents normal curing.

Table 4.11: Results of the effect of power levels at a heating duration of 45 minutes on the splitting tensile strength (at 4.5 hours and 7 days) of mortar specimens under microwave curing

<table>
<thead>
<tr>
<th>Power Level (watt)</th>
<th>Wt of Spec before MCWH (g)</th>
<th>Loss of Water during MCWH (g)</th>
<th>W/C Ratio after MCWH by Wt</th>
<th>Microwave Heating</th>
<th>Normal Curing</th>
<th>7 Days After Mixing</th>
<th>7-day NC Comp. Str (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1502.3</td>
<td>10.83</td>
<td>0.475</td>
<td>132.6</td>
<td>28.6</td>
<td>541.3</td>
<td>116.7</td>
</tr>
<tr>
<td>400</td>
<td>1509.5</td>
<td>16.33</td>
<td>0.462</td>
<td>231.4</td>
<td>50.2</td>
<td>392.8</td>
<td>85.2</td>
</tr>
<tr>
<td>500</td>
<td>1491.3</td>
<td>20.17</td>
<td>0.453</td>
<td>245.4</td>
<td>60.8</td>
<td>389.9</td>
<td>76.6</td>
</tr>
</tbody>
</table>

Note: MCWH represents microwave heating. NC represents normal curing.
Table 4.12: Results of the effect of microwave curing for a heating rate of 400 watts and 45 minutes on the bond splitting tensile strength (at 4.5 hours and 7 days) of mortar specimens

<table>
<thead>
<tr>
<th>Age of MCWH Part (hour)</th>
<th>Wt of Spec before MCWH (g)</th>
<th>Loss of Water during MCWH (g)</th>
<th>W/C Ratio after MCWH by Wt</th>
<th>MCW Heating Bond Tensile Strength (psi)</th>
<th>7-day NC Bond Ten. Str (%)</th>
<th>Normal Curing Bond Tensile Strength (psi)</th>
<th>7-day NC Bond Ten. Str (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>767.3</td>
<td>7.00</td>
<td>0.468</td>
<td>50.1</td>
<td>18.2</td>
<td>274.8</td>
<td>100.0</td>
</tr>
<tr>
<td>4.5</td>
<td>773.7</td>
<td>8.00</td>
<td>0.464</td>
<td>75.5</td>
<td>27.5</td>
<td>274.8</td>
<td>100.0</td>
</tr>
<tr>
<td>168.0</td>
<td>787.3</td>
<td>7.33</td>
<td>0.467</td>
<td>241.2</td>
<td>87.8</td>
<td>274.8</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Note: MCWH represents microwave heating. NC represents normal curing.

Table 4.13: Results of the effect of microwave curing for a heating rate of 400 watts and 45 minutes on the slant shear bond strength (at 4.5 hours and 7 days) of mortar specimens

<table>
<thead>
<tr>
<th>Age of MCWH Part (hour)</th>
<th>Wt of Spec before MCWH (g)</th>
<th>Loss of Water during MCWH (g)</th>
<th>W/C Ratio after MCWH by Wt</th>
<th>MCW Heating Bond Shear Strength (psi)</th>
<th>7-day NC Bond Shear Str (%)</th>
<th>Normal Curing Bond Shear Strength (psi)</th>
<th>7-day NC Bond Shear Str (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>1048.7</td>
<td>16.00</td>
<td>0.447</td>
<td>561.9</td>
<td>19.1</td>
<td>2943.3</td>
<td>100.0</td>
</tr>
<tr>
<td>4.5</td>
<td>1071.0</td>
<td>16.00</td>
<td>0.448</td>
<td>831.4</td>
<td>21.5</td>
<td>2943.3</td>
<td>100.0</td>
</tr>
<tr>
<td>168.0</td>
<td>1004.0</td>
<td>14.00</td>
<td>0.451</td>
<td>1482.4</td>
<td>49.7</td>
<td>2943.3</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Note: MCWH represents microwave heating. NC represents normal curing.
Table 4.14: Results of the effect of microwave curing for a heating rate of 300 watts and 45 minutes on the pull-out bond strength (at 1 day) of mortar specimens

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Embedded Length of 0.50&quot;dia steel bar (in)</th>
<th>Maximum Load (lbs)</th>
<th>Pull-out Strength (psi)</th>
<th>1-day Normal-Cured Pull-out Strength (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 day Microwave Curing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.19</td>
<td>890</td>
<td>477.13</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.63</td>
<td>1075</td>
<td>421.15</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.81</td>
<td>1355</td>
<td>475.93</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.28</td>
<td>975</td>
<td>484.45</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2.50</td>
<td>1475</td>
<td>375.61</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>=</strong></td>
<td><strong>446.85</strong></td>
<td><strong>=</strong></td>
<td><strong>77.14%</strong></td>
</tr>
<tr>
<td><strong>1 day Normal Curing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.19</td>
<td>1105</td>
<td>592.39</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.38</td>
<td>1245</td>
<td>576.43</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.94</td>
<td>1640</td>
<td>538.87</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1.75</td>
<td>1675</td>
<td>609.34</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>=</strong></td>
<td><strong>579.26</strong></td>
<td><strong>=</strong></td>
<td><strong>100.00%</strong></td>
</tr>
</tbody>
</table>

Table 4.15: Results of the effect of power levels at a heating duration of 45 minutes on the compressive strength (at 4.5 hours and 7 days) of concrete specimens under microwave curing

<table>
<thead>
<tr>
<th>Power Level (watt)</th>
<th>Wt of Spec. Before MCWH (g)</th>
<th>Loss of Water during MCWH (g)</th>
<th>W/C Ratio after MCWH by Wt</th>
<th>Microwave Heating</th>
<th>Normal Curing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.5 Hrs After Mixing</td>
<td>7 Days After Mixing</td>
<td>Comp. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
<td>Compr. Strength (psi)</td>
</tr>
<tr>
<td></td>
<td>Compr. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
<td>Compr. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>1539.8</td>
<td>11.67</td>
<td>0.470</td>
<td>1131.8</td>
<td>18.7</td>
</tr>
<tr>
<td>350</td>
<td>1573.2</td>
<td>13.33</td>
<td>0.466</td>
<td>1526.0</td>
<td>28.4</td>
</tr>
<tr>
<td>400</td>
<td>1559.3</td>
<td>14.83</td>
<td>0.482</td>
<td>2671.2</td>
<td>44.0</td>
</tr>
<tr>
<td>450</td>
<td>1570.7</td>
<td>17.67</td>
<td>0.455</td>
<td>2899.6</td>
<td>49.0</td>
</tr>
</tbody>
</table>

Note: MCWH represents microwave heating. NC represents normal curing.
Table 4.16: Results of the effect of power levels for a heating rate of 400 watts at and 45 minutes on the compressive strength (at 1 and 28 days) of mortar and concrete specimens under microwave curing

<table>
<thead>
<tr>
<th>Type of Spec.</th>
<th>Wt of Spec. Before MCWH (g)</th>
<th>Loss of Water during MCWH (g)</th>
<th>W/C Ratio after MCWH by Wt</th>
<th>Microwave Heating</th>
<th>Normal Curing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 day After Mixing</td>
<td>Normal Curing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28 days After Mixing</td>
<td>28 days After Mixing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28 days After Mixing</td>
<td>28-day NC Comp. Str (%)</td>
</tr>
<tr>
<td>Mortar Conc.</td>
<td>1495.5</td>
<td>17.17</td>
<td>0.457</td>
<td>3218.5</td>
<td>47.6</td>
</tr>
<tr>
<td></td>
<td>1603.0</td>
<td></td>
<td></td>
<td>4031.9</td>
<td>60.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4135.7</td>
<td>61.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5838.0</td>
<td>87.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6767.6</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6649.1</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Note: MCWH represents microwave heating.
NC represents normal curing.

Table 4.17: Results of the effect of water/cement ratios for a heating rate of 400 watts and 45 minutes on the compressive strength (at 4.5 hours and 7 days) of concrete specimens under microwave curing

<table>
<thead>
<tr>
<th>W/C Ratio before MCWH by Wt</th>
<th>Wt of Spec. Before MCWH (g)</th>
<th>Loss of Water during MCWH (g)</th>
<th>W/C Ratio after MCWH by Wt</th>
<th>Microwave Heating</th>
<th>Normal Curing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.5 Hrs After Mixing</td>
<td>7 Days After Mixing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Compr. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Compr. Strength (psi)</td>
<td>7-day NC Comp. Str (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7 Days After Mixing</td>
<td>7-day NC Comp. Str (%)</td>
</tr>
<tr>
<td>0.40</td>
<td>1580.7</td>
<td>11.50</td>
<td>0.372</td>
<td>3947.0</td>
<td>60.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2891.9</td>
<td>46.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4944.4</td>
<td>75.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>79.4</td>
<td>100.0</td>
</tr>
<tr>
<td>0.45</td>
<td>1559.7</td>
<td>13.00</td>
<td>0.417</td>
<td>2891.9</td>
<td>46.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2871.2</td>
<td>44.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4958.8</td>
<td>79.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>79.2</td>
<td>100.0</td>
</tr>
<tr>
<td>0.50</td>
<td>1559.3</td>
<td>14.83</td>
<td>0.462</td>
<td>2871.2</td>
<td>44.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4806.7</td>
<td>79.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>79.2</td>
<td>100.0</td>
</tr>
<tr>
<td>0.55</td>
<td>1534.8</td>
<td>15.50</td>
<td>0.509</td>
<td>2785.9</td>
<td>52.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5416.7</td>
<td>102.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4812.4</td>
<td>100.0</td>
</tr>
<tr>
<td>0.60</td>
<td>1530.7</td>
<td>17.83</td>
<td>0.552</td>
<td>1497.2</td>
<td>31.1</td>
</tr>
</tbody>
</table>

Note: MCWH represents microwave heating.
NC represents normal curing.
Table 4.18: A mix proportion for concrete mix using Rapid Set Cement (by H.H. Holmes Testing Laboratories, Inc.)

<table>
<thead>
<tr>
<th>Materials</th>
<th>0.407 w/c Rapid Set Concrete (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed Limestone (Vulcan-McCook)</td>
<td>1770</td>
</tr>
<tr>
<td>Natural Sand (Vulcan-Crystal Lake)</td>
<td>1220</td>
</tr>
<tr>
<td>Rapid Set Cement</td>
<td>650</td>
</tr>
<tr>
<td>Rapid Set-Set Control</td>
<td>6.5</td>
</tr>
<tr>
<td>Air Entrainment (Master Builders MB-VR)</td>
<td>9.75 oz.</td>
</tr>
<tr>
<td>Water</td>
<td>265</td>
</tr>
</tbody>
</table>

Table 4.19: Compressive strength comparison of MCWC cementitious materials and concrete mix using Rapid Set Cement

<table>
<thead>
<tr>
<th>Age*</th>
<th>Compressive Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.407 w/c Rapid Set Concrete</td>
</tr>
<tr>
<td>2 hours 17 min.</td>
<td>2505</td>
</tr>
<tr>
<td>4 hours 17 min.</td>
<td>3485</td>
</tr>
<tr>
<td>4.5 hours</td>
<td>-</td>
</tr>
<tr>
<td>7 hours 17 min.</td>
<td>3875</td>
</tr>
<tr>
<td>9 hours 17 min.</td>
<td>3800</td>
</tr>
<tr>
<td>1 day</td>
<td>-</td>
</tr>
<tr>
<td>7 days</td>
<td>-</td>
</tr>
<tr>
<td>28 days</td>
<td>5090</td>
</tr>
</tbody>
</table>

Note: MCWC represents microwave curing.
* Age counts from the time that water mixed with cement.
~ Test was performed by H.H. Holmes Testing Laboratories, Inc.
Table 4.20: Mix Proportions for PCC, Fibrous PCC, and MCWC cementitious materials (adapted from Parker et al., 1988)

<table>
<thead>
<tr>
<th>Materials</th>
<th>PCC (lbs)</th>
<th>Fibrous PCC (lbs)</th>
<th>0.40 w/c MCWC Concrete (lbs)</th>
<th>0.50 w/c MCWC Mortar (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type III Cement</td>
<td>33</td>
<td>40</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Water</td>
<td>16</td>
<td>18</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Coarse Aggregate</td>
<td>61</td>
<td>52</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>40</td>
<td>35</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Accelerator</td>
<td>5 oz.</td>
<td>6 oz.</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Steel Fibers</td>
<td>-</td>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: PCC represents Portland cement concrete. MCWC represents microwave cure. ~ = to make one cubic foot. * = to make approximately 10-3 in. x 6 in. specimens.
Figure 4-1: The development of compressive strength, splitting tensile strength, and modulus of elasticity of mortar specimens under normal curing
Figure 4-2: Results of the effect of heating rates at the same energy input level on the compressive strength (at 3 hours and 7 days) of mortar specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing)
Figure 4-3: Relative thermal expansion of water and air relative to that of solids [Soroka, 1979] (from Alexanderson, J., "Strength Loses in Heat Cured Concrete," Proc. Swedish Cement Concrete Research Institute, 43, 1972.)
Figure 4-4: Results of the effect of power levels at a heating duration of 45 minutes on the compressive strength (at 3 hours and 7 days) of mortar specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing)
Figure 4-5: Results of the effect of power levels at a heating duration of 45 minutes on the compressive strength (at 4.5 hours and 7 days) of mortar specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing)
Figure 4-6: Results of the effect of delayed times for a heating rate of 400 watts at and 45 minutes on the compressive strength (at 4.5 hours and 7 days) of mortar specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing)
Figure 4-7: Results of the effect of water/cement ratios for a heating rate of 400 watts and 45 minutes on the compressive strength (at 4.5 hours and 7 days) of mortar specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing)
(a) Based on splitting tensile strength (psi)

(b) Based on 7-day normal-cured splitting tensile strength (%)

Figure 4-8: Results of the effect of power level at a heating duration of 45 minutes on the splitting tensile strength (at 4.5 hours and 7 days) of mortar specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing)
Figure 4-9: Results of the effect of power levels at a heating duration of 45 minutes on the compressive strength (at 4.5 hours and 7 days) of concrete specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing)
Figure 4-10: Results of the effect of water/cement ratios for a heating rate of 400 watts and 45 minutes on the compressive strength (at 4.5 hours and 7 days) of concrete specimens under microwave curing (Note: NC = normal curing; MCWC = microwave curing)
Figure 4-11: SEM Micrographs of 0.50 w/c normal-cured mortar sample at 4 and 4.5 hours
Figure 4-11(e)
Figure 4-12(a)

Figure 4-12(b)

Figure 4-12: SEM Micrographs of 0.50 w/c normal-cured mortar sample at 6 hours
Figure 4-13: SEM Micrographs of 0.50 w/c normal-cured mortar sample at 12 hours
Figure 4-13(c)

Figure 4-13(d)
Figure 4-13(g)
Figure 4-14: SEM Micrographs of 0.40 w/c normal-cured concrete sample at 4.5 hours
Figure 4-14(c)

Figure 4-14(d)
Figure 4-15(a)

Figure 4-15(b)

Figure 4-15: SEM Micrographs of 0.40 w/c normal-cured concrete sample at 24 hours
Figure 4-15(c)
Figure 4-16(a)

Figure 4-16(b)

Figure 4-16: SEM Micrographs of 0.50 w/c microwave-cured mortar sample at 4 hours
Figure 4-17(a)

Figure 4-17(b)

Figure 4-17: SEM Micrographs of 0.50 w/c microwave-cured mortar sample at 4.5 hours
Figure 4-17(c)

Figure 4-17(d)
Figure 4-17(e)

Figure 4-17(f)
Figure 4.18 (a)

Figure 4.18 (b)

Figure 4.18: SEM Micrographs of 0.50 w/c microwave-cured mortar sample at 6 hours
Figure 4-19(a)

Figure 4-19(b)

Figure 4-19: SEM Micrographs of 0.50 w/c microwave-cured mortar sample at 12 hours
Figure 4-19(c)
Figure 4-20: SEM Micrographs of 0.40 w/c microwave-cured concrete sample at 4.5 hours
Figure 4-20(g)
Figure 4-21: SEM Micrographs of 0.40 w/c microwave-cured concrete sample at 24 hours
Figure 4-22(a): at 30 minutes

Figure 4-22(b): at 61 minutes

Figure 4-22: ESEM Micrographs of 0.50 w/c normal-cured mortar sample
Figure 4-22(c): at 2 hours

Figure 4-22(d): at 2 hours and 30 minutes
Figure 4-23(a): at 2 hours and 32 minutes

Figure 4-23(b): at 3 hours and 7 minutes

Figure 4-23: ESEM Micrographs of 0.50 w/c microwave-cured mortar sample
Figure 4.23(c): at 3 hours and 18 minutes

Figure 4.23(d): at 3 hours and 18 minutes
Figure 4-24: Comparison of strength development [adapted from Parker et al., 1988]
Chapter 5

Conclusions and Recommendations

5.1 Research Summary

In this research, mortar and concrete specimens are used to study the effects of microwave energy on the compressive strength, tensile strength, and bond strength (between old and new cementitious materials as well as between cementitious material and a steel bar). A number of parameters are studied, including microwave power level, heating rate, heating duration, delayed time, water/cement ratio, and age after microwave heating. The results of microwave-heated specimens are compared with those of normal-cured specimens. In addition, microstructural examination is carried out to study the differences in morphology between microwave-heated specimens and normal-cured specimens.

5.2 Conclusions

The conclusions of this research are as follows:

1. The microwave curing method exhibits a clear trade off between the development of the early strength and later strength. Process leading to high early strength would normally reduce the later strength.
2. Under microwave curing, the compressive strength of concrete specimens is superior to that of mortar specimens.

3. Among the mixes and microwave processes studied in this work, the optimal mix and process for mortar is found to be 400 watts at 45 minutes for a w/c ratio of 0.55. The compressive strength reaches 2255.5 psi at 4.5 hours, while its 7-day strength is 4723.5 psi. Its 7-day strength of specimens under normal curing is 5559.0 psi.

4. Among the mixes and microwave processes studied in this work, the optimal mix and process for concrete is found to be 400 watts at 45 minutes for a w/c ratio of 0.40. The compressive strength reaches 3947.0 psi and 4944.4 psi at 4.5 hours and 7 days, respectively, while its 7-day strength of specimen under normal curing is just 6536.0 psi.

5. From (3) and (4), the performance of microwave-cured concrete is comparable to more expensive rapid hardening materials used in practice.

6. The splitting tensile strength of mortar at later age is reduced by a smaller percentage compared to the compressive strength. This may be due to the nature of the splitting tensile test which measures the strength at the interior of the specimen.

7. The bond splitting tensile strength between old mortar and new mortar paste under microwave curing (at 400 watt, 45 minutes) decreases only 12.2% compared with normal cured mortar.

8. The results of the slant shear test shows that the slant shear bond strength between old mortar and new mortar paste under microwave curing (at 400 watt, 45 minutes) can be impaired by as much as 50% compared with normal cured mortar.

9. The 1-day pull-out bond strength between mortar paste and a steel bar under microwave curing can be reduced by 23% of the strength between the paste and
the bar under normal curing.

10. Under the SEM, at 4.5 hours, the microstructure of samples under microwave heating is denser than that of samples under normal curing due to the acceleration of cement hydration. However, their microstructure at the later age are difficult to distinguish.

5.3 Recommendations for Future Research

Due to time limitation in this research, it is impossible to study all interesting parameters that can affect the results; therefore, the author would like to recommend works that should be done further to complete the final objective of this study, which is to apply this curing technique to pavement repairs and precast concrete fabrication.

Temperature is one of the most important parameters that can affect the strength development, but it has not been measured in this research. Hence, it will be very interesting to study the effects of the microwave energy on the temperature of microwave-heated specimens. Then the temperature control of the heated specimen should be carried out with a feedback loop to obtain the most favorable temperature for cement to hydrate rapidly under microwave heating so that the early strength gain is high and the later strength gain is not impaired very much.

Since the preliminary results of this research show that the later strength is impaired under microwave heating. It is well known that adding the pozzolanic materials, such as, fly ash and silica fume, will increase the strength at later stage because pozzolan materials can react with calcium hydroxide, which formed during cement hydration, to increase the amount of C-S-H. Moreover, addition of pozzolans also helps to improve the workability [Mindess et al., 1981]. The permeability is reduced and durability improves because it is believed that reduction of calcium hydroxide will improve the chemical durability [Mindess et al., 1981]. More importantly, it is found that high temperature can shorten the curing period of pozzolanic concrete [Mindess et al., 1981]. Therefore, it is believed that the use of pozzolans has a strong potential in produce concrete with both high early and later strength under microwave curing.
After the completeness of the study on strength, tests on permeability, durability, freeze-thaw resistance, and other important properties, should be carried out. Microwave applicators for concrete pavement repairs and precast concrete fabrication should then be designed. Plausible preliminary designs for each application are described in Appendix A.
Appendix A

Plausible Preliminary Designs of Microwave Applicators for Concrete Applications

There are two main applications of this curing technique, namely, concrete pavement repair and precast concrete fabrication. This appendix illustrates the basic design of microwave applicators to be used in the applications in order to show whether this technique is practical or not.

A.1 Concrete Pavement Repair

In pavement repairs, it is suggested that the repair technique can be kept the same as described in chapter 2, except that the microwave energy will be applied to accelerate the rate of hardening and rate of strength gain of the concrete paste. It is important to keep in mind that the time at the microwave application is very important because it can significantly affect the early strength as described in chapter 4. The design system to be used in the repairs is shown in Figure A-1. The mode stirrer is used to provide uniform heating, and the metal cavity must be designed to certain dimensions so that the cavity can resonate to obtain the uniform heating, which means that the cavity "can support certain resonant modes or distributions for the electric and
magnetic field, and the currents and charges [Copson, 1975]” in such a way that waves, which are existed inside, can transmit to the heated materials efficiently and uniformly. Hence, microwave energy will reflect from the cavity wall again and again until it is used up in heating the materials. By means of a metallic skirt around the applicator, the leakage of microwave energy can be controlled to stay below the is level required by the Federal emission standard. According to Osepchuk, the Federal emission standard requires the maximum radiation of 10 $\text{watts/m}^2$ at 5 cm from the microwave oven when it is new, and 50 $\text{watts/m}^2$ at 5 cm thereafter [1984]. The standard test is conducted by heating a load of 275 ml of water in the oven.

A.2 Precast Concrete Fabrication

Unlike pavement repairs, the precast concrete fabrication can use this curing technique directly because the microwave applicators to be used in the fabrication can be adapted from the applicators designed for the food industry. A plausible design of microwave applicator to be used in the precast concrete industry is shown in Figure A-2. The initial products will come in from the loading port and go through the shielding sheet, which is used to protect the leakage of the microwave energy. Then, they will be heated by microwave energy, and at the same time they will move by the rolling plate until they reach the exiting port and exit through the shielding sheet. After that, they will be cured further under a moisture condition and will be removed from the moulds later. It is noted that the heating duration can be controlled to be used for various products which require different amount of energy.
Figure A-1: Design system for pavement repairs by using microwave energy
Figure A-2: Design system for precast concrete fabrication by using microwave energy
References


