CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

6.1 Conclusions

The objectives of this research were to (a) investigate the mechanisms of changes in the dielectric properties of plain containing pozzolan materials and reinforced concrete, (b) characterize the microstructure of microwave-cured plain and reinforced concrete, (c) study the mechanism of microwave heat generation, heat dissipation, and mass transfer of plain containing pozzolan materials and reinforced concrete, and (d) formulate mathematical models for the relationships between microwave curing and mass transfer for steel-reinforced concrete.

In order to achieve the stated goals, detailed experimental and computational methodologies were used. The method experimentally studied the interaction between microwave energy and Type I reinforced cement pastes during the first 24-hours hydration period. The second method developed a theoretical microwave-heating model to achieve high-temperature curing using microwave energy in associated a single-mode rectangular waveguide.

The microwave system used to transfer microwave energy in order to heat or cure the reinforced pastes, mortars and concretes consisted of the following:

- The microwave system used was a monochromatic microwave at a frequency of 2.45 GHz .
- Microwave energy was generated by a magnetron and transmitted directly along the propagation direction (+z) of a rectangular wave guide toward a water load situated at the end of the waveguide to ensure that a minimal amount of microwave energy would be reflected back to the sample.
- A warming water load was circulated through the cooling tower in order to reduce the temperature in the water load system.
- A sample was arranged perpendicular to the propagation direction.
- A Type K thermo-couple with a 0.1 mm diameter was inserted at the center of the sample for the purpose of monitoring the temperature rise.

- During a 10-minutes period of microwave heating, the output of the microwave magnetron was controlled at 1000 W. The microwave plane wave traveled directly along the wave guide and made contact with the sample surface; the wave was then reflected and transmitted. By using a wattmeter, incident, reflected and transmitted waves were monitored.

It can be summarized that:

6.1.1 Dielectric permittivity of reinforced cement-based materials

The dielectric permittivity of reinforced cement-based materials is affected by the initial water-to-solid mass ratio (w/s), the cement type, the presence/lack of pozzolan, and the aggregate type. It should be noted here that though the volumetric fraction of water and the superplasticizer of a given mixture may be small, they strongly affect the dielectric permittivity of the cement. This is because both water and the superplasticizer have high dielectric permittivity. The change in the dielectric permittivity of cement-based materials, therefore, is relatively high and remains constant during the dormant period. However, the change in the dielectric permittivity decreases rapidly when the hydration reaction resumes, and it continues to decrease during the acceleratory period.

6.1.2 Microwave-assisted curing of pastes and concretes

The study took into account microwave energy's ability to accelerate hydration reactions and increases in temperature within the microwave-cured reforced sample, as well as the effects of water-to-solid mass ratios, pozzolan materials, mortar and concrete, delay times, power level, application duration, sequential process, and the environment's normal and low pressure. Furthermore, the characteristics of microwave-cured specimens and normal (lime-saturated deionized water) and autoclave curing were compared in detail. The test results showed that the temperature increased monotonically among the positions of measurement during the microwave-curing process. The typical micrographs of the microwave-cured paste at the age of 4 hours after mixing, 28 days after curing in lime-saturated deionized water, and when subjected to microwave energy showed that the samples consisted of hydrated phases and pores, as well as cores of $Ca(OH)_2$ dendrite crystals or other crystals (marked CH), C–S–H, and granular structure. Furthermore, some ettringite (Aft) was found in the samples cured by microwave energy. From the SEM–EDS results, it was observed that although the measured Ca/Si ratios of the pastes were similar in magnitude, they consistently decreased when the temperature decreased. For compressive strengths, the microwave-cured pastes developed strength quite rapidly in accord with the maintenance of the level of microwave power and time of application. In addition, the water content of the pastes' hydration products was affected depending on the w/s, and the $Ca(OH)_2$ contents were affected due to the completion of the hydration reaction.

6.1.3 A theoretical model to predict the heat transfer of reinforced cement paste subjected to microwave energy

To predict the extent to which temperature will increase, the model explored the interactions between the microwave (electromagnetic field) and cement paste, that is, the heat dissipation (conduction mode) model, by using Multiphysics Modeling and Simulation: COMSOL. The modeling results showed that the simple model, that is, a specific physical model, with assumptions and initial and boundary conditions, can predict some aspects of temperature increases.

6.2 Recommendations for future study

Given that current trends in clean energy are emphasizing sustainable development and environmentally friendly processes, microwave energy is gradually becoming a more popular energy source for heating and drying in various industrial applications. However, microwave energy has been put to such use only very gradually because of a lack of basic knowledge and serious concerns regarding radiation safety and hazards to biological tissue. Thus, these issues together with the socio-technical questioning of this method need to be clarified.

Still, in the future, there will be industrial-scale applications for which conventional curing methods will not be appropriate. Therefore, further issues are the compatibility of mixed concretes and curing conditions, heat- and mass-transfer mechanisms, and numerical tools to predict heat and mass transfer during heating by microwave energy. The use of microwave energy to improve the properties of cement-based materials is a relatively new area of research that is attracting significant interest because microwave heating has many advantages, among which are rapid heat generation, high-energy penetration, instantaneous and precise electronic control, and clean process. In addition, conventional curing methods have many limitations. For example, they take a long time to reach the strength required for water curing. In addition, due to the inherent thermal insulation of concrete, their hydration products are non-uniform, which causes different temperatures to occur in processed concrete under high-stream and temperature-curing conditions. Some essential points that illustrate the performance of microwave energy are as follows:

The second point concerns the heat- and mass-transfer mechanisms within the heated concrete during microwave curing. A number of studies have shown that microwave curing improves the generation and transportation of heat and mass within the heated concrete material, which are key performance factors in regard to energy efficiency. This is due to microwave energy's inherent ability to volumetrically generate heat from the inside to the outside. However, the assumption that no chemical reactions occur within the concrete is incorrect. The hydration and pozzolanic reactions take place naturally; therefore, the difficulty may be a definitive point in the development of microwave-curing in determining when and how to apply microwave energy in a way that is appropriate for achieving a particular reaction in the cement.

The third point concerns the numerical tools used to predict heat and mass transfer during heating using microwave energy. This study developed a model to account for a range of aspects. Further, the study evaluated variations in temperature as they related to the heating time, frequency, and sample size of the cement paste with water-to-cement ratios (w/c) with weights of 0.25, 0.38, and 0.45. The model developed here is an example of efficient computational prototyping.

The last point concerns the compatibility of microwave-heating mechanisms and the suitability of the equipment and systems associated with them. In other words, these components should be closely compatible with the concrete material to be processed. Heating mechanisms that take place inside a multi-mode cavity are somewhat more complicated than mechanisms that occur in a single-mode cavity. However, multi-mode microwave systems are generally used in industry. The way to solve this problem is to extrapolate the results of a single mode and then predict the phenomena that occur in a multi-mode cavity as accurately as possible.