Chapter 6
SUMMARY, CONCLUSION, AND RECOMMENDATIONS

6.1 SUMMARY OF WORK PERFORMED

As a central part of this study, a special experimental technique was developed which made possible the preservation of the compressive stress-induced microcracks in concrete as they exist under applied loads. This technique involved injecting a molten-metal alloy into the induced cracks and solidifying it before unloading.

A total of eight experiments were performed, five on normal-strength, and three on high-strength concrete specimens. The specimens were loaded up to 90% of their ultimate strength. For the normal-strength concrete specimens, a no-load experiment was conducted initially to determine the fracture status of the specimen prior to loading. In the second experiment, the specimen was subjected to uniaxial compression. The third and fourth experiments were partially confined experiments. Confining stress was used to generate triaxial compression and was supplied by stainless steel wires wound around the concrete specimens. In the partially confined experiments, the wire was wound one-third of the way from each end of the specimen. The fifth experiment used a fully confined specimen which had wire wound around its entire length. The experiments on the high-strength concrete specimens were no-load, uniaxial, and partially confined experiments.

After each experiment, four specimens, parallel to the direction of maximum applied stresses, were extracted from the concrete cylinders. These specimens were polished and prepared for scanning electron microscope (SEM) observations. Fifty five images were taken from each specimen, bringing the total number of images to over 2,220. The images were analyzed by an advanced-computerized image analyzer.

The concept of stereology, which deals with the interpretation of three-dimensional structures by means of their two-dimensional sections, was applied to analyze the images. Two-dimensional measurements were also performed to determine crack length and orientation. The experimental results obtained were also compared to some of the existing micromechanical models.

6.2 SUMMARY OF FINDINGS AND CONCLUSIONS

Concrete has the inherent quality of being heavily cracked even before a load is applied. When concrete specimens were subjected to compressive loading, microcracks were generated by several different mechanisms and had an orientation that was generally within 15 degrees of the direction of the maximum compression. The microcracks observed were generally short. The average crack length was from 49.6 microns for the fully confined specimen, to 51.8 microns for the uniaxial specimen. Microcrack orientation, density, length, and branching were strongly influenced by the amount of confining stress to which they were subjected. The average orientation of the microcracks, which was computed from the absolute values of angles from the vertical--i.e., the direction of maximum compression--increased as the confining stress increased. The microcrack density distribution, which represents the number of microcracks per unit of observation area, decreased as the confining stress increased. The specimen subjected to uniaxial compression had the highest crack density, and the specimen loaded under fully confined condition had the lowest value. In the partially confined specimens, the crack length and density were observed in both confined and unconfined portions of the specimen. The crack densities in the center and edge were smaller in the confined portion than in unconfined portion. The number of cracks per observer area also decreased with confinement. The surface area of the crack, S_V, which is a stereological measurement, was strongly influenced by the confining stress; and as the confining stress increased, crack surface area decreased. Crack lengths were also assessed stereologically, and they showed that with increasing confinement, crack lengths decreased. Similar behavior was observed with the percent crack area measurements and in terms of the absolute number of cracks per unit of observed area. The average length was longest in the uniaxial experiment, and shortest in the fully confined experiment. In the partially confined specimens, both the crack length and density in the center and edge of the sample were smaller in the confined portion than in the unconfined portion. In the same specimens, the average crack length was smaller in the center portion of the specimen than along the edge. As the confinement increased, crack branching in the specimens decreased. The number of branching nodes in the normal-strength concrete was much higher than in the high-strength concrete. As high-strength concrete is more brittle, fracture in high-strength concrete is associated with less branching than in normal-strength concrete. Interfacial cracks, the cracks in the interface of aggregate and cement paste, were strongly influenced by the amount of confinement. Interfacial microcracks decreased as the amount of confinement increased.

Three micromechanical models were used to compare the experimental results against the theoretical models. They were: the differential scheme, the Mori-Tanaka model, and a crack-growth simulation model. The first two models determine the final modulus of elasticity of a material, based on its initial modulus and the crack density. The final modulus of elasticity was computed on the basis of the initial modulus of elasticity, obtained from the stress-strain diagram, and the measured crack densities. They were in close agreement with the measured modulus at the end of the experiments. The analysis in the differential scheme was performed in both two and three dimensions. The uniaxial and fully confined specimens were compared to the theoretical models. The predicted elastic moduli were in agreement with the measured values, and the differences varied between 2 and 8 percent. The crack growth simulation model used the initial pre-load crack pattern and the elastic constants of the concrete specimens to generate crack growth with increasing compressive loads. As with the previous models, the uniaxial and fully confined specimens were examined against the crack growth model. The differences in crack densities obtained from the crack growth model for the uniaxial and fully confined loadings were identical to the results obtained from the experiments.

The molten-metal-injection technique used in this research is an efficient, cost effective, and reliable method for the preservation of microcracks in concrete as they exist under load.

6.3 RECOMMENDATIONS FOR FUTURE RESEARCH

Using the molten-metal-injection technique, it is possible to observe crack propagation in concrete under compressive loading. The concrete specimens should be loaded at 20% increments of their ultimate strength up to the failure of the sample. This way, crack length, density, orientation, and interaction can be observed at different stages of loading; and the propagation of cracks can be quantified with the increase in load.

The molten-metal-injection technique should be extended to structural lightweight concrete in order to study the fracture of the aggregates in concrete. Lightweight aggregate concrete is made with lightweight-cellular aggregates so that its unit weight is less than normal-weight concrete. In lightweight aggregate concrete, fracture passes through the cellular aggregate particles because both the transition zone and the cement paste are generally stronger, whereas in normal-weight concrete, since the aggregate particles are dense and strong, fracture is usually in the transition zone or the bulk cement paste, not through the aggregate.

Another potential application of the molten-metal-injection technique is to the study of concrete made with pozzolanic materials. Pozzolans are siliceous, or siliceous and aluminous, materials. When added to the concrete mix, they greatly enhance the properties of concrete. Concrete made with pozzolans are generally stronger and more durable. Using the molten-metal-injection technique, the effects of different kinds of pozzolanic materials on the micromechanical behavior of concrete could be investigated. This could prove to be a very useful study.

Air voids in concrete, either of the entrapped or entrained type, are capable of adversely affecting its strength and permeability. The Wood's metal technique could be employed to quantify the porosity of concrete and to study the effect of air voids on the overall behavior of the material.

The type and size of aggregates used has a great effect on the strength and behavior of concrete. The smaller the aggregate, the stronger the concrete. The molten-metal-injection technique can be used to study the effects of different types and sizes of aggregates on fracture of concrete.

The design of the cell apparatus should be modified to develop an apparatus capable of testing concrete in tension, i.e. 3-point load or the Brazilian test. Tensile cracks could then be preserved as they exist under load, and their behavior analyzed.

The crack simulation growth model used in Chapter 5 does not take aggregates into account. A viable model for crack growth in concrete should incorporate aggregates into the simulation. This could be achieved by randomly distributing pockets of a higher modulus within the modeled matrix to simulate the aggregates in concrete.