Ph.D. THESIS
UCB/SEMM-94/19

STRUCTURAL ENGINEERING, MECHANICS, AND MATERIALS

GENERATION AND INTERACTION OF COMPRESSIVE STRESS-INDUCED MICROCRACKS IN CONCRETE

by

KAMRAN MOSTASHAR NEMATI

Committee in charge:

Professor Paulo J. M. Monteiro, Chair
Professor Ben C. Gerwick, Jr.
Professor Robert Brady Williamson
Professor Alice M. Agogino

DECEMBER, 1994

DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF CALIFORNIA, BERKELEY
BERKELEY, CALIFORNIA

The dissertation of Kamran Mostashar Nemati is approved:

12/14/94

Professor Paulo J.M. Monteiro, Chair — Date

12/11/94

Professor Ben C. Gerwick, Jr. — Date

12/10/94

Professor Robert Brady Williamson — Date

12 Dec '94

Professor Alice M. Agogino — Date

University of California at Berkeley

1994

Generation and Interaction of Compressive Stress-Induced Microcracks in Concrete

by

Kamran Mostashar Nemati

ABSTRACT

Generation and Interaction of Compressive Stress-Induced Microcracks in Concrete

by

Kamran Mostashar Nemati

Doctor of Philosophy in Civil Engineering
University of California at Berkeley
Professor Paulo J. M. Monteiro, Chair

This thesis presents the results of experimental and theoretical studies of the micromechanical behavior of concrete under different loading conditions. Cylindrical specimens of normal and high-strength concrete were subjected to testing under uniaxial and confined compression. An alloy with a low melting point was used as a pore fluid. At the stress or strain of interest, this alloy was solidified to preserve the stress-induced microcracks as they exist under load.

Scanning electron microscopy (SEM) was employed to capture images from the cross sections of the concrete specimens. These images were then used to study the generation, orientation, density, length, and branching of the compressive stress-induced microcracks and the effect of confinement on microcrack behavior. The microcracks were generated by a number of different mechanisms and had an orientation that was generally within 15 degrees of the direction of the maximum applied stress. The density, average length, and branching of the microcracks decreased as the confining stress increased. The confining stress showed a pronounced influence on interfacial cracks, also known as transition zone cracks, which occur at the interface of cement paste and aggregate. The amount of interfacial cracking decreased significantly as the confining stress was increased. Stereological analysis which interprets three-dimensional structures by means of two-dimensional sections, was used on the computerized images. Crack orientation, crack surface area, and crack length

were determined stereologically. The resulting stereological measurements indicated that the crack orientation, surface area, and length decreased as the confining stress increased.

Three micromechanical models, the differential scheme, the Mori-Tanaka method, and a crack growth simulation model were used to examine the experimentally obtained data against the theoretically developed micromechanical models. The final modulus of elasticity for the concrete specimens was calculated using the first two models, based on the measured crack densities, which gave an approximation that was very close to the actual measured moduli. The crack growth model was used to generate and propagate microcracks for uniaxial and fully confined cases, and it also revealed behavior similar to that shown in the experimental results.

Paulo J. M. Monteiro
Chairman, Thesis Committee

To my parents

ACKNOWLEDGMENT

During my years of graduate study at Berkeley many people have given me support, guidance, and friendship. Foremost among these is my adviser, Professor Paulo Monteiro. He has shared his great creative and analytical skills with patience, endless encouragement, and generosity. It has been my very good fortune to have had such a conscientious and inspirational adviser.

Much credit also goes to my mentor and exemplar, Professor Ben C. Gerwick, Jr., who inspired me to study concrete. I owe a great deal of my success to Professor Gerwick. I would also like to thank the other members of my research committee, Professors Robert Brady Williamson and Alice M. Agogino for their detailed and thoughtful comments.

I wish to express appreciation to Professor Neville G. W. Cook of the Department of Mining Engineering and Dr. Larry Myer of Lawrence Berkeley Laboratory for their guidance in designing the test apparatus and for advice on experimental procedures. Special thanks goes to Mr. William MacCracken of the Department of Civil Engineering for his insight and ingenuity in conducting experiments.

The hospitality of Dr. Karen Scrivener during my many visits to the Imperial College of Science and Technology in London is greatly appreciated. Dr. Scrivener's advice was extremely valuable and pivotal. I also wish to thank Dr. Stephen Laing for his help in computer programming and for his friendship.

I am grateful to both Professor John Kemeny of the University of Arizona, and Dr. Robert Zimmerman of Lawrence Berkeley Laboratory, for their help with micromechanical modeling of fractures in concrete.

I would like to express my deepest gratitude and appreciation to ICF Kaiser Engineers, Inc. In particular I wish to thank Mr. Michael Jones and Mr. Richard Nunes for their patience, support, and encouragement, as well as for allowing me to maintain full-time employment while completing my graduate work. I could not have finished my doctorate without their support. I would also like to thank Diane Michelle Williams, Dr. Edgar Becker, Mike Phillips, and Steve Sims for their friendship and encouragement.

The years I have spent in residence at the International House at Berkeley have constituted the best time of my life. I am exceedingly lucky to have made such great friends there as Peter Kennedy, Orla Feely, Jerry Murphy, Cormac Conroy, Bo Petterson, Nathalie Richart, Michel Chalhoub, Catherine Faure, Dariush Mirfendereski, Alison Green, Nils Tarnow, Hamid Savoj, and Yutaka Tanaka.

Finally, I would like to thank my late father and my mother for their constant concern, support, and encouragement throughout my life. There is no better way to express my appreciation than to dedicate this thesis to my parents.

TABLE OF CONTENTS

Abstract 1

Acknowledgments iv

Table of Contents vi

List of Figures x

List of Tables xvi

Nomenclature xvii

CHAPTER 1 INTRODUCTION

1.1 Background 1

1.2 Methods of Study of Microcracking 4

1.2.1 Early Methods 5

1.2.2 Proposed Method 8

1.3 Objectives...9

1.4 Summary of the Chapters 10

CHAPTER 2 EXPERIMENTAL TECHNIQUE

2.1 Introduction..12

2.2 Concrete Specimens 12

2.3 Confinement...15

2.4 Test Equipment....18

2.4.1 Pedestal....18

2.4.2 Vessel....19

2.4.3 Piston....19

2.4.4 Top Cap....20

2.4.5 Heater....21

2.5 Wood's Metal....21

2.6 Experimental Procedure....22

2.7 Experiments Conducted....28

2.8 Specimen Preparation....29

2.8.1 Cutting....29

2.8 2 Polishing....30

2.8.3 Specimen Identification....31

2.8.4 Preparation for Scanning Electron Microscope (SEM) Analysis....32

CHAPTER 3 SCANNING ELECTRON MICROSCOPY, IMAGE ANALYZER, AND STEREOLOGY

3.1 Introduction....33

3.2 Scanning Electron Microscopy....33

3.3 Image Analyzer....35

3.4 Stereology and Concrete....37

3.4.1 Introduction....37

3.4.2 Basic Measurements....37

3.4.2.1 Number of point intersections, P_L 38

3.4.2.2 Surface-to-Volume ratio, S_V 39

3.4.2.3 Length of line per unit area, L_A 41

3.4.3 Degree of Orientation 44

3.4.4 Application of Stereology To Concrete Fracture Mechanics....................45

CHAPTER 4 OBSERVATION RESULTS AND ANALYSIS OF DATA

4.1 Introduction..50

4.2 Characterization of Microcrack Initiation 50

4.3 Orientation of Microcracks..56

4.4 Microcrack Density Distribution 64

4.5 Microcrack Length Distribution 72

4.6 Microcrack Branching 81

4.7 Interfacial Cracks 83

CHAPTER 5 MICROMECHANICAL MODELS FOR CONCRETE

5.1 Introduction..91

5.2 Elastic Modulus Models 91

5.2.1 Differential Scheme..92

5.2.2 Mori-Tanaka Model 96

5.3 Crack Growth Simulation Model 98

5.3.1 The Maximum Energy Release Rate Criterion, G-Criterion....................98

5.3.2 Crack growth and Propagation 100

5.3.3 Review of Analytical Micromechanical Model 102

5.3.4 Distribution of Microcracks in the Material 102

5.3.5 Parameters Used in the Crack Growth Model 105

5.3.6 Program Overview 108

5.3.7 The Crack Growth Simulation Model Results 110

CHAPTER 6 SUMMARY, CONCLUSION, AND RECOMMENDATIONS

6.1 Summary of the Work Performed...114

6.2 Summary of Findings and Conclusion..115

6.3 Recommendations for Future Research 117

REFERENCES..119

APPENDICES...129

Appendix A: Experiments Conducted..130

Appendix B: Image Analyzer Computer Programs...134

Appendix C: Test Cell Design..155

LIST OF FIGURES

Figure 1.1 Polished section from a concrete specimen. 2

Figure 1.2 Diagrammatic representation of the transition zone and bulk cement paste in concrete..3

Figure 2.1 Normal-strength concrete specimens used in the experiments...14

Figure 2.2 Pedestal 18

Figure 2.3 Vessel..19

Figure 2.4 Piston 20

Figure 2.5 top Cap 20

Figure 2.6 Wood's metal 21

Figure 2.7 Diagram of the test apparatus 23

Figure 2.8 Heating scheme diagram..24

Figure 2.9 Schematic diagram of the test assembly 24

Figure 2.10 Pouring molten metal into the vessel 25

Figure 2.11 Inserting the thermocouple into the top cap 25

Figure 2.12 Placing the heater and the insulation 26

Figure 2.13 Temperature and load control devices..26

Figure 2.14 Nitrogen dispensed through a high pressure regulator 27

Figure 2.15 Post-experiment cooling of the cell..27

Figure 2.16 Extrusion of concrete specimen..28

Figure 2.17 Raising the vessel..28

Figure 2.18 Raising the vessel by aircraft cable 28

Figure 2.19 Specimen prior to and after Wood's metal injection 28

Figure 2.20 Axial cut of the concrete cylinder 29

Figure 2.21 Lateral cut of the concrete cylinder 29

Figure 2.22 Specimen extraction 29

Figure 2.23 A lateral section showing macrocracks filled with metal alloy 30

Figure 2.24 Specimen placed on glass and aluminum base for SEM study 30

Figure 2.25 Specimen extraction and numbering scheme 31

Figure 3.1 Scanning electron microscope (SEM) and Kontron Image Analyzer 35

Figure 3.2 Flow chart for stereological steps 36

Figure 3.3 Model of deriving the relationship $S_V = 2P_L$ 39

Figure 3.4 Geometry involved in the determination of the probability that random normals lie between θ and $\theta + d\theta$ 40

Figure 3.5 Model of deriving the relationship $L_A = (\frac{\pi}{2})P_L$ 42

Figure 3.6 Geometry involved in the determination of the probability that elementary segments lie between θ and $\theta + d\theta$ 43

Figure 3.7 A SEM backscatter image 46

Figure 3.8 Establishing threshold in histogram 46

Figure 3.9 Wood's metal identification by establishing threshold levels in histogram 47

Figure 3.10 Crack network 47

Figure 3.11 Scrap command 47

Figure 3.12 Binary-thinned image of the crack network in concrete 48

Figure 3.13 Array of straight parallel lines....49

Figure 4.1 SEM micrographs from the no-load experiment....51

Figure 4.2 SEM micrographs from the partially confined experiment....52

Figure 4.3 SEM micrographs of microcracks propagating from a pore....52

Figure 4.3 SEM micrographs of aggregate cracking....53

Figure 4.5 SEM micrographs from the no-load experiment for high-strength concrete specimen....54

Figure 4.6 SEM micrographs from the partially confined experiment for high-strength concrete....55

Figure 4.7 Average crack orientation for normal-strength concrete....56

Figure 4.8 Average crack orientation for high-strength concrete....57

Figure 4.9 Crack orientation for normal-strength concrete....59

Figure 4.10 Crack orientation for high-strength concrete....59

Figure 4.11 Number of intercepts for smoothed cracks....60

Figure 4.12 Number of intercepts for smoothed cracks....60

Figure 4.13 Rose of the number of intersections diagrams for high-strength concrete....61

Figure 4.14 Rose of the number of intersections diagrams for normal-strength concrete....62

Figure 4.15(a) SEM micrographs showing crack tips at higher magnification....63

Figure 4.15(b) SEM micrographs showing crack tips at higher magnification....64

Figure 4.16 Crack density, Γ, as a function of confinement for normal-strength concrete....66

Figure 4.17 Crack density, Γ, as a function of confinement for high-strength concrete....66

Figure 4.18 Diagrammatic representation of crack length and crack density at confined and unconfined portions of Experiment #3 67

Figure 4.19 Diagrammatic representation of crack length and crack density at confined and unconfined portions of Experiment #4 68

Figure 4.20 Number of cracks as a function of confinement for normal-strength concrete 68

Figure 4.21 Number of cracks as a function of confinement for high-strength concrete 69

Figure 4.22 Percent cracked area as a function of confinement for normal-strength concrete 69

Figure 4.23 Percent cracked area as a function of confinement for high-strength concrete 70

Figure 4.24 Crack surface area (S_V) as a function of confinement condition for normal-strength concrete 71

Figure 4.25 Crack surface area (S_V) as a function of confinement condition for high-strength concrete 71

Figure 4.26 Crack length as a function of confinement condition for normal-strength concrete 72

Figure 4.27 Crack length as a function of confinement condition for high-strength concrete 72

Figure 4.28 Histogram of microcrack length distributions for the no-load experiment of the normal-strength concrete 73

Figure 4.29 Histogram of microcrack length distributions for the uniaxial experiment of the normal-strength concrete 73

Figure 4.30 Histogram of microcrack length distributions for the partially confined (1) experiment of the normal-strength concrete 74

Figure 4.31 Histogram of microcrack length distributions for the partially confined (2) experiment of the normal-strength concrete 74

Figure 4.32 Histogram of microcrack length distributions for the fully confined experiment of the normal-strength concrete 75

Figure 4.33 Histogram of microcrack length distributions for the no-load experiment of the high-strength concrete 75

Figure 4.34 Histogram of microcrack length distributions for the uniaxial experiment of the high-strength concrete 76

Figure 4.35 Histogram of microcrack length distributions for the partially confined experiment of the normal-strength concrete....76

Figure 4.36 COV of crack length as a function of confinement for normal-strength concrete....77

Figure 4.37 COV of crack length as a function of confinement for high-strength concrete....78

Figure 4.38 Stress intensity factors due to local tension P and confining stress, σ_3 78

Figure 4.39 Stereological measurement of crack length as a function of confinement condition for normal-strength concrete specimens....80

Figure 4.40 Stereological measurement of crack length as a function of confinement condition for high-strength concrete specimens.....80

Figure 4.41 3-way and 4-way crack branching nodes....81

Figure 4.42 Crack branching nodes as a function of confinement for normal-strength concrete 82

Figure 4.43 Crack branching nodes as a function of confinement for high-strength concrete 82

Figure 4.44 The flow chart for interfacial crack identification computer program....84

Figure 4.45 Interfacial crack in the normal concrete specimen subjected to uniaxial loading....85

Figure 4.46 Scrap with the higher upper limit for the area range....86

Figure 4.47 Scrap with the lower upper limit for the area range 86

Figure 4.48 Close the image in Figure 4.47....86

Figure 4.49 Open the image in Figure 4.48 86

Figure 4.50 Scrap the image in Figure 4.49 87

Figure 4.51 Correlate every pixel which is both in figure 4.46 and 4.50 87

Figure 4.52 Correlating every pixel that is either in Figure 4.46 or 4.49 but not common to them 87

Figure 4.53 Scrap the image in Figure 4.52 87

Figure 4.54 Scrap the image in Figure 4.52 88

Figure 4.55 Crack smoothing of the image in Figure 4.54 88

Figure 4.56 Effect of confinement on interfacial microcracks of normal-strength concrete 89

Figure 4.57 Effect of confinement on interfacial microcracks of high-strength concrete 90

Figure 5.1 Schematic diagram of an idealized crack 93

Figure 5.2 (a) Plate with crack $2a$; (b) Load-displacement diagram 100

Figure 5.3 Computer flow chart for the Du model calculations 102

Figure 5.4 Histogram of entire microcrack length distribution for the no-load experiment on normal-strength concrete 104

Figure 5.5 The random cracks generated in concrete specimen 105

Figure 5.6 Concrete specimen boundary input in algorithm 108

Figure 5.7 Rectangular boundary 109

Figure 5.8 Crack propagation simulation for uniaxial loading 111

Figure 5.9 Crack propagation simulation for fully confined condition 112

LIST OF TABLES

Table 2.1 Normal-strength concrete mix design 13

Table 2.2 High-strength concrete mix design 13

Table 2.3 Experiments conducted...29

Table 3.1 List of basic stereological symbols and their definition 38

Table 4.1 Number, length, and orientation of microcracks 57

Table 4.2 Data from the stereological analysis 58

Table 4.3 Crack density for different loading conditions...............................65

Table 4.4 Coefficient of variation of cracks length..77

Table 4.5 Percentage of interfacial cracks..89

Table 5.1 Modulus of elasticity obtained from micromechanical Models....98

Table 5.2 The microcrack lengths used in the Du model.............................104

Table 5.3 Material properties of concrete specimen 107

NOMENCLATURE

Å	Angstrom
f_c'	Ultimate Strength
FM	Fineness Modulus
GPa	Giga Pascal
K	Coefficient of Permeability
KN	Kilo Newton
lb	Pound
HRWR	High Range Water Reducer
LEFM	Linear Elastic Fracture Mechanics
MPa	Mega Pascal
μm	Micrometer (10^6 m)
MSA	Maximum Size Aggregate
pcf	Pounds per Cubic Feet
pcy	Pounds per Cubic Yard
psi	Pounds per Square inch
RHA	Rice Husk Ash
SEM	Scanning Electron Microscope
yd	Yard