

**EXPERIMENTAL INVESTIGATION OF HIGH
PERFORMANCE CONCRETE UNDER
REPEATED COMPRESSIVE LOADING**

by

R.B.KHADIRANAIKAR

DEPARTMENT OF CIVIL ENGINEERING

*A thesis submitted in fulfilment of the requirements
for the award of the degree of*

DOCTOR OF PHILOSOPHY

to the



**INDIAN INSTITUTE OF TECHNOLOGY, DELHI
NEW DELHI, INDIA**

APRIL, 2003

I. I. T. DELHI
LIBRARY
No. TH-3049

note - Testing
road bearing structures

TH
691.32:624.042
KHA - E



Dedicated to the Everlasting

Memory of My

Grand Mother

Parents

And

Father-in-Law

Shri. M. H. Babakkanavar

CERTIFICATE

This is to certify that the thesis entitled "**Behaviour of High Performance Concrete under Repeated Compressive Loading**" being submitted by **R.B.Khadiranaikar** to the Indian Institute of Technology, Delhi for the award of the Degree of Doctor of Philosophy in Civil Engineering, is a record of bonafide research work carried out by him. **Mr. R.B.Khadiranaikar** has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard.

This thesis or any part thereof, has not been submitted to any other University or Institute for the award of any degree or diploma.



Dr.Alok Madan
Assistant Professor



Prof. S.N.Sinha
Professor and Head

Civil Engineering Department
Indian Institute of Technology, Delhi
New Delhi – 110 016, India

ACKNOWLEDGEMENTS

I wish to express my profound gratitude and indebtedness to my research supervisors **Prof. S. N. Sinha**, Professor and Head and **Dr. Alok Madan**, Assistant Professor, Civil Engineering Department, Indian Institute of Technology, Delhi, for their guidance and supervision throughout the duration of this research. The knowledge and experience that I have gained working under them will forever be valuable and appreciated. The staff of the structural Engineering Laboratory and Civil Engineering Workshop deserves special thanks for their cooperation and assistance in the Laboratory work.

I am thankful to the Government of Karnataka and Shri. V.C. Charantimath, Chairman, Governing Council, B.V.V. Sangha, Bagalkot for deputing me under Quality Improvement Program. I would also like to place on record the cooperation, assistance and moral boosting provided by Prof. Eshappa Shetra, Principal and Dr. R.N. Herkal, Professor and Head, Civil Engineering Department, Basaveshwar Engineering College, Bagalkot. I am grateful to A.I.C.T.E. and M.H.R.D. for providing me scholarship under Q.I.P.

No superlative will be able to do full justice in expressing the feelings and heartfelt appreciation for the contribution of my wife and children for bearing with me throughout the course of study and the successful completion of this thesis.


R.B. KHADIRANAIKAR

ABSTRACT

In this study, an experimental investigation was conducted to study the behaviour of high performance concrete under repeated compressive loading. Stress-strain characteristics, energy dissipation characteristics, stiffness degradation, brittleness and mode of failure are discussed.

The cylinder concrete specimens with flared ends having 150 mm diameter and a height of 400 mm were tested to investigate the behaviour under repeated compressive loading. Three grades of high performance concrete were investigated. Three types of tests were conducted for each grade of concrete: (i) Monotonic tests where load is increased to failure; (ii) Repeated loading – unloading in which the peak of each loading cycle approximately coincides with the monotonic curve. The stress-strain hysteresis of this test possessed a locus of common points, which is a point of intersection of reloading curve with the previous unloading curve; (iii) Tests consisting repeated loading-unloading in which the repeated load was applied as in the second type except that in each cycle loading and unloading were repeated several times; each time the load was released when the reloading curve intersected the initial unloading curve. This point of intersection gradually descended and stabilised at a lowerbound point. Such lowerbound points are termed as stability points and the further cycling led to the formation of a closed hysteresis loop.

Single general mathematical expression is proposed for the determination of the envelope stress-strain curve, the locus of common points and the locus of stability points for all the three grades of concrete, which provides a reasonable fit with experimental data. Further a stability point curve for each grade of concrete is used in defining the permissible stress level of high performance concrete structures, where reduction of compressive strength due to the effect of repeated loading have to be taken in to account. It is found that the level of plastic (residual) strain in the material is an important factor in defining the permissible stress under repeated loading.

A study was also made on the energy dissipation characteristics of high performance concrete under repeated compressive loading. Empirical expressions were suggested for the variation of energy dissipation ratio with the envelope strain and plastic strain. The relation between energy dissipation and plastic strain can be used to identify the point of load history at which the process of strength deterioration begins. The total energy has been divided in to three components representing the energy dissipated in damage, energy dissipated in damping mechanism and elastic strain energy. Cumulative damage energy indicates the damage of the material. Lower strength concrete (i.e. M1 concrete) experienced more damage prior to peak strain and after the peak strain higher strength concrete indicated higher cumulative damage energy. Based on energy concepts brittleness indices were worked out for the three grades of concrete. Brittleness index increases with the increase in strength.

Stiffness degradation and strength deterioration under repeated compressive loading were presented and it was quantified by mathematical expressions with respect to envelope strain, plastic strain and energy dissipation ratio. High performance concrete experienced strength deterioration and stiffness degradation as the number and intensity of load repetition increased.

A mathematical model is proposed to obtain the stress-strain reloading and unloading curves for high performance concrete under repeated compressive loading. Both reloading and unloading curves were found to depend on the plastic strain level. It was shown that the reloading curves could be represented by exponential formula. The model for reloading curves involved plotting the reloading curves from a common origin by transferring them to a new normalised coordinate system. The unloading curve at any cyclic load level was modelled by a simple parabola. The model predictions compare well with the experimentally obtained stress-strain reloading and unloading curves.

TABLE OF CONTENTS

	Page No.
TABLE OF CONTENTS	iv
LIST OF FIGURES	ix
LIST OF TABLES	xiv
NOTATION	xv
Chapter 1. INTRODUCTION	
1.1 Introduction	1
1.2 Justification of Present Investigation	2
1.1 Objectives and Scope of Present Investigation	6
Chapter 2. LITERATURE REVIEW	
2.1 Introduction	13
2.2 Behaviour of Concrete under Sustained Cyclic Loads	15
2.3 Uniaxial Cyclic loading	19
2.3.1 Envelope Unloading and Reloading Curves	20
2.3.2 Common Points	26
2.3.3 Non Recoverable Strains	30
2.3.4 Stress-Strain Relation	31
2.3.5 Failure Mechanism	37
2.4 Experiments on Mortar Specimens	42
2.5 Biaxial Loading	42
2.5.1 Solid Cylindrical Specimens	42
2.5.2 Hollow Cylindrical Specimens	46
2.5.3 Cubical Specimens	48
2.5.4 Plate Specimens	50
2.5.5 Previous Investigations on Microcracking	57

2.6	Tensile Strength.....	60
2.6.1	Direct Tensile Strength.....	60
2.6.2	Indirect Tensile Strength	62
2.7	Deformation	65
2.7.1	Static Modulus.....	65
2.7.2	Dynamic Modulus.....	67
2.8	Poisson's Ratio	68
2.9	Summary.....	68

Chapter 3. HPC MIX PROPORTIONING

3.1	Selection of Materials.....	72
3.1.1	Cement.....	72
3.1.2	Coarse Aggregate	74
3.1.3	Fine Aggregate.....	75
3.1.4	Mineral Admixtures.....	76
3.1.4.1	Microsilica	76
3.1.4.2	Flyash	77
3.1.4.3	Slag.....	78
3.1.5	Chemical Admixtures	79
3.2	Design of HPC Mixes	81
3.2.1	ACI 211- 4R Standard Practice	81
3.2.2	Mehta and Aitcin Simplified method	86
3.2.3	de Larrard's Method (1990).....	89
3.2.4	British Method (BRE 1988).....	92
3.3	Materials and Mix Proportioning.....	93
3.3.1	Mixing, Casting and Curing	98
3.3.2	Mix Proportions	98
3.4	Summary.....	99

Chapter 4. EXPERIMENTAL PROGRAM

4.1	Introduction	102
4.2	Test Specimen	102
4.3	Instrumentation	103
4.4	Test procedure	106
4.5	Summary	110

Chapter 5. BEHAVIOUR OF HPC UNDER UNIAXIAL REPEATED COMPRESSIVE LOADING

5.1	Introduction	111
5.2	Test Results and Evaluation	115
5.2.1	Stress-Strain Envelope Curve	115
5.2.2	Common point and stability point curves	123
5.2.3	Analytical Curves	123
5.3	Concept of Cyclic Permissible Stress	141
5.4	Plastic Strain Variations	144
5.5	Failure Mode	155
5.6	Summary	161

Chapter 6. ENERGY DISSIPATION CHARACTERISTICS OF HPC UNDER REPEATED COMPRESSIVE LOADING

6.1	Introduction	163
6.2	Energy Dissipation Capacity	164
6.3	Damage and Energy Dissipation in HPC	183
6.3.1	Strain Energy	186
6.3.2	Damage Energy	190
6.3.3	Damping Energy	195
6.4	Brittleness Index	199
6.5	Summary	202

Chapter 7. STIFFNESS DEGRADATION OF HPC UNDER UNIAXIAL REPEATED COMPRESSIVE LOADING

7.1	Introduction	204
7.2	The Coordinate System	207

7.3	Stiffness Degradation.....	208
7.3.1	Stiffness Degradation with respect to Envelope Strain.....	208
7.3.2	Stiffness Degradation with respect to Plastic Strain.....	214
7.3.3	Stiffness Degradation with respect to Energy Dissipation.....	218
7.4	Summary.....	223
Chapter 8.	REPEATED COMPRESSIVE LOADING - UNLOADING CURVES FOR HPC	
8.1	Introduction	224
8.2	Stress - Strain Coordinate System.....	226
8.3	Unloading - Reloading Stress - Strain Curves.....	226
8.3.1	Unloading Curves.....	226
8.3.2	Reloading Curves.....	234
8.4	Summary.....	244
Chapter 9.	SUMMARY CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH	
9.1	Summary.....	245
9.2	Conclusions	247
9.2.1	Behaviour under Uniaxial Repeated Compressive loading	247
9.2.2	Energy Dissipation Characteristics.....	249
9.2.3	Stiffness Degradation	250
9.2.4	Loading - Unloading Curves.....	250
9.3	Other observations.....	251
9.4	Recommendations for Future Study	251
	REFERENCES.....	253
	APPENDIX-A.....	269