

**CONSTITUTIVE MODELLING OF
REACTING LINEAR VISCOELASTIC CONCRETE**

by

**MILAN SUTER
DEPARTMENT OF CIVIL ENGINEERING**

**Submitted
in the fulfillment of the requirement for the degree of**

DOCTOR OF PHILOSOPHY

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI
NEW DELHI, INDIA
JULY, 2008**

Material testing, Concrete

TH

624.012:620.1

SUT-C

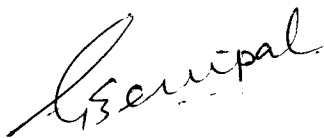
Acc. No. JH-3684



CERTIFICATE

This is to certify that the thesis entitled “**Constitutive Modelling of Reacting Linear Viscoelastic Concrete**” being submitted by Milan Suter to the Indian Institute of Technology, Delhi for the award of the degree of **Doctor of Philosophy** is a bonafide record of research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirements for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or diploma.



(Gurmail S. Benipal)
Assistant Professor
Department of Civil Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi – 110016
India

Acknowledgements

On this occasion, I wish to express my deepest respect and gratitude to my thesis supervisor Dr. Gurmail S. Benipal for his constant guidance, inspiration and motivation for this research work at every stage. He is a person who is always ready to help and to solve every doubt at any moment even in his busy schedule. Nothing can be compared to his guidance and there is no word to express my gratitude and indebtedness to him.

I am grateful to Prof. B. Bhattacharjee and Dr. A. K. Singh for their constant advice and support whenever I needed.

I take this opportunity to render my thanks to Mr. Sumedha Chakma, Mr. Umesh Kumar Pandey, Dr. R. R. Babu, Dr. Hanumant Rao, Mr. Munirami Reddy and Mr. Deepak Kumar for their continuous concern and support from the very beginning of my research work.

I can not forget to express my heartfelt thanks to Mr. Amitava Samanta for his constant inspiration and moral support till the completion of my thesis.

I have completed my Thesis work only because of the blessings of my parents. My Thesis is dedicated to them. I would like to mention the continuous support of my family members and all of them who always inspired me to complete this research work.



(Milan Suter)

Entry No: 2001RCE013

Abstract

Concrete is known to be an aging viscoelastic material. It exhibits considerable long-term creep, recovery and relaxation. Ongoing chemical reactions in concrete constitute another source of its viscoelastic behaviour. Ambient temperature has a multifold effect on mechanical behaviour. During their service life, concrete structures are subjected to simultaneous effect of service loads and ambient environment containing aggressive chemicals. For satisfactory performance of concrete structures, their design has to be based on sound understanding of all these aspects of behaviour of concrete.

Early creep theories, classical rheological models and empirical laws proposed by many researchers have proved to be unsatisfactory. Solidification theory proposed by Bazant and co-workers in 1989 has achieved some success in simulating the observed aging creep of hydrating concrete. It has been modified later by Bazant and co-workers in 1997 as microprestress solidification theory claimed to be capable of predicting aging creep of hydrating as well as hydrated concrete, transitional thermal creep and Pickett effect in drying creep. It has also been extended by combining it with time-shift theory by Grasley and Lange. These theories do not deal with behaviour of reacting concrete. Available theories of reacting concrete, like that due to Eierle and Schikora, are not based on any physico-chemical mechanism of deterioration or enhancement of concrete stiffness and viscosity. Thus, there is a need and scope for proposing appropriate constitutive models for simulating the observed aging thermochemomechanical behaviour of concrete.

The objective of the present Thesis is to study the aging thermoviscoelastic behaviour of concrete involved in some reactions including hydration. This objective has been achieved by proposing a new constitutive model, called Unified Constitutive Model, for reacting concrete. The proposed model is capable of simulating the various aspects like aging creep, recovery, relaxation, divergence, mobility, dissipation, etc., of observed long-term behaviour of reacting concrete subjected to general stress, strain and temperature histories. In this Thesis, concrete has been assumed to be homogeneous isotropic linear elastic solid undergoing small deformations.

The proposed Unified Constitutive Model (UCM) is based upon two physical mechanisms which transform the elastic concrete into an aging viscoelastic solid: The Dissolution-Precipitation (DP) Mechanism proposed by Benipal in 1995 and a physical

mechanism involving continuous process of bond breakage and restoration motivated by Adaptive-Link Mechanism proposed by Drozdov in 1998 for solid polymers.

According to dissolution-precipitation mechanism, the various linear elastic constituent phases of reacting concrete are assumed to be uniformly distributed and arranged in parallel arrangement. Creep in concrete is caused by the gradual transformation of its stressed solid reacting phase into stress-free solute on dissolution. It is the gradually increasing elastic deformations due to stiffness degradation on dissolution of stressed reacting solid phase which manifests as creep. The reaction products precipitating as stress-free solid phase gets stressed as and when their natural configuration changes. Aging is sought to be explained by the change in material stiffness and viscosity with progress of reaction. Using this chemico-mechanical mechanism, dissolution-precipitation theory has been proposed in this Thesis. As per this theory, the rate of any creep strain component is proportional to the rate of reaction as well as the instantaneous value of the corresponding total strain component. However, the proposed dissolution-precipitation theory predicts purely elastic behaviour for concrete not involved in any reactions and negative creep recovery. For better predictions, an empirical rheological model obtained by arranging in parallel the reacting element with a Maxwell element with time-dependent viscosity has also been proposed.

Second physical mechanism involving the continuous process of bond breakage and restoration has been proposed to remove these lacunae. The random nature of thermal motion resulting in continual breaking and restoration of chemical bonds between adjacent molecules vibrating at different frequencies has been ignored. All the constituent phases of concrete have been assumed to experience the same instantaneous fractional rate of bond breakage and restoration. Further, this fractional rate of bond breakage and restoration has been assumed to decay exponentially and asymptotically with age in a deterministic manner. As per this mechanism, the rate of any creep strain component is proportional to the instantaneous value of this fractional rate and to the corresponding elastic strain component. It is proved here that the aging is caused by age-dependence of material viscosity even though the material stiffness remains constant.

Using this physical mechanism alone, a constitutive model called Aging Maxwell Model (AMM), has been proposed for concrete not involved in any reactions. For constant fractional rate of bond breakage and restoration, the uniaxial version of this constitutive model reduces to the conventional Maxwell Rheological Model.

The effect of constant ambient temperature on viscoelastic behaviour of the material point has also been incorporated in Unified Constitutive Model. Two different expressions have been proposed for the rate of reaction and the fractional rate of bond breakage and restoration to simulate their peculiar functional dependence upon time and temperature.

In the absence of any reactions including hydration, the proposed Unified Constitutive Model reduces to Aging Maxwell Model. The Dissolution-Precipitation mechanism remains operational so long as the reactions continue whereas the physical mechanism based upon bond breakage and restoration is ever present and renders the concrete viscoelastic. However, as the fractional rate of bond breakage and restoration becomes infinitesimally small at later ages, Dissolution-Precipitation theory can be considered to be valid for very mature concrete involved in some reactions. Obviously, for hydrating concrete and for young concrete involved in some reactions, Unified Constitutive Model has to be used. For constant values of rate of reaction and of fractional rate of bond breakage and restoration, the special uniaxial case of Unified Constitutive Model with constant stiffness reduces to the Standard Linear Rheological Model.

The proposed model have been calibrated and empirically validated by the available experimental data on creep, recovery and relaxation of hydrating, reacting concrete or cement paste at different temperatures. The quantitative predictions of the model are quite accurate. The long-term behaviour of concrete involved in hydration, sulphate attacks, leaching, alkali-silica reaction, etc., has been predicted. The proposed constitutive model has also been shown to predict satisfactorily various qualitative aspects of observed long-term behaviour of concrete subjected to general stress, strain and temperature histories. Principle of superposition has been proved. Creep coefficients have been shown to be same for all strain components and all stress components have been shown to relax at the same fractional rate. The results presented in the Thesis are expected to be relevant for creep-based design and durability mechanics of concrete structures.

Contents

Certificate	ii
Acknowledgement	iii
Abstract	iv
Contents	vi
List of Figures	x
List of Tables	xiv
List of Symbols	xv

I Introduction

1.1. General Remarks	1
1.2. Objectives and Scope	5
1.3. Format of The Report	6

II Literature Review

2.1. General Remarks	7
2.2. Experimental Data	8
2.2.1. Hydrating Concrete	8
2.2.2. Reacting Concrete	13
2.3. Creep Mechanisms and Theories for Hydrating Concrete	15
2.3.1. Early Creep Mechanisms and Hypotheses	15
2.3.2. Classical Rheological Models	18
2.3.3. Empirical Models	19
2.3.4. Solidification Theory	21
2.3.5. Microprestress Solidification Theory	25
2.3.6. Time-Shift Solidification Theory	26
2.3.7. Other Constitutive Models	27

2.4. Creep Mechanisms and Theories for Reacting Concrete	30
2.4.1. Dissolution-Precipitation Mechanism and Theory	30
2.4.2. Other Constitutive Models	35
2.5. Codes and Standards	36
2.5. Closure for Chapter II	37

III Constitutive Model for Reacting Elastic Concrete

3.1. General Remarks	39
3.2. Dissolution-Precipitation (DP) Mechanism	40
3.3. Dissolution-Precipitation (DP) Theory	41
3.3.1. Basic Postulates	41
3.3.2. Derivation of Governing Equations	44
3.4. Equivalent Phenomenological Model	56
3.4.1. Normal Stress/Strain Histories	56
3.4.2. General Stress/Strain Histories	59
3.4.3 Gradual Stress Redistribution amongst Phases	66
3.5. Model Calibration and Validation	68
3.5.1. Identification of Relevant Material Parameters	68
3.5.2. Calculation of Relevant Material Parameters	72
3.5.3. Prediction of Behaviour of Reacting Concrete	81
3.6. Discussion and Interpretation	83
3.6.1. Viscoelasticity	83
3.6.2. Durability Mechanics	90
3.7. Closure for Chapter III	93

IV Empirical Rheological Model for Reacting Viscoelastic Concrete

4.1. General Remarks	114
4.2. Reacting Rheological Element	115
4.2.1. Proposed Rheological Model	115
4.2.2. Governing Differential Equations	115
4.2.3. Creep	117
4.2.4. Superposition Principle	121
4.2.5. Recovery	122

4.2.6. Relaxation	122
4.3. Model Calibration and Validation	124
4.4. Discussion and Interpretation	125
4.5. Closure for Chapter IV	128

V Constitutive Models for Inert Concrete

5.1. General Remarks	138
5.2. Microprestress Theory.....	139
5.3. Phenomenological DP Model: Constant Stiffness Case	142
5.4. Aging Maxwell Constitutive Model	146
5.5. Calibration and Validation of Proposed Models	153
5.6. Discussion and Interpretation	155
5.7. Closure for Chapter V	156

VI Constitutive Model for Reacting Viscoelastic Concrete

6.1. General Remarks	164
6.2. Proposed Unified Constitutive Model	165
6.3. Model Calibration and Validation	167
6.6. Discussion and Interpretation	173
6.7. Closure for Chapter VI	177

VII Constitutive Model for Reacting Thermoviscoelastic Concrete

7.1. General Remarks	201
7.2. Time-Dependent Behaviour of Concrete at Constant Temperature	202
7.2.1. General Unified Model	203
7.2.2. Model Calibration and Validation	205
7.2.3. Special Cases	206
7.2.3.1. General Dissolution-Precipitation Model	206
7.2.3. 2. General Aging Maxwell Model	207
7.3. Discussion and Interpretation	207
7.4. Closure for Chapter VII	209

VIII Critical Evaluation

8.1. General Remarks	216
8.2. Theoretical Significance	216
8.3. Empirical Validation	218
8.4. Practical Relevance	223
8.4.1. Creep	223
8.4.2. Durability Mechanics	224

IX Conclusions

9.1. Concluding Remarks	227
9.2. Scope for Future Research	233

References	235
-------------------------	-----

Appendices

A1. Publications out of the Present Thesis	245
---	-----

A2. Curriculum Vitae of the Candidate	246
--	-----