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

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.

GS Benipal

(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

(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, there 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