Characterization of the Shrinkage Behavior of High Performance Cement Based Materials for Structural Rehabilitation
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Tensile stresses might be generated in cement based materials when volumetric changes due to moisture loss, temperature changes, or chemical reactions are prevented by a source of restraint. When tensile stresses exceed the actual value of the tensile strength of the material, this may result in cracking. Cracks can accelerate the premature deterioration of the material and reduce the durability of the structure. Therefore, restrained shrinkage cracking is considered one of the most critical issues for thin concrete structures such as highway pavements, industrial floors, bridge decks, and also for partial depth repairs, jacketing and overlays on existing structures.

New advances in construction methods, materials, and admixtures have renewed interest on early age cracking in cement-based materials due to restrained shrinkage. During the last few years, concrete technologists have studied the mechanism governing early age cracking in concrete members, especially after the introduction of high performance materials such as high strength concrete (HSC) with its increased material brittleness and fiber reinforced concrete (FRC), with its capacity to control cracking due to restrained shrinkage.

The assessment of the shrinkage cracking potential could not be performed with traditional tests for plain and fiber reinforced concrete; it should be determined by means of a restrained shrinkage test that considers both the effect of restraint conditions and material properties. During the last three decades, a number of studies have been carried out which have primarily used three types of tests: linear, plate, and ring tests (Chapter 2).

This work concerns the study of the behavior of high performance materials, i.e. fiber reinforced concrete (FRC) subjected to restrained shrinkage conditions. The main goals of this study are: the explanation of the physical significance of restrained shrinkage behavior of concrete (Chapter 3), the determination of the effects of the fiber reinforcement on restrained shrinkage cracking (Chapter 4), the determination of the influence of size and geometry of the restrained ring test (Chapter 5), and the proposal of a standard test method for the evaluation of cracking sensitivity of high performance materials.
Nei materiali a base cementizia si possono sviluppare rilevanti sforzi di trazione quando le variazioni volumetriche vengono impedite dalla presenza di vincoli. Queste possono essere dovute ai cambiamenti di umidità e di temperatura, oltre che alle reazioni chimiche che avvengono all’interno della matrice cementizia. Quando gli sforzi di trazione superano il valore della resistenza del materiale, si innescano fessure che ne accelerano il deterioramento e che, conseguentemente, ne condizionano la durabilità. Per questo motivo, la fessurazione dovuta al ritiro vincolato viene considerata come uno dei principali problemi delle strutture in cemento armato con spessore ridotto.

I recenti progressi compiuti nel campo dei nuovi materiali ed degli additivi per calcestruzzi, hanno portato il mondo della ricerca ad un nuovo interesse per la fessurazione precoce dei materiali a base cementizia. Nel corso degli ultimi anni, i tecnologi hanno studiato i meccanismi che governano la fessurazione dovuta a ritiro vincolato, in particolar modo dopo la diffusione sul mercato di materiali ad alte prestazioni, come il calcestruzzo ad alta resistenza (HSC) ed il calcestruzzo fibrorinforzato (FRC).

La valutazione del potenziale di fessurazione per il ritiro vincolato, non può essere effettuata attraverso le usuali prove previste per il calcestruzzo tradizionale e fibrorinforzato, ma deve essere determinato per mezzo di una prova di ritiro impedito che consideri sia l’effetto delle condizioni di vincolo che le proprietà del materiale. Per questa ragione, numerosi studi sono stati effettuati negli ultimi tre decenni attraverso tre tipi di prova: la prova lineare, la prova di piastra ed il Ring Test (Capitolo 2).

Questo lavoro di tesi tratta lo studio del comportamento a ritiro dei materiali ad alte prestazioni sviluppati per applicazioni di rinforzo strutturale. Gli obiettivi principali sono: la comprensione del significato fisico del ritiro vincolato (Capitolo 3); la determinazione degli effetti del rinforzo fibroso sul comportamento del materiale soggetto a ritiro libero o vincolato (Capitolo 4); lo studio parametrico delle dimensioni e della geometria del Ring Test (Capitolo 5); e la proposta di un nuovo metodo di prova per la valutazione della sensibilità alla fessurazione dei materiali a base cementizia ad elevate prestazioni.
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# TABLE OF CONTENTS

1 INTRODUCTION ........................................................................................................... 3

2 LITERATURE REVIEW .............................................................................................. 7
2.1 Shrinkage .................................................................................................................. 8
2.1.1 Plastic shrinkage ................................................................................................. 8
2.1.2 Drying shrinkage ............................................................................................... 9
2.1.3 Autogenous shrinkage ..................................................................................... 19
2.1.4 Carbonation shrinkage ..................................................................................... 20
2.2 Literature test methods .......................................................................................... 21
2.2.1 Linear test ........................................................................................................ 21
2.2.2 Plate test .......................................................................................................... 28
2.2.3 Ring test ........................................................................................................... 29
2.3 Standard test methods ........................................................................................... 46
2.3.1 Ring test .......................................................................................................... 46
2.4 References ............................................................................................................. 53

3 ANALYTICAL MODELS ....................................................................................... 59
3.1 Introduction ............................................................................................................. 59
3.2 Creep and shrinkage analysis ................................................................................ 61
3.2.1 Aging linear viscoelasticity ............................................................................ 61
3.2.2 ACI 209R-92 Model ....................................................................................... 67
3.2.3 Solving the aging linear viscoelastic equations ............................................ 71
3.3 Restrained shrinkage analysis ................................................................................ 75
3.3.1 Linear model .................................................................................................. 75
3.3.2 Strain compatibility equations ....................................................................... 77
3.3.3 Model A1 - Effective Modulus method ....................................................... 78
3.3.4 Model A2 - Age-Adjusted Effective Modulus method ............................. 81
3.3.5 Model A3 - Numerical solution of history integrals .................................. 83
3.3.6 Cracking model ............................................................................................. 84
3.3.7 Comparison of the analytical models ............................................................ 88
3.4 Case study ............................................................................................................. 95
3.4.1 Ring test ....................................................................................................... 95
3.4.2 Sensitivity study ............................................................................................ 103
3.5 Concluding remarks ......................................................................................... 107
3.6 References ......................................................................................................... 110
# TABLE OF CONTENTS

4  EXPERIMENTAL RESULTS ................................................................. 113
  4.1  Introduction .......................................................................................... 113
  4.2  Mechanical properties .......................................................................... 117
    4.2.1  Materials ......................................................................................... 117
    4.2.2  Mix design and specimens ................................................................. 119
    4.2.3  Mechanical properties of concrete ..................................................... 123
    4.2.4  Test results ........................................................................................ 127
  4.3  Free shrinkage tests ................................................................... 132
    4.3.1  Free shrinkage test ........................................................................... 132
    4.3.2  Test results ........................................................................................ 136
  4.4  Restrained shrinkage tests ............................................................. 140
    4.4.1  Introduction ....................................................................................... 140
    4.4.2  Specimen geometry ......................................................................... 141
    4.4.3  Test execution .................................................................................... 144
    4.4.4  Test results ........................................................................................ 147
  4.5  Concluding remarks ................................................................. 159
  4.6  References ..................................................................................... 161

5  NUMERICAL ANALYSES .................................................................. 163
  5.1  Introduction ....................................................................................... 163
  5.2  Finite element analysis .................................................................... 165
    5.2.1  Modeling approach ........................................................................ 165
    5.2.2  Material properties ......................................................................... 166
    5.2.3  Finite element modeling ................................................................ 173
    5.2.4  Validation of the FE model .............................................................. 175
  5.3  Parametric studies ........................................................................ 176
    5.3.1  Aim of the study ............................................................................. 176
    5.3.2  FE model – AASHTO Designation PP 34-99 .................................. 176
    5.3.3  Numerical model ........................................................................... 177
    5.3.4  Effect of geometry .......................................................................... 180
    5.3.5  Effect of material toughness ............................................................ 181
    5.3.6  Numerical results .......................................................................... 182
  5.4  Concluding remarks ................................................................. 185
  5.5  References ..................................................................................... 186

6  CONCLUSION ................................................................................... 187
CHARACTERIZATION OF THE SHRINKAGE BEHAVIOR OF HIGH PERFORMANCE CEMENT BASED MATERIALS FOR STRUCTURAL REHABILITATION
1 INTRODUCTION

Tensile stresses might be generated in concrete when volumetric changes are prevented by a source of restraint. Volumetric changes are a result of several factors, such as moisture loss, temperature changes, or chemical reactions taking place in concrete. When tensile stresses exceed the actual value of the tensile strength in the material, they may result in cracking. Restrained shrinkage cracking is one of the most critical issues that leads to early damage for thin concrete structures such as highway pavements, industrial floors, bridge decks, but also for partial depth repairs, jacketing and overlays on existing structures. Cracks allow water and chemical products to penetrate into the concrete increasing the effects of freeze-thaw damage, spalling due to sulfate and chloride penetration, and corrosion of steel reinforcement. These causes may result in premature deterioration of the material and in potential deficiencies of the structural performance of the element.

Restrained shrinkage cracking generally occurs in the first few days after placement of concrete, due to the high initial rate of shrinkage and the slow developing of mechanical properties with the progress of hydration process. Stresses arise from the combined action of an imposed strain history, due to shrinkage, and the relief of the induced stresses due to creep relaxation. Therefore, restrained shrinkage cracking can be considered a complex process depending both on the boundary conditions of the element (i.e. surrounding environmental conditions and restraint conditions), and the mechanical properties of the material (i.e. tensile strength, elastic modulus, creep relaxation, and fracture toughness).

New advances in construction methods, materials, and admixtures have renewed interest on early age cracking in cement based materials due to restrained shrinkage. During the last few years, concrete technologists have been studying the mechanism governing early age cracking in concrete members, especially after the diffusion of high strength concretes (HSC), materials with low water-to-cement ratio, that have an high cracking potential with regard to restrained shrinkage. Despite an increased tensile strength, high strength concretes (HSC) develop higher stress rates and earlier age of cracking, due to an increased material brittleness.

As concrete is characterized by a poor tensile strength, a number of different techniques have been developed to improve the concrete resistance to tensile stresses
induced by shrinkage: steel reinforcement, welded wire fabric, post-tensioned steel reinforcement and fiber reinforcement. The latter, a short randomly distributed fiber reinforcement, has been shown as one of the more promising techniques in controlling shrinkage cracking of concrete members. The addition of fibers increases the material toughness, and, thus, the energy required to the cracking process. After cracking occurs, fibers bridge across the crack resulting in crack width control and stress transfer. However, the cracking sensitivity of fiber reinforced concrete (FRC) is largely influenced by the type, volume, and geometry of fibers.

Conventional laboratory tests for fiber reinforced concrete (i.e. uniaxial tensile testing, four point bending test on beams, and flexural testing of round panels), provide useful information on fracture properties (i.e. direct tensile strength, modulus of rupture, and fracture energy) but cannot be used to estimate the actual shrinkage cracking potential of a given concrete mixture. The assessment of the shrinkage cracking potential should...
be determined by means of a restrained shrinkage test that can consider both the effect of restraint conditions and the effect of time-depending material properties. Many studies have been carried out, mainly using three types of test: the linear test, the plate test and the ring test. The linear restrained column type test gives a simple uniaxial stress development but suffers from the disadvantage of not providing a constant degree of restraint that makes this test complex. The plate test provides a biaxial restraint to evaluate both biaxial and plastic shrinkage. The ring test provides a nearly constant degree of reaction through an axis-symmetric specimen geometry. In this type of test, a concrete specimen is cast around an inner steel ring which provides a constant degree of restraint to the shrinkage deformation; the steel ring is also used to evaluate the induced tensile stresses in concrete through the measure of the steel compressive strains with strain gauges.

This work concerns the study of the behavior of high performance materials, i.e. fiber reinforced concrete (FRC) and high strength concrete (HSC), subjected to restrained shrinkage conditions. Accordingly, the main objectives of this work are listed below:

1. Explain the physical significance of restrained shrinkage behavior of concrete by means of the application of the linear aging viscoelasticity theory.
2. Determine the effects of the fiber reinforcement in controlling restrained shrinkage cracking in concrete members.
3. Determine the influence of size of the restrained ring test and define an optimized geometry.

This thesis is a result of a wide study that addresses the issue of restrained shrinkage cracking of high performance materials through the development of analytical models, the execution of experimental tests, and the performing of numerical analyses on non-linear finite element models. These issues are argued and presented in six chapters, listed below:

- Chapter 2 presents the results of a wide literature research study that concerns the characterization of shrinkage behavior of new high-performance materials for structural rehabilitation. Besides comprehensive theoretical description of the shrinkage phenomenology, the research summarizes the experimental tests conducted and the models developed for the study of restrained shrinkage over the last three decades.

- Chapter 3 presents an overview on creep and shrinkage analysis of concrete structures. The aging linear viscoelasticity theory is used to describe the restrained
1 INTRODUCTION

shrinkage behavior and to predict the age of first cracking in simple case studies. Analytical models present the influence of the material properties on the development of stresses into the material. In particular, the influence of shrinkage, elastic modulus and creep relaxation are discussed in detail. The exact linear solution for the restrained ring test is presented.

- Chapter 4 presents the results of several series of experiments performed on different ring-type (e.g. AASHTO Designation PP 34-99) and modified notched ring-type specimens. Concerning the ring test, the cracking sensitivity of plain and fiber reinforced concrete (FRC) mixtures is assessed. In particular, the effect of fiber addiction on the age of first cracking and the post-peak behavior. This chapter also presents an alternative test procedure based on the use of notched ring specimen. The aim of this proposal is to have a direct measure of the crack opening displacement, in addition to the cracking initiation time.

- Chapter 5 presents the influence of material properties and specimen geometry on the cracking sensitivity of concrete mixtures in ring-type test, via non-linear numerical analysis on finite elements models. In this chapter the results of a parametric study on the parameters affecting the material behavior (i.e. shrinkage strain, elastic modulus, and creep relaxation), and the parameters determining the geometry of the test (steel thickness, concrete thickness and notch depth) are presented. An optimized geometry for ring-type test is defined.

- Chapter 6 is a summary of the conclusions and an outline of the findings of this work.