

RESTRAINED SHRINKAGE CRACKING IN CONCRETE

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INTRODUCTION

Early age cracking is one of the most troublesome problems currently faced in the construction of concrete pavements. Early age cracking occurs during the first few weeks after placement due to a high initial rate of shrinkage along with slowly developing material properties. Cracking reduces the load carry capability while leading to premature deterioration which shortens overall pavement life. When volumetric changes caused by shrinkage or temperature are restrained by subbase friction, inclusions, or reinforcement; tensile stresses develop which can result in early age cracking. This paper summarizes the results of a continuing long term investigation on cracking due to restraint including:

- the development of test methods to assess shrinkage cracking potential (1,2),
- the effect of higher strength (3), wire mesh reinforcement (4), fiber reinforcement (5,6), and shrinkage reducing admixtures (2,7) in the prevention of early age cracking, and
- the development of modeling techniques to predict the age of first cracking (8,9)

A micro-concrete (10 mm maximum aggregate size) has been used with 1:2:2:0.5 mix proportions (cement: fine aggregate: coarse aggregate: water) throughout this study with the exception of the cellulose fiber mixes which had a water content of 0.55 and the addition of silica fume for high strength concrete.

TEST METHODS

Currently, no standard test method exists to assess a pavement's susceptibility to shrinkage cracking. Shrinkage cracking due to restraint is not only dependent on free shrinkage; but is also influenced by time dependent development of material parameters including: stiffness, fracture resistance, creep relaxation, and the degree of restraint. Several researchers (10-12) have used linear specimens restrained at both ends to investigate shrinkage cracking. Use of these linear geometries results in the development of uniaxial tensile stresses which can easily be related to specific structural applications. However due to laboratory difficulties in providing sufficient end restraint and avoiding eccentricities, research at Northwestern has relied upon the use of restrained ring specimens as shown in Figure 1.

Used as early as 1939 (13), ring specimens provide a simple test method in which the effect of restrained shrinkage cracking can be easily studied. In this test, concrete is cast between an inner rigid steel ring and a PVC form as shown in Figure 1a. After demolding, the concrete dries and consequently wants to shrink. The rigid steel core prevents deformations due to shrinkage resulting in the development of tensile stresses. Although the circumferential stress distribution is non-linear and radial stresses exist, an appropriate choice of specimen dimensions can be used to approximate a uniaxial state of stresses (within 10% for the specimen dimensions as shown in Figure 1a) while still maintaining a thickness of three times the minimum aggregate size. An optical illuminated microscope has been designed to rotate around the specimen to measure the crack openings as shown in Figure 1b. In addition to being free to rotate, the height of the microscope is adjustable to provide width measurements at different locations along the length of the crack.

More recently linear specimens restrained at the base have been developed to compare specimen geometry and restraint conditions as shown in Figure 2 (2). Thin specimens have been selected to minimize the moisture gradient effects which exist in specimens of larger geometry. Steel strips have been welded on a rigid base to simulate subbase friction and multiple cracking has been observed. An optical microscope was used to measure crack openings.

EFFECTS OF MATERIAL COMPOSITION

Several alterations in material compositions have been proposed to reduce the susceptibility to shrinkage cracking including the use of expansive agents, higher strength concrete, short randomly distributed fibers, and shrinkage reducing admixtures.

Higher Strength Concretes

Early investigations based on a strength of materials approach related the age of first cracking to the tensile strength of concrete. Based on these concepts increased tensile strength (often high early) was proposed as one solution to solve the early age cracking problems. In addition to higher strength, the use of pozzolanic materials and high-range water reducing admixtures has become a common method used to increase material density and durability thereby resulting in high performance concrete. It has been recently shown that, despite higher tensile strength, high performance concrete demonstrates higher shrinkage rates, decreased creep relaxation, and an increase material brittleness leading to earlier ages of first cracking (2,3,11,12). A recent study (3) investigated the effect of increased strength through the use of silica fume and its influence on early age cracking. In this study it was observed that free shrinkage does not correlate directly with weight loss as shown in Figure 3, suggesting that free shrinkage in silica fume modified concrete does not correspond directly with water content or water loss. Possible explanations for this difference may include a finer pore structure which increases internal forces or increases in autogenous and chemical shrinkage. In addition, it has been suggested that higher strength concrete may exhibit less creep relaxation and consequently the stresses generated in the pavements may be higher (11). Figure 4a (2) illustrates the difference between stresses calculated based on shrinkage strain alone (circles) and then recalculated considering creep relaxation (crosses) (14) which can significantly reduce stress. Figure 4b (3) provides the results of an early age (3 day) compressive creep test performed with varying percentages of silica fume. A significant reduction in specific creep was observed with the addition of silica fume. This investigation showed that increases in compressive strength are often accompanied by a significant increase in the age at first cracking as shown in Figure 5a. In addition, Figure 5b shows earlier age cracking results in wider crack openings due to higher shrinkage and lower creep relaxation. To limit crack openings, reinforcement or welded wire fabric is often added. Accurate placement of the reinforcement is often difficult, costly, and may result in corrosion concerns. It is for this reason that short randomly distributed fiber reinforcement has been investigated as one possible solution to this problem.

Fibers

Recent investigations have shown the use of short randomly distributed fibers (5,15) to significantly limit the effects of shrinkage cracking. The addition of fibers increases material toughness necessitating increased energy to propagate a crack (16). After cracking occurs, fibers bridge crack openings resulting in reduced crack width and fibers transfer stress across the crack to distribute smaller less detrimental cracks throughout the specimen. The efficiency of fibers is dependent on several factors including fiber length, aspect ratio, volume, strength, stiffness, and bond with the matrix. To evaluate the efficiency of different fiber types three different materials were investigated including: cellulose, polypropylene, and steel. The addition of fibers is often reported in literature to have significant reduction in the free shrinkage of paste and mortar specimens, however substantial reductions in free shrinkage are not often observed in concrete (10% reduction with steel fibers) (1). Steel fibers are widely used as secondary reinforcement in engineering practice due to the high fiber strength and elastic modulus. Use of polypropylene fibers has recently increased due to the low material cost, favorable performance, and corrosion resistance. Figure 6a provides results of the age at first visible cracking ($\sim 100 \mu\text{m}$) with various percentages of fiber (1,4-6). It should be noted that while fiber reinforced concrete appears to delay the age to first cracking, strain gages mounted on the specimen revealed discontinuities in strain development suggesting the existence of 'invisible' micro-cracks. Figure 6b illustrates a significant reduction in crack opening with increases in fiber volume. The results of these studies show steel fibers significantly reduce crack openings due to increased fiber stiffness, while polypropylene and wood fibers exhibit similar behavior reducing cracks to approximately 1/3 the opening experienced in plain concrete. Fiber additions above the volumes presented often result in difficulties in achieving a workable mix. A fiber volume of at least 0.25% appear necessary to have a significant reduction in crack width.

Shrinkage Reduction

An alternative method to limit shrinkage cracking is to reduce drying shrinkage. Drying shrinkage occurs over time as water is removed from concrete resulting in the development of internal tensile stresses causing shrinkage (17). Different alcohol based organic admixtures have been investigated to reduce shrinkage in concrete (7,18). It has been proposed (19) that these admixtures reduce the surface tension of water which alters the internal development of tensile forces created during shrinkage. Additional explanations for the reduction in drying shrinkage may be attributed to the reduction in pore size as determined from mercury intrusion porosimetry (MIP) testing (7). Recently, a commercially available form of this shrinkage reducing admixture has been made available which has been successfully shown to significantly reduce of drying shrinkage (2). Results of free shrinkage tests (Figure 7a) illustrate a 25% reduction in free shrinkage with 1% SRA and nearly a 45% reduction with 2% SRA. This reduction in free shrinkage strains results in lower tensile stress development and consequently reductions in the age at first cracking of ring specimens as shown in Figure 7b.

MODELING APPROACHES

Several different modeling approaches have been investigated to predict the age of first cracking including: strength of materials, damage mechanics, and fracture mechanics. A summary of each method is described below including comparisons with experimental results and time material inputs required for calculations.

Conventional Strength Modeling

A conventional strength of materials approach has been presented as one method to predict the age of first cracking as shown in Figure 8. In this figure tensile strength is plotted as a function of time with the development of shrinkage stress (dashed line) and stress after creep relaxation (solid line). While this model provides a good conceptual method for visualizing the age of first cracking, it is often inaccurate due to the low slopes of both intersecting curves. Tensile strength of concrete is often difficult to calculate directly and large material scatter exists, as a result modulus of rupture or tensile splitting values are often used as an approximation to the tensile strength. In addition, this model can not account for the addition of fibers or precracking and consequently it often results in erroneous predictions (20). It is for this reason that an approach based on damage mechanics was investigated.

Damage Mechanics

To account for the addition of fibers, Grysowski and Shah (8) developed a model which uses damage mechanics to predict the age of first cracking. In this model, the shrinkage in the specimen is subdivided in several time steps and an incremental approach was taken. Specimen strains are calculated based on the difference between a reference deformation (perfectly rigid = 0) and deformations due to free shrinkage. Creep relaxation is considered as both a time and load dependent function to produce an overall specimen stress. These strains are compared to the material's resistance through the use of a constitutive relationship which accounts for both cracked and uncracked segments. The response of the uncracked element is assumed to be non-linear to incorporate pre-cracking is shown using Figure 9a in which the parameters include: elastic modulus, Poisson's ratio, tensile strength, creep relaxation, and a damage parameter. After the developed stresses reach the tensile strength of the material, a cohesive crack consistent with experimental observations (21-23) is introduced to transfer tensile stresses. Figure 9b illustrates strain compatibility for the case of cracked concrete. In uncracked concrete the overall specimen strain is separated into an uncracked component (as described above), and a cracked component which includes cohesive and interfacial stresses calculated based on the width of the crack opening. A linear relationship between stress transfer and crack opening is assumed. If the stress accumulated in the uncracked element exceeds the tensile strength of the material subsequent cracking will develop which is treated in a similar manner. This method accurately predicts the age at first cracking, number of cracks, and crack width. It should be noted however, that significant experimental work is required and manual calculations of material parameters and specimen response can be time consuming. It is for this reason that a failure criteria based on fracture mechanics was investigated.

Fracture Mechanics

A fracture mechanics failure criteria is currently preferred for four main reasons. First, cement based materials exhibit quasi-brittle behavior in which a stable crack may occur initially without leading to material failure. Second, fracture mechanics provides a method of accounting for the additional energy required to propagate a crack in fiber

reinforced concrete where strength design does not. Third, tensile strength criteria does not correspond well with experimental results. Finally, the fracture model may be automated to reduce time-consuming manual calculations.

Many fracture mechanics models have been developed to describe the failure of concrete structures (24). The approach used in this model is based on fracture resistance (R-Curve) concepts as presented by Shah et al. (9). Figure 10a provides a pictorial description of the fracture resistance (R-Curve) and strain energy release rate, alternatively called the crack driving energy (G-curve). An initial flaw in the concrete is assumed as a crack of length (a_0). As the load increases the G-Curve moves from point b to point c. The crack then begins to propagate in a stable manner until the G-curve reaches point d at which unstable crack propagation results in failure.

This model fits continuous time functions to discrete time dependent material parameters for stiffness and fracture properties. Stress developed is calculated by coupling the effects of shrinkage strain and creep stress relaxation (2,21) as shown in Figure 4a. Because the magnitudes of shrinkage and creep stresses are generally similar, ignoring creep relaxation effects introduces significant errors in the prediction of the age of first cracking. The age of first cracking is determined by solving the energy balance conditions (i.e. energy curves are tangent as shown in Figure 10) using numeric functions which vary the values of " t " and " Δa ". The stable solutions obtained from the above steps provide the age of shrinkage cracking and the maximum stable crack extension. Figure 10b illustrates favorable comparison between the model predictions and experimental results for several different mixes.

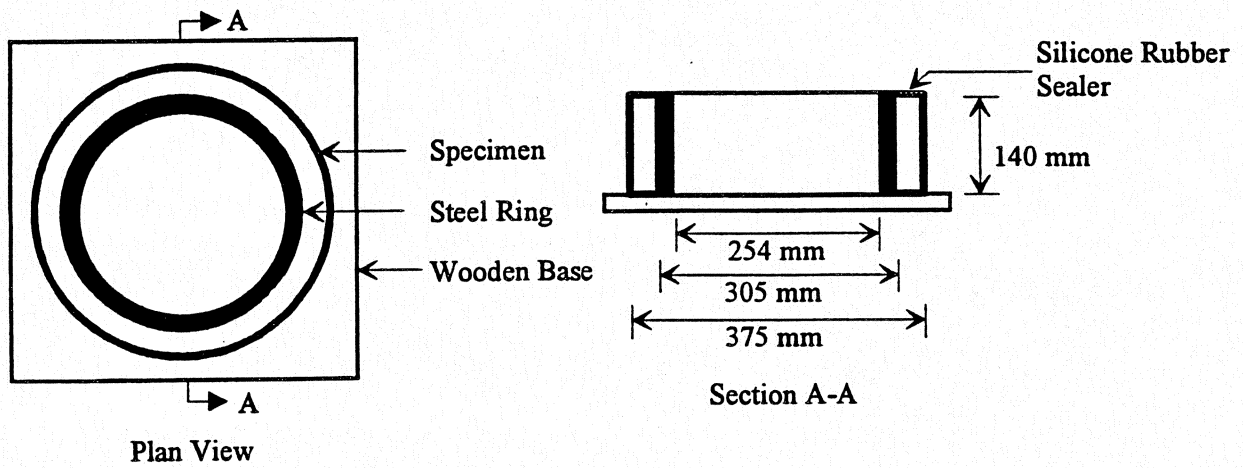
CONCLUSIONS

Based on the current results of this long term investigation several conclusions can be drawn.

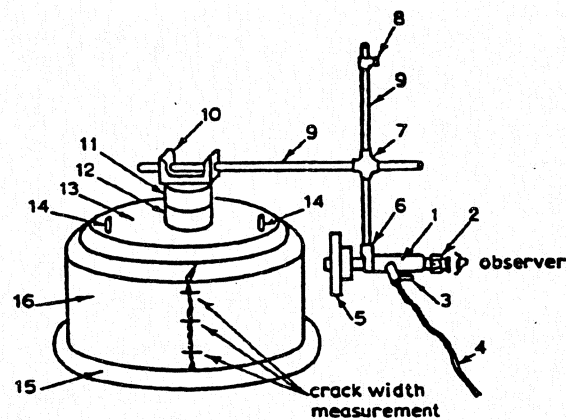
- Ring specimens can be used as an effective test method to simulate restraint conditions which occur in concrete pavements. Due to the ease of experimental set-up, the ring test be easily performed on site along with other quality control methods.
- Earlier ages of first cracking are generally observed with an increase in compressive strength. This is especially true in specimens in which the water to binder ratio is decreased through the use of superplasticizing agents.
- Short randomly distributed fiber reinforcement (steel, polypropylene, and cellulose) result in significant delays in the age to visible first cracking ($\sim 100 \mu\text{m}$) and significant reductions in crack openings, although a significant reduction in free shrinkage is not observed.
- Shrinkage reducing admixtures can be used to drastically reduce free shrinkage, nearly 25% with 1% SRA and 44% with 2% SRA by weight of cement.
- Tensile creep significantly reduces stresses generated at early ages. Understanding the behavior of early-age tensile creep is vital in the prediction of early age cracking.
- Conventional strength of materials does not accurately predict the age of first cracking.
- A damage mechanics based model can be used to predict the age of first cracking, although extensive testing and calculations are often required.
- Predictions of the fracture based model demonstrate favorable comparison with experimental observations.

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- Figure 10: Fracture Mechanics Approach To Predict Age At First Cracking: a) R Curve And b) Comparison Of Theoretical Predictions With The Age Of First Cracking



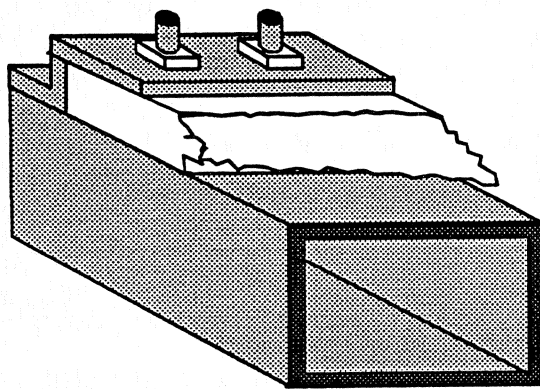
(a)



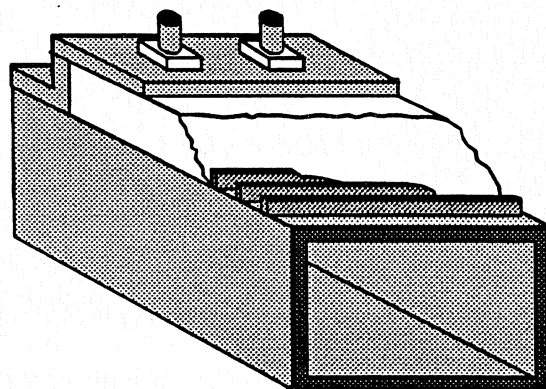
- 1 microscope
- 2 filar eyepiece
- 3 focusing knob
- 4 internal illumination
- 5 fluorescent lamp
- 6, 7, 8, 9, 10, 11, microscope, mounting, hardware
- 12 preloaded bearing pivot
- 13 mounting plate
- 14 dowel pins
- 15 wooden base
- 16 specimen

(b)

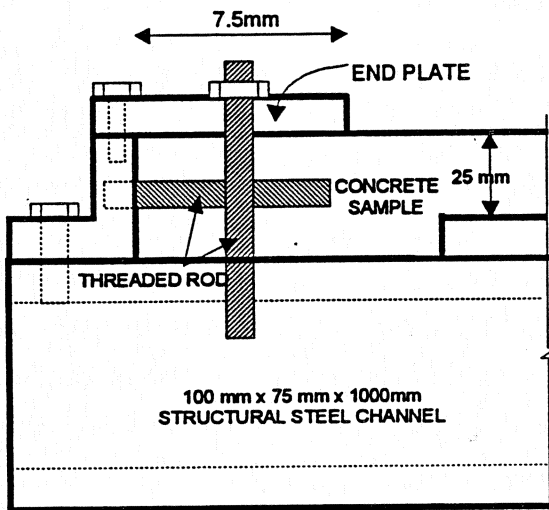
Figure 1: a) Restrained Ring Geometry and b) Optical Microscope Used For Measuring Crack Openings (adapted from 1,5)



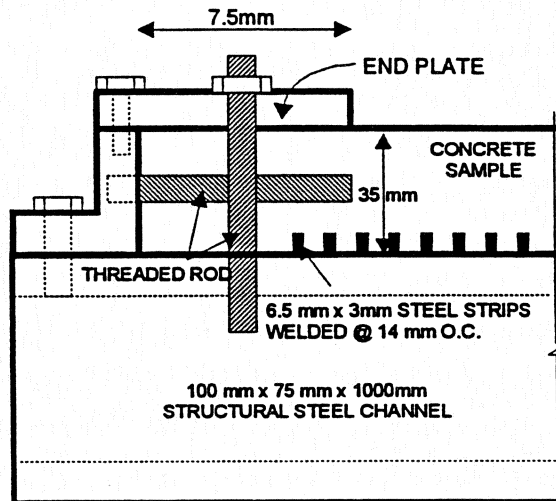
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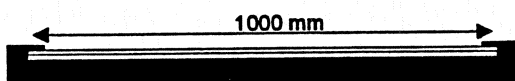
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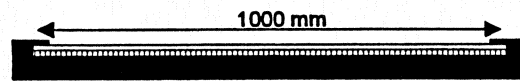
END SUPPORT DETAIL



END SUPPORT DETAIL



SIDE VIEW

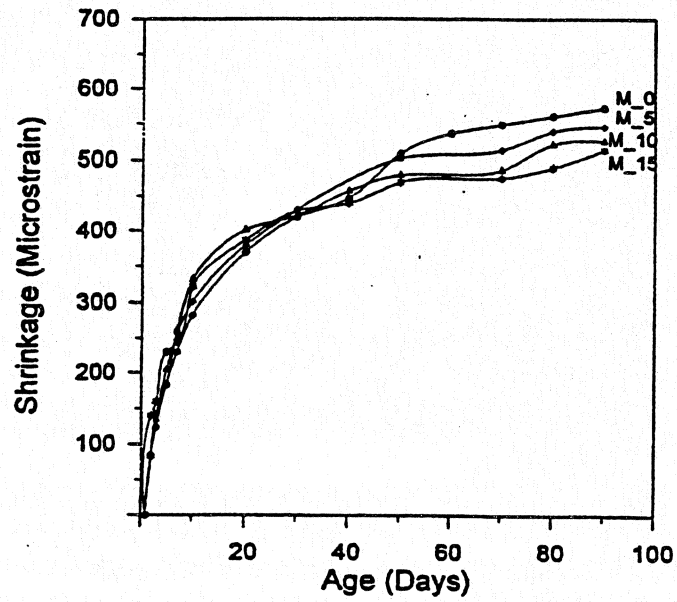


SIDE VIEW

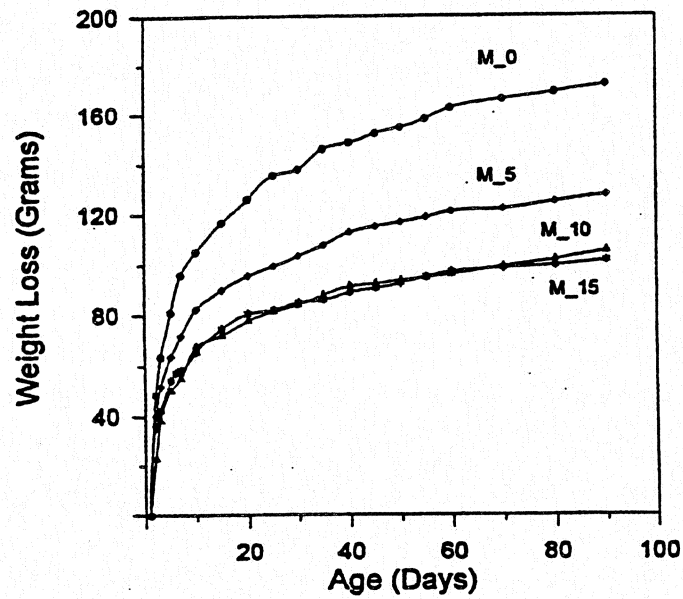
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RESTRAINED BASE AND END

Figure 2: Restrained Base Slab Geometries (2)

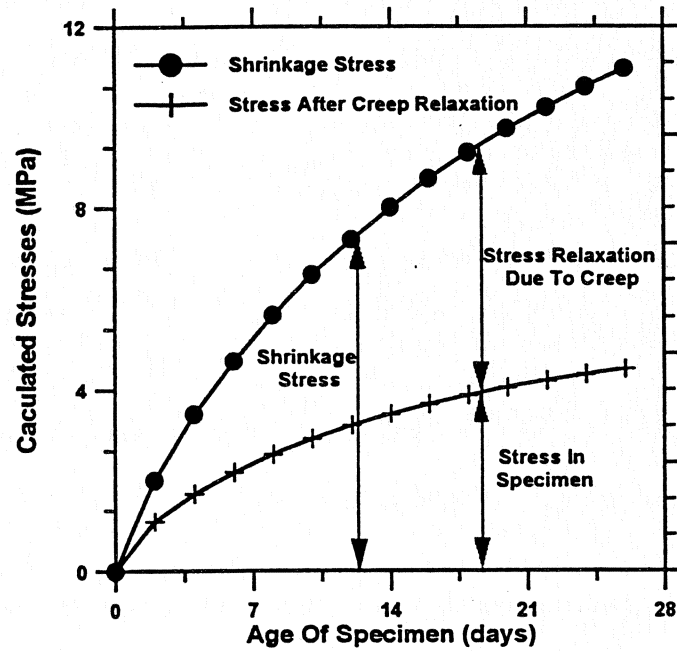


(a)

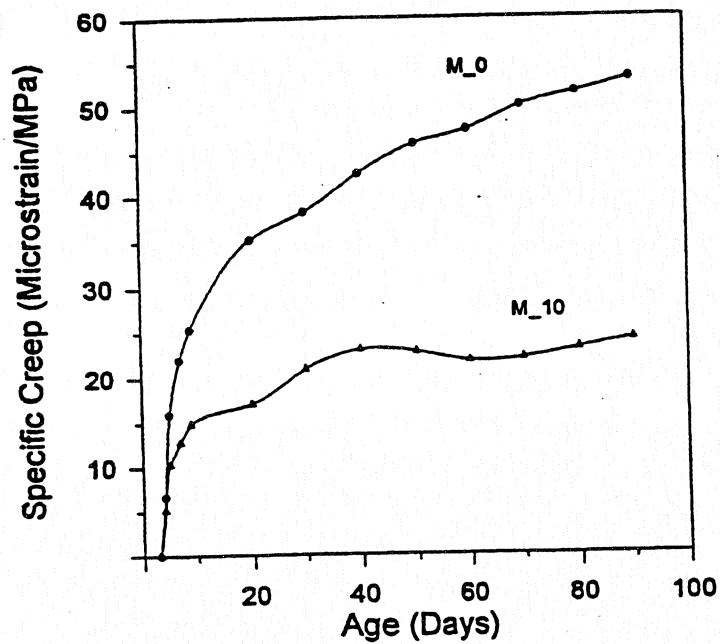


(b)

Figure 3: a) Free Shrinkage with Increase in Silica Fume Content and b) Weight Loss with Increase in Silica Fume Content (3) note: M-0 = 0% Silica Fume By Weight of Cement



(a)



(b)

Figure 4: a) Creep Relaxation and b) Specific Creep with Increasing Silica Fume Content (3)
 note: M-0 = 0% Silica Fume By Weight of Cement

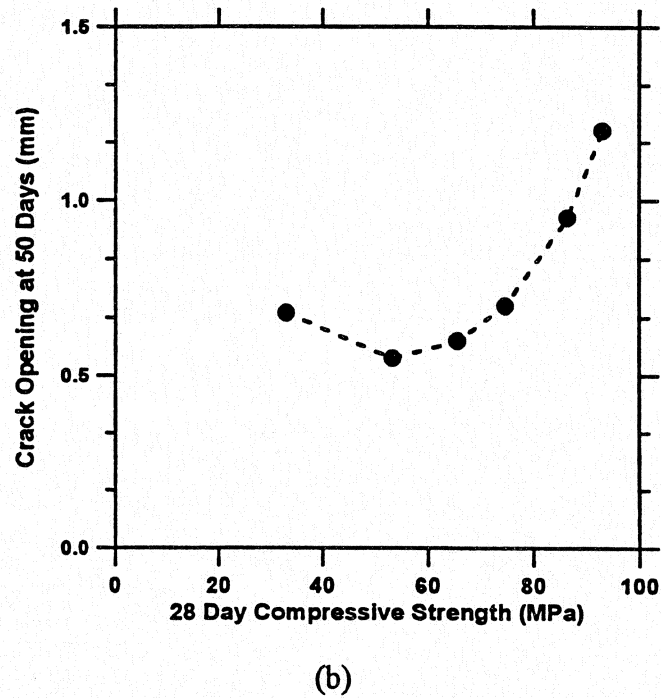
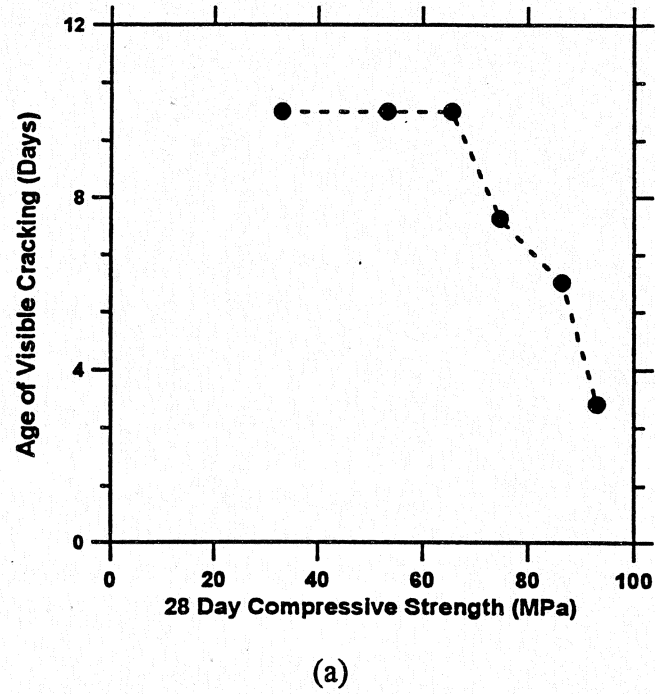
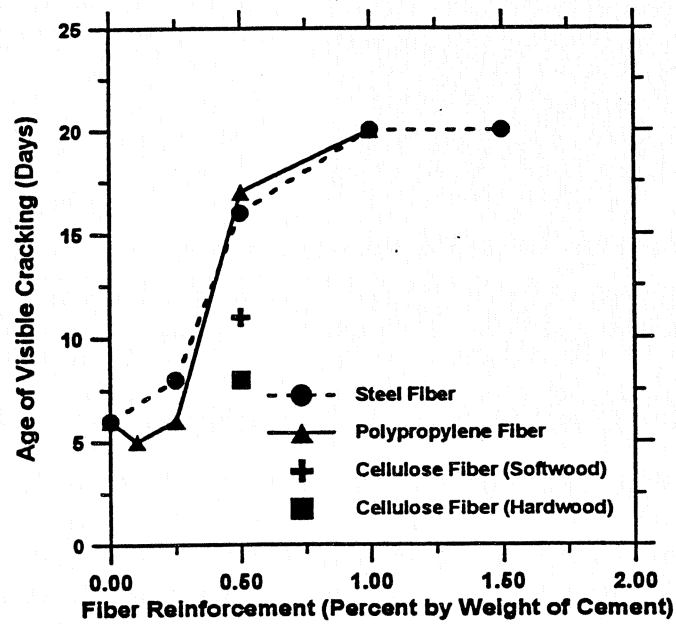
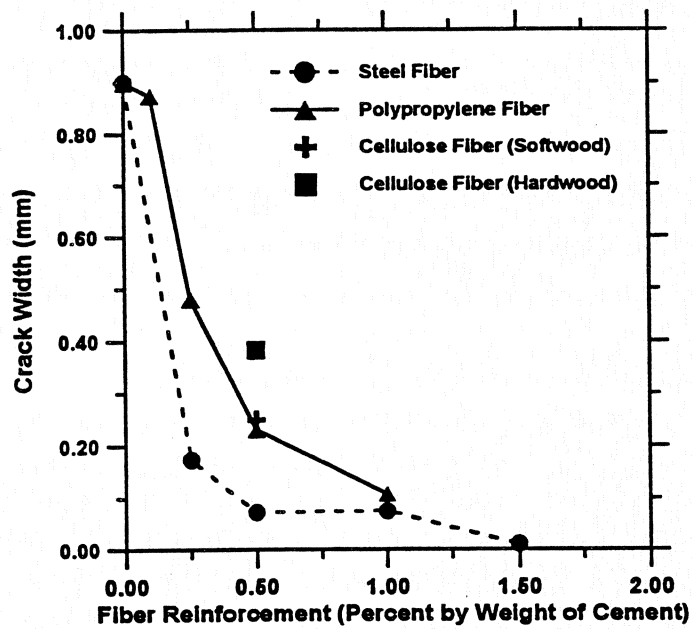


Figure 5: Effects of Increased Strength on a) Age at First Cracking and b) Crack Openings (2,3)

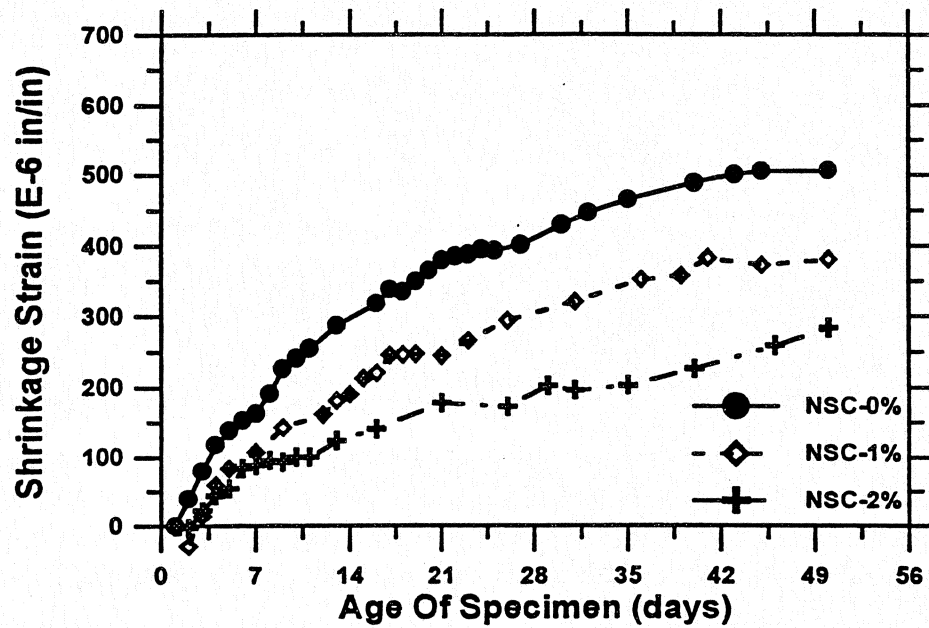


(a)

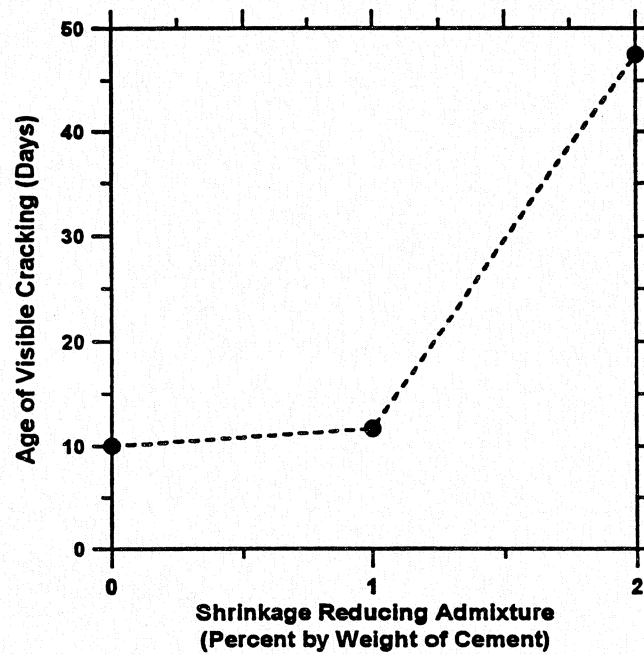


(b)

Figure 6: Influence of Fibers on a) Visible Age of First Cracking and b) Crack Openings (1,4,5,6)



(a)



(b)

Figure 7: The Effect Of Shrinkage Reducing Admixtures In Normal Strength Concrete (NSC):
a) Free Shrinkage and b) Age At First Cracking (2)

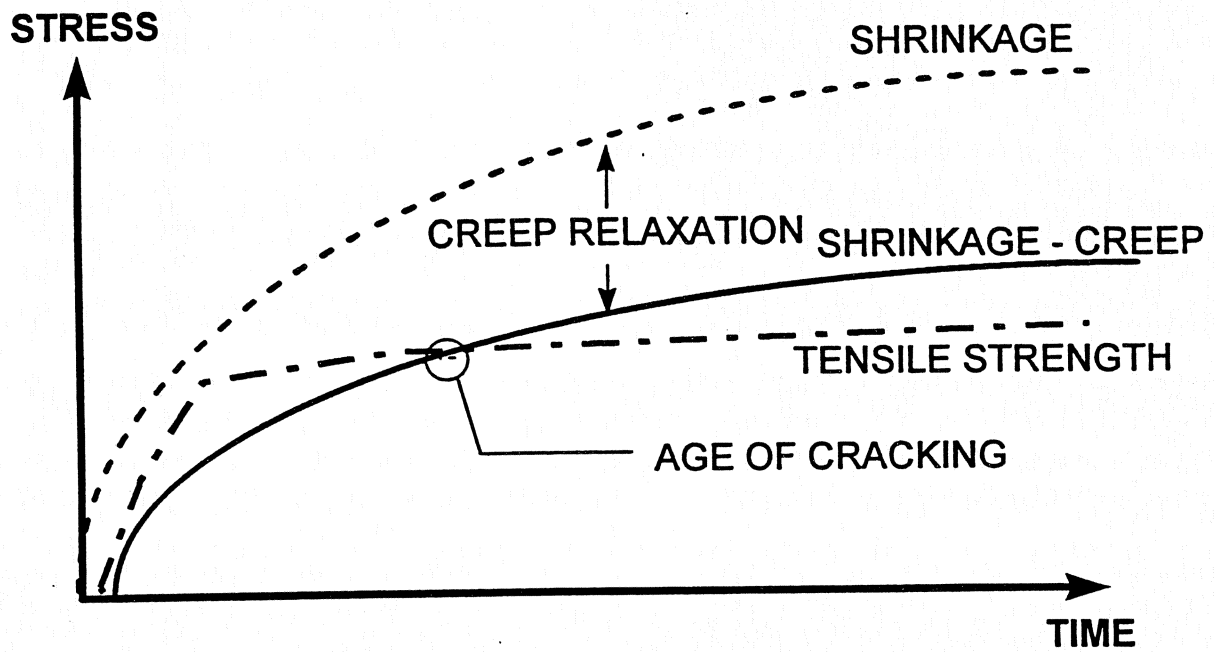


Figure 8: Conventional Strength Of Materials Approach To Predict Age At First Cracking

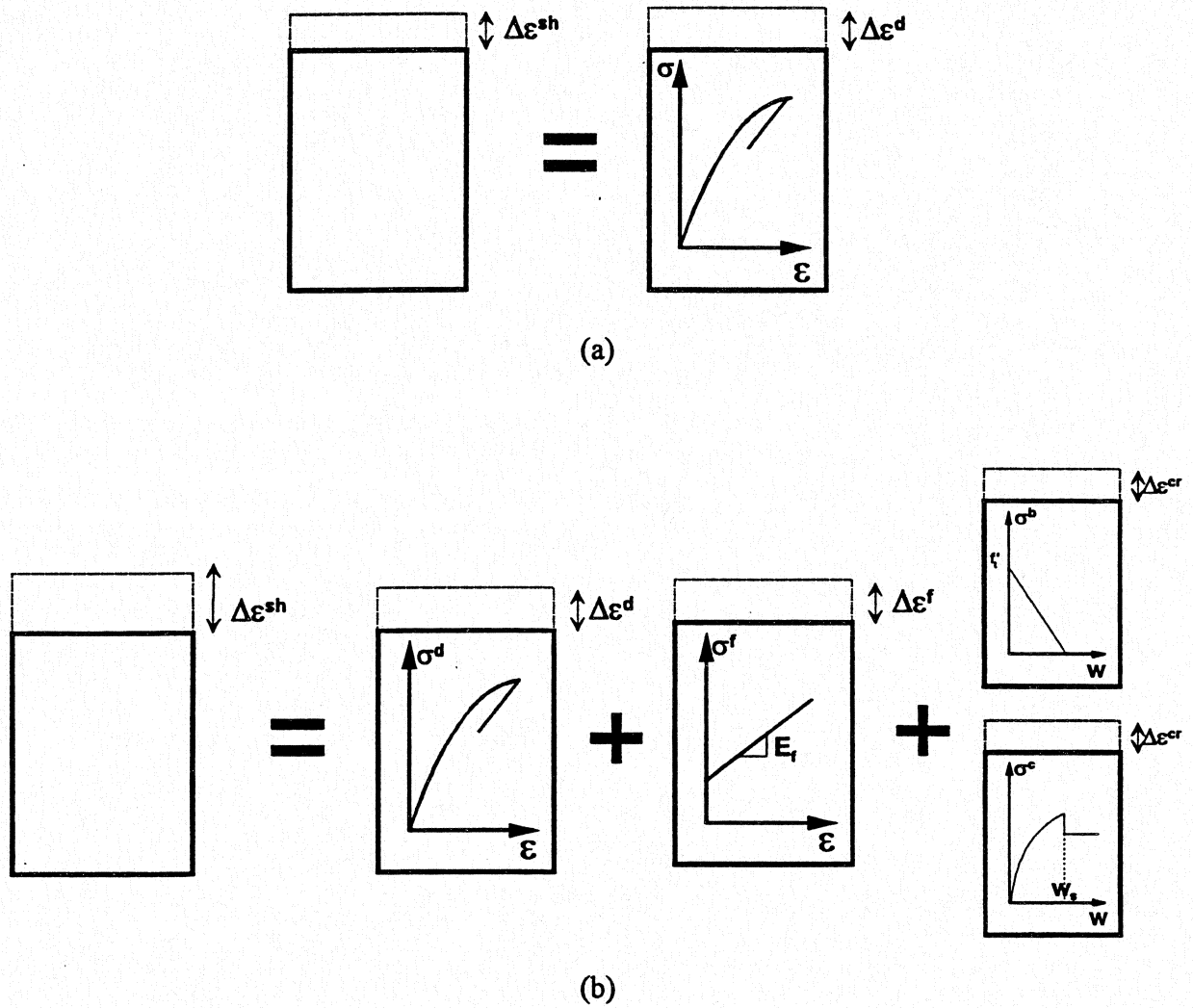


Figure 9: Damage Mechanics Approach To Predict Age At First Cracking: a) Before Cracking and b) After Cracking (Including the Uncracked Strain, the Effective Modulus of the Exposed Fibers, and the Strain of the Cracked Zone) (1,8)

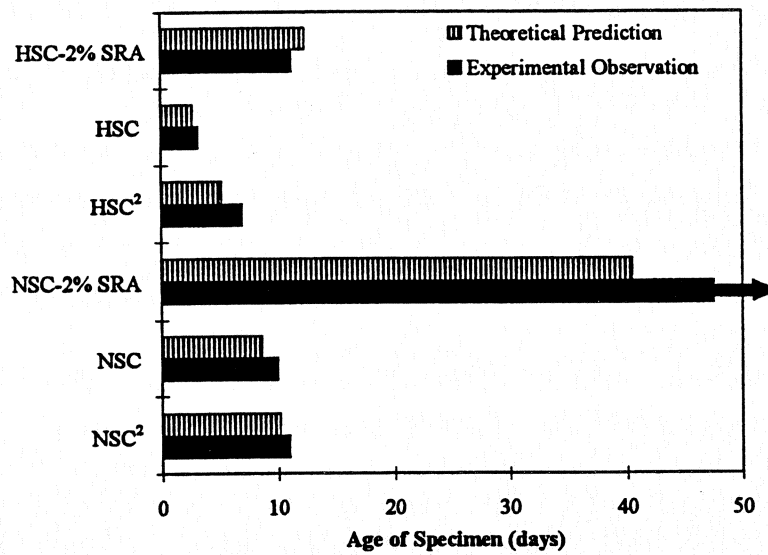
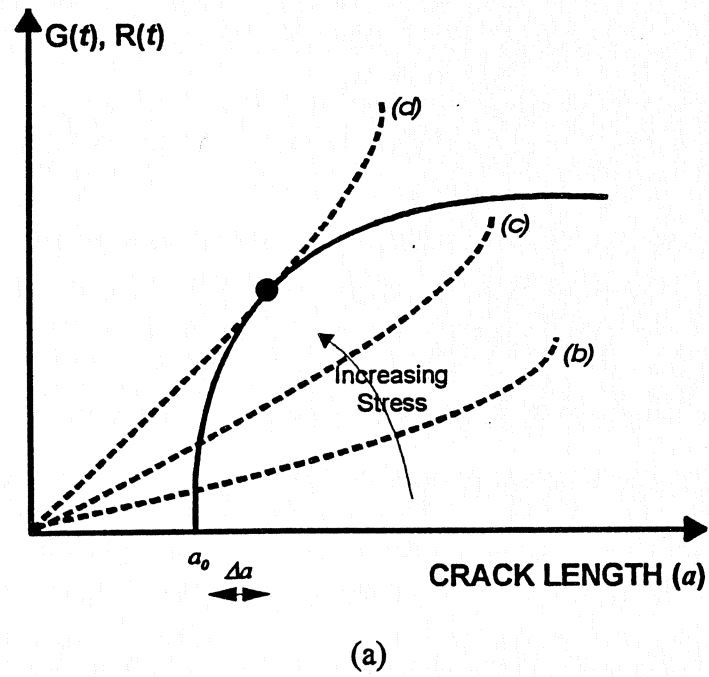


Figure 10: Fracture Mechanics Approach To Predict Age At First Cracking In Ring Specimens:
a) R Curve And b) Comparison Of Theoretical Predictions With The Age Of First Cracking for
Normal (33 MPa) and High Strength Concrete (90 MPa) (2, 9)

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