# Development of a Device to Evaluate the Cracking Potential of Concrete Mixtures

By

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Prepared by

**UTCA**

University Transportation Center for Alabama
The University of Alabama, The University of Alabama at Birmingham,
and The University of Alabama in Huntsville

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**UTCA Theme: Management and Safety of Transportation Systems**

# University Transportation Center for Alabama

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**16. Abstract**
Developments in material technology during past decades, including the introduction of a wide range of concrete mixtures, ingredients, and combinations, led to the development of high-performance concrete (HPC). However, despite advances in technology and practice, concrete bridge decks and pavement still crack often, causing the premature failure of concrete structure. It is important to understand the fundamental behavior of concrete mixtures, where mixture proportions, constituent materials, and environmental factors have decisive effects. This report addresses research conducted to explore the tensile characteristics of HPC, using an innovative, experimental device. Developing such an instrument will help understand HPC characteristics. This device restrains the concrete when the concrete starts to decrease in volume. The restraint inhibits the movement of the concrete, which induces uniform tensile stress in the concrete. Once the tensile capacity (strength or strain capacity) of the concrete has been exceeded, cracking happens. The procedure to conduct this experimental approach and compile its data is described. A pilot laboratory study has been performed and the feasibility of the device to evaluate concrete mixtures confirmed.



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## List of Abbreviations

| | |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| ACI | American Concrete Institute |
| ASCE | American Society of Civil Engineers |
| ASTM | American Society for Testing and Materials |
| AWS | American Welding Society |
| FHWA | Federal Highway Administration |
| PCA | Portland Cement Association |
| RILEM | International Union of Laboratories and Experts in Construction Materials, Systems, and Structures (French: *Reunion Internationale des Laboratoires et Experts des Materiaux*, *Systemes de Construction et Ouvrages*) |
| SHRP | Strategic Highway Research Program |
| TRB | Transportation Research Board |

## Executive Summary

Developments in material technology during past decades, including the introduction of a wide range of concrete mixtures, ingredients, and combinations, led to the development of high-performance concrete (HPC). However, despite advances in technology and practice, concrete bridge decks and pavement still crack often, causing the premature failure of concrete structure. It is important to understand the fundamental behavior of concrete mixtures, where mixture proportions, constituent materials, and environmental factors have decisive effects. This report addresses research conducted to explore the tensile characteristics of HPC, using an innovative, experimental device. Developing such an instrument will help understand HPC characteristics. This device restrains the concrete when the concrete starts to decrease in volume. The restraint inhibits the movement of the concrete, which induces uniform tensile stress in the concrete. Once the tensile capacity (strength or strain capacity) of the concrete has been exceeded, cracking happens. The procedure to conduct this experimental approach and compile its data is described. A pilot laboratory study has been performed and the feasibility of the device to evaluate concrete mixtures confirmed.

# Section 1
# Introduction

In ancient times, the need for a material that would assist in constructing shelters, temples, and statues encouraged mankind to search for a material that would bond stones, bricks, or wood. They discovered cement. The Egyptians were the first to use cement, 5000 years ago, in the form of gypsum mortar as a binding agent. Around 300 B.C., Romans used a similar material made of slaked lime volcanic ash called *pozzuolana*. It was not until 1756 that a British engineer, John Smeaton, made the first modern concrete by adding pebbles as a coarse aggregate and mixing powered brick into the cement. Another English researcher, Joseph Aspdin, invented portland cement in 1824. Since then, portland cement has remained the dominant material in concrete production and construction. The invention of portland cement has played an important role in global development.

Concrete has gone through numerous developments in the last 70 years due to a holistic approach toward enhancing its properties, such as durability and strength. Therefore, the invention of high-performance concrete (HPC) was natural. It paved the way for engineers to develop more sophisticated structures that can be constructed economically and can sustain harsh environmental conditions.

Reinforced concrete structural members crack when they are being loaded, when they are being restrained from shrinkage, or when they are improperly designed or constructed. Sometimes these cracks are stable and invisible. However, most cracks that develop at an early age are unstable and may become visible. This happens because the concrete material is not strong enough to resist the propagation of cracks when they occur.

*Early age* is defined in this research as the period starting with the mixing of the concrete and ending when rapid thermal and hydraulic processes in the concrete have finished. Early-age cracks may develop in concrete while it is still gaining strength. Therefore, the initiation and growth of every early-age crack compromises the long-term performance of concrete (Moon 2006) by reducing the load-carrying surface area and thus the total structure capability to sustain load. To add to this complex problem, these cracks are typically ignored in the design of most concrete structures. In many cases, these premature cracks have significant impacts that need to be considered in the design, but they are typically ignored by designers. The existing test methods and design methodologies need to be updated to better quantify the cracking potential of different concrete mixtures. This was one reason we set up a new testing procedure and apparatus. The success of this project will provide researchers with a useful assessment tool to evaluate the performances of concrete mixtures at early ages.

## 1.1 Scope

The outcome expected from this research is summarized in the following points:

- Better understanding of the high tendency of HPC to crack.
- Better understanding of concrete volumetric changes resulting in the total shrinkage of concrete (chemical and drying shrinkage).
- Better understanding of concrete mechanical behavior at very early ages.
- Better understanding of concrete crack formation and fracture, passing through the main three phases (crack initiation-crack propagation-crack development).
- A new apparatus to use as a selection tool for concrete mixtures and other materials.

## 1.2 Objective

The main purpose of this research is to develop a new laboratory setup and procedure that effectively and conveniently evaluates the strain and stress capacity of concrete mixtures. This can be achieved by an experimental technique that should enable the assessment of early-age cracks in concrete specimens by quantifying the effect of restraint on concrete cracking as well as its effect on the transferences of stresses across the cracks (Ferraris and Lobo 1998). Using this setup a database will be formed based on the strain and stress capacity analysis for different concrete mixes batched, which will eventually serve as a selection criteria for concrete mixtures.

It is noted that the research is concerned with evaluating the potential of this device in assessing the restrained volumetric changes for different concrete mixtures. The assessment will continue from the first 12 hours up to the first 2 weeks while the concrete skeleton, where early-age cracking takes place, is forming and hardening.

## 1.3 Outline

The primary purpose of this research is to assess a new method to evaluate the cracking potential of fully restrained concrete mixtures from the time they are being casted until they crack. The scope can be seen in Figure 1-1.

This research is divided into six tasks:

- *Task 1: Literature Review, Broad Scope*

  Collection and review of relevant literature, including HPC specifications and materials, tensile stresses development in fresh concrete, and new or modified devices that assess early-age cracking.

- *Task 2: Literature Review, Concentrated*

  Evaluation of the methods or devices used in this field, the arguments used by researchers, and the research findings.

- *Task 3: Research Development*

Based on the information gathered in tasks 1 and 2, restraint and the other factor affecting the early-age performance of HPC are identified and discussed. In addition, evidence for the effect of the HPC material constituents on early-age performance is reviewed. The outline for this project is identified in Figure 1-1, in which an interlocked relationship is shown between the three areas covered in this research. The common intersection between the three areas is the outcome expected from this research: "new device."

- *Task 4: Implementation*

Development of an experimental work plan using the information obtained in the three previous tasks. The information gathered will support the current effort for building the new device and help define whether the new device meets its design requirements.

- *Task 5: Production*

Using the developed method, evaluating the susceptibility of concrete batches to cracking will be conducted. Concurrently, a collecting phase for each specimen criteria is conducted, in addition to identifying the necessary requirements for the specimens to pass test requirements.

- *Task 6: Analysis*

In this task, the final report documenting research procedures and findings will be established. This report includes the following information:

- Detailed information for setting-up the apparatus.
- Detailed documentation of the experimental work plan.
- Pilot study on the feasibility of the device.

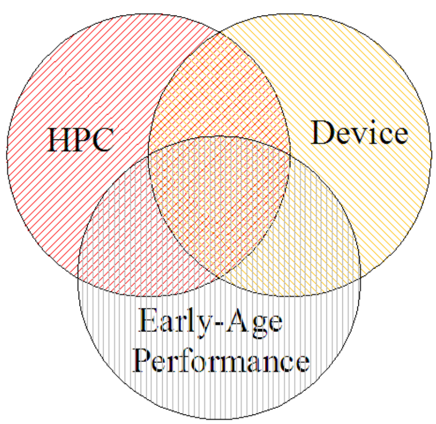


**Figure 1-1. Different factors correlated in this research**

# Section 2
# Background

Over the years, HPC has faced speculation for its brittle behavior. However, its high early-age strength and overall enhanced performance has encouraged most prestigious engineering communities to recommend it for bridges. The HPC definition presented in this paper identifies a set of concrete performance characteristics sufficient to estimate the long-term concrete durability and strength of highway bridges. It might cost more upfront per cubic foot than normal concrete mixtures, but in the long term it could save maintenance and repair expenses due to its superior expected enhanced performance and sustainability. Therefore, HPC potentially costs less over the long term for large projects.

This chapter includes an extensive review of HPC definitions, components, performance at early ages, and previous experimental approaches for evaluating its performance. This chapter also briefly discusses the sensitivity of HPC tensile strength to its mixture components, especially at early ages.

## 2.1 High-performance concrete

HPCs are mixtures developed for particular applications and environments. Its applications are numerous, but it is usually used in structures subjected to extreme exposure conditions, such as high-rise buildings, bridges, and tunnels. HPC made it possible to build longer spans or use fewer beams (Shutt 1996). Small-scale HPC applications include high-strength structural columns, less permeable parking garage decks, and abrasion-resistant hydraulic structures. According to the PCA, for any concrete mixture to achieve enhanced durability, higher strength, and more durability, it has to meet the basic guidelines of HPC mixtures:

- Strong aggregate (coarse and fine aggregate).
- High portland cement content (from 400 to 600 $kg/m^3$ or 675 to 1000 $lb/yd^3$).
- Low W-CM ratio (from 0.20 to 0.45).
- Chemical and mineral admixtures.

### *2.1.1 History of HPC*

Over the years, HPC has gained more than one definition due its rapid development. According to the American Concrete Institute (ACI), HPC is the concrete mixture meeting a special combination of performance and uniformity requirements that cannot always be achieved when using conventional constituents and normal mixing, placing, and curing practices (ACI 116R). The SHRP defines HPC mixtures by a low W-C ratio. HPC is usually designed for a compressive strength of 6,000 psi (41 MPa) or higher. Concrete with compressive strength greater than 6,000 psi (41 MPa) can be produced using only cement as the binding material, but it requires lots of effort and experience. It is common to add performance-enhancing substances to the HPC blend, such as superplasticizers, polymers, or supplementary cementitious materials, which would enable it to easily achieve such high strength.

In the 1940s, the search for stronger concrete with higher capacity to sustain loads and enhanced properties led scientists and engineers to specify concrete with low W-C ratios, which led to the invention of "High Strength Concrete-HSC." It was exclusively used in columns of high-rise buildings. In the 1950s, 5000 psi was considered an HSC, while in the 1960s, 7500 psi was considered an HSC. In those days, it was generally recognized that higher-strength concrete has superior mechanical properties and performs better than normal-strength concrete; however, as time passed, it became clear that this type of concrete did not necessarily perform better.

In the 1980s, construction professionals began to refer to "high-performance concrete" instead of "high-strength concrete" (Smith 1996). However, lots of people in construction consider "high-performance concrete" vague. There are doubts about the concrete's overall performance compared with its compressive strength. For instance, HPC ultimate tensile strength varies between 5% and 8% of its ultimate compressive strength, while in normal concrete it is usually 10%. Thus, tensile properties are not improved accordingly (Gruman, *et al*. 2009). However, both sides believe that more research must be conducted to enhancing overall performance rather than strength. As ACI says, *all HSC is also HPC, while not all HPC is HSC*.

The benefits of using HPC for construction, and bridges especially, are well known and well documented. Research by Ralls and Carrasquillo (1994) thoroughly describes the design and construction details for the Louetta Road Overpass bridges in Houston. These bridges were the first in the US to be fully made of HPC. In other research, Smith verifies HPC's cost-effectiveness due to less material being used, in addition to faster construction (Smith 1996).

Recently, there has been a series of design studies published, all leading to the same conclusion that the use of HPC as a constructional material would significantly improve the strength and durability aspects of concrete structures (Douglas and Thomas 1990). To do so, the HPC mixture must possess superior characteristics:

- Higher compressive strength.
- Higher durability.
- Early-age strength.
- Toughness.
- High modulus of elasticity.
- Volume stability.
- Resistance to chemical attacks such as sulfide attacks.
- Diminished alkali-silica reaction.
- Resistance to surface abrasion, freeze-thaw, and water erosion.
- Lower permeability.
- Ease of placement and workability.
- Lower heat of hydration.

- Better aesthetic properties.
- Long-term mechanical properties.
- Longer life in severe environmental conditions.

In North America, there is no singular or generalized practice for proportioning HPC, although a guide has been developed by the ACI (ACI 211.4R). It solely depends on requirements, trends, experience, and common practices from one region to another (Mindess, *et al*. 2003). But according to FHWA, HPC mixtures have to be maintained within certain parameters regardless of practices, trends, or considerations. As seen in Table 2-1, HPC is always designed for long-term performance strength or durability, while maintaining other fundamental characteristics such as workability, compaction without segregation, long-term mechanical properties, early-age strength, and volume stability.

**Table 2-1. Design criteria for HPC according to the FHWA regulations (FHWA 2006)**

| Strength Criteria | Durability Criteria |
| --- | --- |
| Compressive Strength | Freeze-Thaw |
| Modulus of Elasticity | Scaling |
| Shrinkage | Abrasion |
| Creep | Chloride Permeability |

Concretes possessing most of these characteristics often have higher strength. Therefore, it is not possible to provide a unique definition of HPC without considering the performance requirements of the intended use of that mixture, as seen in Table 2-2, where the different HPC criteria and the methods to evaluate those criteria to ASTM standards are addressed. In this table, HPC mixtures are distinguished by the major design requirement, but they still need to meet other enhanced criteria. However, not all properties can be achieved at the same time.

### *2.1.2 Early-age cracking*

In this research, early-age shrinkage is defined as the time-dependent decrease in concrete volume from its original placement volume. It begins immediately after concrete placement and continues up to 14 days. The concrete transformation takes place through three periods to reach its designated strength; these three phases can be seen in Figure 2-1. During the fluid period, the concrete mixture is still a liquid. Then there is a setting period, where the concrete undergoes early stiffening by the formation of a skeletal frame. Finally, there is the initial hardening, where the concrete is considerably rigid.

Early-age shrinkage and tensile stress take place immediately after the setting of concrete. It is affected by the properties of the concrete-mixture constituents and their proportions; environmental conditions; and a couple external factors, such as the degree of restraint and the construction techniques and curing methods performed (Hadidi and Saadeghvaziri 2005). But for early-age cracks to occur, an interaction of several factors other than early-age shrinkage and tensile stress must take place. These factors include high rate of shrinkage, high elastic modulus, a high degree of restraint, creep, stress relaxation, and fracture toughness (Shah, *et al*. 2004).

**Table 2-2. "Selected properties of high-performance concrete" (Kosmatka and Wilson 2011)**

| Property | Test method | Criteria that may be specified |
|---|---|---|
| High strength | ASTM C 39 (AASHTO T 22) | 70 to 140 MPa (10,000 to 20,000 psi) at 28 to 91 days |
| High-early compressive strength | ASTM C 39 (AASHTO T 22) | 20 to 28 MPa (3000 to 4000 psi) at 3 to 12 hours or 1 to 3 days |
| High-early flexural strength | ASTM C 78 (AASHTO T 97) | 2 to 4 MPa (300 to 600 psi) at 3 to 12 hours or 1 to 3 days |
| Abrasion resistance | ASTM C 944 | 0 to 1 mm depth of wear |
| Low permeability | ASTM C 1202 (AASHTO T 277) | 500 to 2000 coulombs |
| Chloride penetration | AASHTO T 259 & T 260 | Less than 0.07% Cl at 6 months |
| High resistivity | ASTM G 59 | |
| Low absorption | ASTM C 642 | 2% to 5% |
| Low diffusion coefficient | Wood, Wilson and Leek (1989) Test under development by ASTM | 1000 x $10^{-13}$ m/s |
| Resistance to chemical attack | Expose concrete to saturated solution in wet/dry environment | No deterioration after 1 year |
| Sulfate attack | ASTM C 1012 | 0.10% max. expansion at 6 months for moderate sulfate exposures or 0.5% max. expansion at 6 months for severe sulfate exposure |
| High modulus of elasticity | ASTM C 469 | More than 40 GPa (5.8 million psi) (Aitcin 1998) |
| High resistance to freezing and thawing damage | ASTM C 666, Procedure A | Durability factor of 95 to 100 at 300 to 1000 cycles (max. mass loss or expansion can also be specified) |
| High resistance to deicer scaling | ASTM C 672 | Scale rating of 0 to 1 or mass loss of 0 to 0.5 kg/m³ after 50 to 300 cycles |
| Low shrinkage | ASTM C 157 | Less than 400 millionths (Aitcin 1998) |
| Low creep | ASTM C 512 | Less than normal concrete |

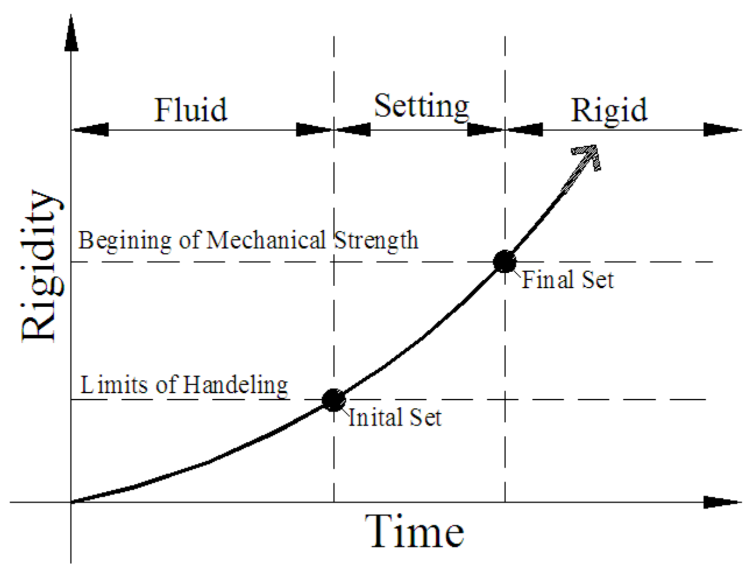


**Figure 2-1. Relationship between time and concrete mixture rigidity**

Among the listed factors that lead to premature HPC cracking, the most influential is restraint. Restrained shrinkage and its effect, "early-age cracking," not only reduce the load capacity of the structure but lead to hazardous corrosion of the rebars. Subsequently, the failure to control early-age cracks leads to deterioration of the structures; in some cases it might also lead to catastrophic results, such as the collapse of a bridge or structure.

Early-age cracks are identified as tensile cracks that develop before the concrete gains sufficient tensile strength, as seen in Figure 2-2. Early-age cracking can be difficult to control by means of structural design; however, it needs to be carefully evaluated and estimated for durability purposes. The volumetric changes that render the early-age cracks take place from the first day up to the 28th day, beyond which they are considered late-age cracks. Restrainment and the increased brittleness of HPC coupled with volumetric changes cause these high-strength mixtures to become more vulnerable to brittle failures than traditional concrete mixtures. It often starts with minor shrinkage cracks in the concrete, which are hairline, random, intermittent, multiple, and meandering; these cracks later form larger continuous cracks.

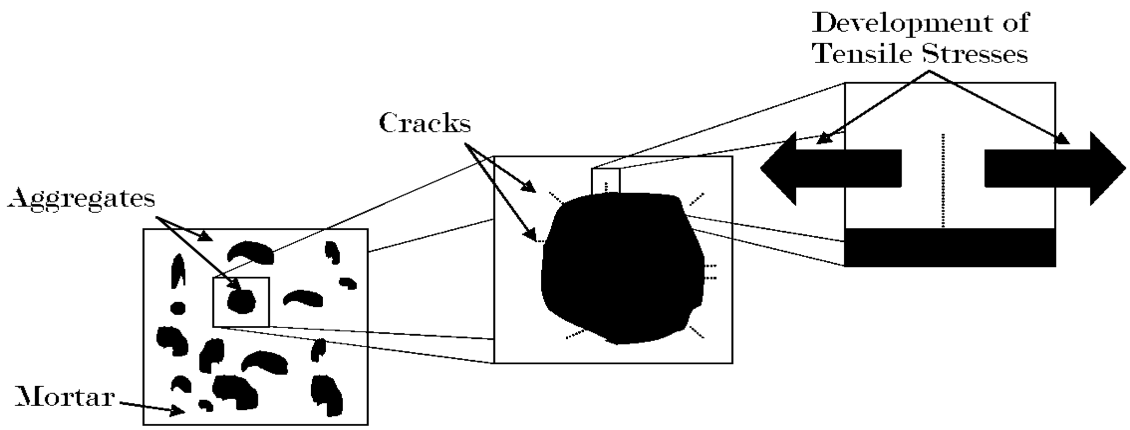


**Figure 2-2. Development of cracks due to the propagation of tensile stresses (Pease, *et al*. 2004)**

Early-age cracking has been found to occur in concrete bridge decks, slabs, and pavements, when the volume changes—associated with drying, hydration, and temperature reduction—are restrained. It is usually non-uniformly scattered, equal in width, V-shaped, wider at the exposed surface, and diminishing as it increases in depth. Figure 2-3 shows the difference in the cracking patterns between HSC, which is an HPC, and normal-strength concrete.

It is thought that any early-age cracking in HPC is a durability problem due to the natural brittle response of HPC toward volumetric changes. Properties such as tensile strength, elastic modulus, coefficient of thermal expansion, evaporation, shrinkage, settlement, and capillary pressure in HPC suggest that early-age cracking is not durability related, nor is it related to the mechanical features of the concrete. It is after the development of early-age crack formation that durability issues become more evident. Today, the characteristics considered include permeability, freeze-thaw resistance, abrasion resistance or any combination of these (Russell 1999). It has become more common to use durability to define the service lifetime of concrete.

Increasing the life span of concrete could increase the initial cost but in the long-run, would eventually decrease the total cost due to the low maintenance and repair costs required. Therefore, extending the life span is a critical aspect in decreasing overall project costs. Consequently, without fully addressing the early-age cracks, the service lifetime of the concrete would not be properly addressed.

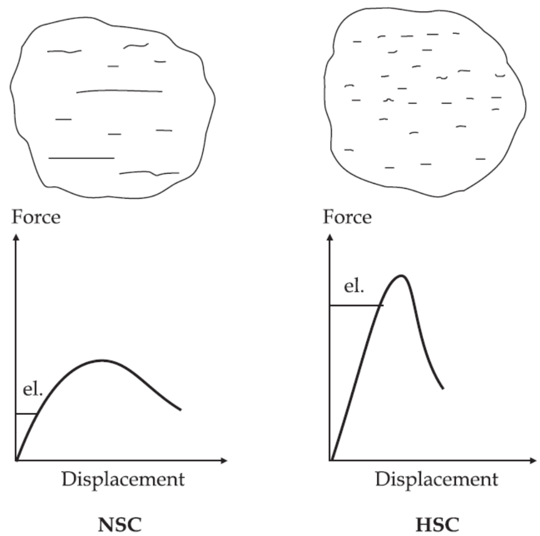


**Figure 2-3. Schematic representation of the stress-stain curve and the corresponding cracking pattern (Suryawanshi 2007)**

### *2.1.3 Why HPC?*

Over the last decade, the use of HPC has emerged as an important alternative to deteriorating infrastructure. Many state departments of transportation have implemented HPC, but the results vary. Today, due to growing concern regarding the durability of newly integrated concrete mixtures, it is important to investigate and understand the tensional behavior of these mixtures under restraining conditions using new methodology. Understanding such behavior will improve overall concrete performance, especially when the concrete is subject to restraints.

The continuing research carried out on HPC and its applications parallels the growing demand for high-strength material all over the world. It became a trend to use high-strength materials such as HPC in different applications. HPC has always been critiqued, especially when it used in highly sophisticated structures. The use of HPC without having a sufficient understanding of its properties and the factors leading to its durability has resulted in inconsistent reports about its performance.

As a result, HPC has been chosen as an experimental material for this research. In addition to its future role in the concrete industry (Smith 1996), there is a universal interest in the behavior and performance of such highly strengthened material. The results will support the rising confidence in HPC as a material with superior characteristics such as strength, durability, and workability.

Such characteristics are considered fundamental properties for HPC mixtures, so it was expected that the construction industry would exploit the newly acquired material and knowledge.

In 1993, FHWA started promoting the use of high-performance materials and advocating greater use of HPC in bridges on the state level. HPC was used in bridge decks, girders, piers, and abutments. By the end of 1998, nine bridges had been completed under this national program. However, because there are few data available on the long-term results of HPC and because it has relatively high initial cost, both states and private contractors are reluctant to use it even though it offers long-term benefits to bridge construction. Therefore, HPC has been considered by many researchers to be the future of the concrete industry. It could even be considered an environmentally friendly product due to these factors:

- Less concrete being consumed, especially in large projects.
- High reuse of industrial waste products and materials in its ingredients, such as mineral admixtures.
- Fewer maintenance requirements due to its higher durability.
- More sustainable and longer lasting.

### 2.2 Materials

This section describes the characteristics of the raw materials used in HPC. It also addresses the factors affecting concrete strength and durability from an HPC perspective. According to the PCA, a properly designed concrete mixture will possess workability for fresh concrete and the required durability and strength for hardened concrete. This can be only attained by careful selection of raw materials, accurate mix design and proportioning, and an appropriate mixing procedure. The influential factors affecting the selection of raw materials for HPC are aggregate, water content, W-CM ratio, cement type, cement content, air content, mineral admixture, and chemical admixture. Figure 2-4 shows the major ingredients used in this project.

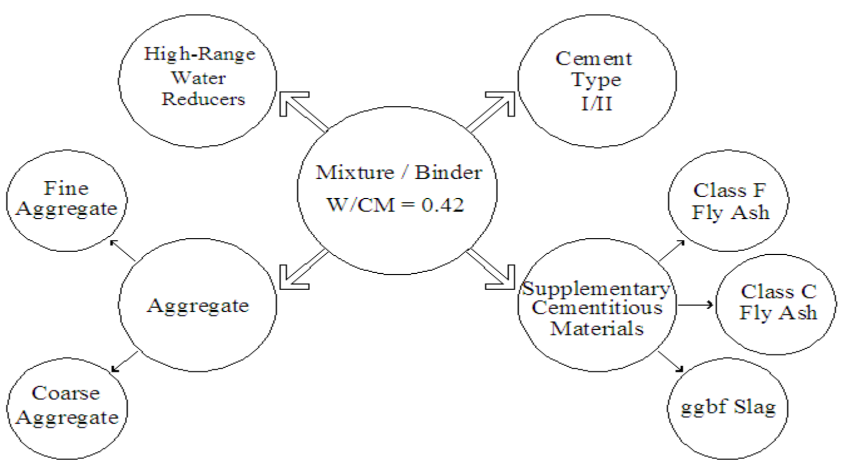


**Figure 2-4. Object hierarchy of the binder class**

Concrete mix design is affected by two factors: environment and cost. These two factors can be interpreted through the choice of suitable ingredients and the accurate proportioning of these ingredients in the mixture. According to the ACI, the selection of concrete proportions is a balance between economy and placing, strength, durability, density, and appearance requirements (ACI 211.1). Although HPC can be made with a wide range of materials, the proper selection of materials is essential to the optimal mix. Compared to conventional concrete, HPC is generally much more sensitive to material changes, material properties, quality, and quantity. In any HPC mixture, strength is a major aspect; it is the first thing specified for every HPC mix and is even considered an index for its other properties. Therefore, the process of selecting suitable ingredients and determining their relative amounts is central to producing concrete of required strength, durability, and workability with all possible economy. These considerations are the key step to achieving the desired and expected outcome from an HPC mixture. Still, the required ingredients for any HPC mixture could be affected by other conditions, such as the budget, experience, and local availability of materials.

HPC is usually used in structures in harsh conditions, so its high strength, low permeability, and material selection help it withstand the natural elements. With today's technology, it became easier to produce a concrete mixture with characteristics that enable it to resist the worst environmental conditions and achieve design requirements. The use of mineral and chemical admixture in addition to portland cement is almost essential to ensure the required characteristics (Russell 1999).

Additives are divided into two types, mineral and chemical admixtures, where the mineral additives include fly ash, silica fume, and furnace slag. These admixtures are extremely beneficial to reducing the plastic shrinkage and cracking of concretes (Zhang, *et al*. 2008), while chemical admixtures such as high-range water-reducers are needed to ensure that the concrete is easy enough to transport, place, and finish. These chemical admixtures are essential for HPC production, as it is impossible to attain workable mixtures with low W-CM ratios without their use.

### *2.2.1 Cement "I/II"*

Ordinary portland cement comes in a variety of types. In the U.S., these are classified as Type I, II, III, IV, and V. These types are distinguished from one another by minor differences in their chemical composition.

Type I/II is generally a modification of Type I to reach properties that cannot be achieved using normal Type I portland cement. It has to meet Type II requirements and most of the requirements of Type I. Type I/II cement meets the $C_3A$ requirements of Type II and the compressive strength requirements of Type I. The main difference between Type I and Type II is that Type II has better sulfate resistance and lower heat of hydration during concrete mixture than does Type I. Both types have a minimum Alite ($C_3S$) content of 55% by weight. Alite ($C_3S$) rapidly increases the initial set and the early-age strength of the hydrated mixtures, which suits HPC needs.

### *2.2.2 Aggregate*

Another major constituent of concrete is aggregate. Aggregate includes sand, crushed stone, gravel, slag, ashes, and burned clay. It is an inert granular material, along with water and portland cement, vital for forming the concrete paste. For a good concrete mix, the aggregate needs to be clean, hard, strong particles free of absorbed chemicals or coatings of clay or other fine materials that could cause the deterioration of concrete. Aggregates, which account for 65% to 80% of the total volume of concrete, strongly influence concrete's hardened properties. Therefore, aggregate must be selected carefully for HPC mixtures, as weaker aggregates may lessen the resistance to loads and cause failure to start in the aggregate rather than in the interfacial transition zone (ITZ) or in a void, where it normally occurs.

In any HPC mixture, the aggregate particle shape and surface texture should be angular, elongated, and rough-textured. Such criteria usually require more water to produce workable concrete; thus, there is a need for additives in HPC mixtures. These additives ensure that the required workability of the mixture is maintained. Generally, during aggregate selection, flat and elongated particles are avoided or are limited to about 15% of the mix by weight. There will be some variation in aggregate properties, but that is tolerable as long as they remain within the guidelines of aggregate selection. The criteria that control the selection of aggregate follow:

- Grading.
- Durability.
- Particle shape and surface texture.
- Abrasion and skid resistance.
- Unit weights and voids.
- Absorption and surface moisture.

*a) Coarse Aggregate*

Coarse aggregate consists mainly of gravel, and the remaining percentage is crushed stone. It is the aggregate of which 95% is retained on the no. 4 sieve during sieve analysis. Coarse aggregates are in general any particles greater than 0.19 inch (4.75 mm), but they usually range between 0.375 and 1.5 inches (9.5 mm to 37.5 mm) in diameter (ACI Committee 211 1993). For each concrete strength level, there is an optimum size for the coarse aggregate that will yield the greatest compressive strength per unit mass of cement (Russell 2000). In general, a smaller aggregate will result in a higher compressive-strength concrete. On the other hand, use of the largest possible coarse aggregate is essential to increasing the modulus of elasticity or reducing creep and shrinkage. Two types of coarse aggregate were selected for this research. Both are locally available and convenient for HPC mixtures. The two types are limestone and river gravel, as seen in Table 2-3.

**Table 2-3. Coarse aggregate types**

| Coarse Aggregate: |
|---|
| ☐ Crushed Limestone |
| Low Absorption less than 1% |
| Medium Absorption between 1% and 2% |
| High Absorption greater than 2% |
| ☐ Washed River Gravel |
| Medium Absorption |

*b) Fine aggregate*

Fine aggregate consists mainly of sand, but more precisely it is the material of which 95% passes through the no. 4 sieve. According to ACI, fine aggregates with a fineness modulus in the range of 2.5 to 3.2 are preferable for HPC. Concretes with a fineness modulus less than 2.5 may be sticky and result in poor workability and high water requirements (Russell 2000). The type of aggregate used in this experiment is Alabama state sand.

### *2.2.3 High-Range Water Reducer*

Super-plasticizer or high-range water-reducing admixture (HRWR) is a chemical admixture essential in HPC mixtures to ensure adequate workability in a low W-CM ratio mixture. It is called *water reducer* due to its ability to reduce the water needed to produce a workable concrete mixture. It is generally known for increasing the workability of fresh (plastic) concrete. It also significantly improves the strength and durability of the concrete mixture. HRWR is one of the seven types of chemical admixtures that ASTM C494 specified can be used in HPC mixtures.

Along with mineral admixtures, HRWR is the fourth HPC ingredient, after cement, water, and aggregate, due to its influence on the HPC mixtures. It provides the required slump with less water and a stronger concrete without increasing the amount of cement. It ensures that cement particles are surrounded by water and hydrated, reducing water content from 12% to 40% while maintaining workability or increasing the concrete slumps from 8 to 11 inches. This improves its strength as well as durability (Wiegrink, *et al*. 1996).

### *2.2.4 Supplementary Cementitious Materials*

Supplementary Cementitious Materials (SCM) are mineral admixtures comprised of inorganic materials that have pozzolanic nature. As mentioned, they along with chemical admixtures are the fourth ingredient in HPC mixtures. They are added to the concrete mix to improve the properties of concrete or to replace portland cement. They make the concrete mixture stronger, more durable, and easier to work.

According to the PCA, fly ash and furnace slag generally reduce the permeability of concrete even when the cement content is relatively low. This is consistent with the results shown in several papers (Kjellsen, *et al*. 2000), where 10% of SCM resulted in a 20 to 25% increase in direct tensile strength and a 10% to 20% increase in flexural and compressive strength, with little effect on the modulus of elasticity. Brittleness appeared to increase with the presence of SCM. Other researchers are concerned that increasing SCM has more disadvantages than advantages (Wiegrink, *et al*. 1996) and that concrete mixtures with higher SCM content show a higher tendency to crack, higher shrinkage, and lower creep. Cracking in such mixtures develops in a much faster manner, and the cracks are wider than those developed in a normal-strength concrete. Test results gathered by Chang, *et al*. (2008) indicate that the shrinkage deformation of concrete between 1 and 3 hours is 0.01 mm, equal to a strain of $20\times10^{-6}$ (mm/mm) or a tensile stress of about 2.4 MPa, and that the shrinkage deformation of concrete between 3 and 12 hours increased to a strain of $278\times10^{-6}$ (mm/mm), indicating a growing rate of crack development with increasing silica fume content.

There are several types of SCM used around the world, but in this experiment only two types will be used: fly ash and ground granulated blast furnace (GGBF) slag.

***2.2.4.1 Fly Ash*** Fly ash is commonly used in HPC production, where it can bring performance and economic benefits. It is known to increase early-age and long-term strength, and it decreases concrete permeability (Itani, *et al*. 2006). It was found that with a replacement range of 5% to 20%, fly ash sufficiently decreases autogenous shrinkage. The more fly ash, the less autogenous shrinkage there is, although the returns to fly ash decrease once fly ash passes 20% of the mixture. This effect is clear, especially from the initial setting to an age of one day (An, *et al*. 2006). It also improves the workability of HPC and its resistance to sulfate and alkali attacks, freezing, and thawing. However, some researchers indicate that increasing fly ash has more drawbacks than benefits, such as increasing crack width (Li, *et al*. 1999).

The ASTM C618 identifies two types of fly ash - Class C and Class F. These types are used in this research. The main difference between them is their lime, calcium, silica, alumina, and iron content, where the chemical properties of the fly ash are largely dictated by the chemical compositions of the coal burned in its production.

a) *Class F*

   The burning of harder, older bituminous coal typically produces class F fly ash; it usually contains around 10% lime. Class F ash requires a lime-providing agent and the presence of water to start forming a cementitious mixture. It is used due to its ability to reduce the bleeding and segregation potential of fresh concrete. In addition, it increases compressive strength, reduces drying shrinkage and permeability, lowers the heat of hydration, and reduces the creep effect in the hardened concrete.

b) *Class C*

   Class C ash is produced from the burning of the younger subbituminous coal. It is mostly useful for HPC mixtures where self-hardening characteristics and improved permeability performance are required.  Unlike Class F, self-cementing Class C does not require an activator.  Class C fly ash generally contains more than 20% lime, a much higher proportion than Class F.  Alkali and sulfate contents are usually higher in Class C.

***2.2.4.2 Ground Granulated Blast Furnace*** Ground granulated blast furnace slag (GGBF slag) is a byproduct of steel production that is typically used to replace portland cement.  In HPC mixtures, achieving low permeability is a necessity.  The permeability could reach 2,000 coulombs and even lower, which is considered a mixture with very low permeability, according to AASHTO T277 and ASTM C1202.  This can be achieved using GGBF slag in HPC mixtures.

The advantages of increasing GGBF slag content include low hydration heat and a finer pore structure.  GGBF slag also increases the degree of hydration of the cementitious materials, causing a decrease in the W-C ratio and concrete permeability and improving durability.  However, mixtures with high GGBF slag content may exhibit a higher sensitivity to cracking at early ages, especially for highly restrained mixtures (Darquennes, *et al*. 2009).  For instance, in the Netherlands most mixtures contain slag contents of up to 70%, and the results recorded showed faster development of autogenous-shrinkage stresses than in conventional mixtures (Lura, *et al*. 2001).  These results agree with Li, *et al*. (1999), who found that replacing 50% of the cement with GGBF slag would not significantly change the shrinkage strain but would change the restrained shrinkage cracking of the concrete.

## 2.3 Early-age Performance

Early-age performance is defined in this research as the resultant effects from the volumetric changes and restraint that occur after the mixing of concrete.  Volumetric changes are a major concern when addressing the potential of premature cracking in concrete mixtures.  Although bridge-deck cracking can be attributed to various causes, concrete volumetric change is often considered the main contributor.  Concrete experiences volumetric change as a result of internal and external causes that have mechanical, thermal, or hydraulic origins (Glisic and Inaudi 2001).  It consists of two particular phases, starting with the thermal expansion, which is the increase in volume when the concrete temperature is rising due to cement hydration.  This expansion is followed by contraction and cooling.

As the concrete contracts and cools, it shrinks, and if this shrinkage is restrained by a structural element, reinforcement, or surrounding stable concrete, tensile stresses develop.  Concurrently, localized internal stresses develop due to the heterogeneity of the mortar-aggregate mixture (Moon 2006).  Once these tensile-stress concentrations overcome the increasing tensile strength, microcracks develop.  Consequently, tensile stresses are released, and eventually premature cracking develops.  This procedure is summarized in Figure 2-5.

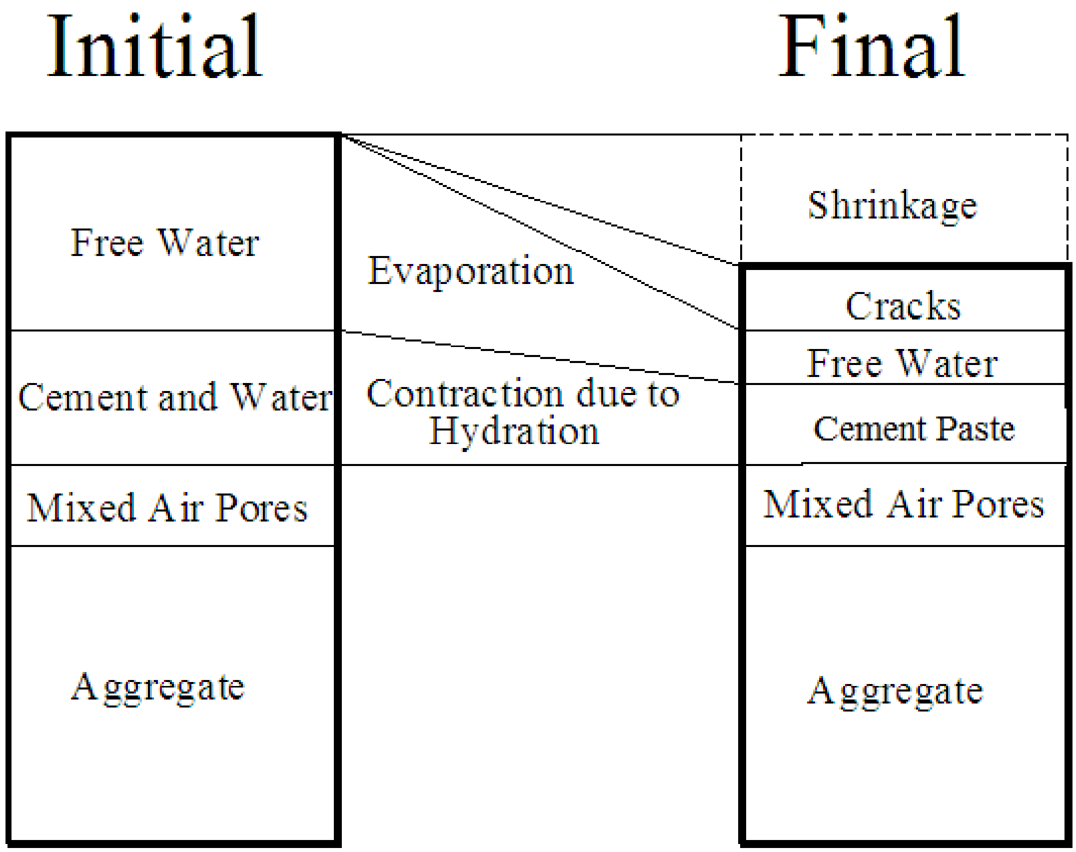


**Figure 2-5. Composition change before and after cement hydration (Kronliif, *et al*. 1995)**

Volumetric changes are assumed to begin at the time of drying, but in reality, volume changes occur immediately after the cement and water come in contact, during concrete mixing. The shrinkage rate is greatest during the first hours and days of the aging of the concrete. First-day shrinkage can significantly contribute to total shrinkage, even if the concrete construction and curing conditions are ideal. Technically, shrinkage will continue for the life of the concrete, but most shrinkage occurs within the first 90 days after placement.

Under site-operating conditions, restraint from shrinkage or volumetric changes is the main reason for premature concrete cracking. Experiments have shown that the stresses developed from restrained deformations are 60% higher than the stresses developed from free shrinkage deformations (Habel, *et al*. 2006). However, other researchers have identified additional factors that lead to premature cracking: tensile strength of the concrete at early ages; the magnitude, type, and rate of shrinkage; non-uniform moisture distribution in concrete; the degree of restraint; time-dependent material property development; stress relaxation; geometry of the structure; and fracture resistance (Shah, *et al*. 2004; Golterman 1995; Sadouki and Wittmann 2000). Understanding the consequences of volumetric changes in fresh concrete is vital to predicting crack formation. The sources of the early-age shrinkage cracking are presented in Table 2-4.

**Table 2-4. Origins of early-age shrinkage cracks (Glisic and Inaudi 2001)**

| | Mechanical | Thermal Actions | Hydraulic Actions |
|---|---|---|---|
| Internal | - | Hydration heat | Hydration processes |
| External | Load | Ambient temperature variation, natural or artificial | Ambient humidity variation, natural or artificial |

There can be numerous causes of early-age shrinkage cracking, as seen in Table 2-4. The volumetric changes in this research are limited to the shrinkage that occurs with loss of moisture (i.e. Hydraulic Actions). Therefore, we focus on three of the principal non-loading causes: drying shrinkage, autogenous shrinkage, and plastic shrinkage. It is expected that these three may act separately, simultaneously, or concurrently at the site conditions.

### *2.3.1 Drying Shrinkage*

Drying shrinkage in concrete is caused by loss of moisture in the paste. It is defined as the shrinkage caused by the loss of water due to evaporation after concrete hardening takes place. It usually occurs after concrete has reached initial set. It is a problem for large flat structures, such as bridge decks and pavements, in which the exposed surface area has a relatively high proportion to volume (high S/V ratio) of the placed concrete.

Concrete ingredients alter the rate of drying shrinkage. There are a variety of factors as well:

- Environmental conditions (temperature and relative humidity).
- Shape (surface area to volume ratio).
- Concrete material factors:
  - Volume of Aggregate
  - Elastic modulus of the aggregate
  - Type of cement
  - W-CM ratio
  - Water content

In normal-strength concretes, plastic shrinkage is considered a subsequent event of drying shrinkage, while autogenous shrinkage is considered an integral part of the drying shrinkage. But in HPC, due to the low porosity of the mixture, drying shrinkage does not play such as large a role as autogenous or plastic shrinkage. It is not even considered as much of a threat. It can be eliminated easily with proper handling and curing techniques, such as preventing moisture loss and providing time for the material to gain sufficient strength.

### *2.3.2 Autogenous Shrinkage*

Autogenous shrinkage is simply the internal shrinkage of concrete; it can be defined as changes in concrete volume not due to moisture transfer to the surrounding environment. It is a phenomenon that occurs without any water loss from the mixture to the surrounding environment after the concrete has initially set, where partial consumption of the mixing water takes place to allow continuous cement hydration in a low W/CM mixture. Physically, autogenous shrinkage is the contraction of the cement gel (loss of water molecules) due to the continuous hydration of cement particles.

Autogenous shrinkage was first described in the 1930s as a factor contributing to total shrinkage that was difficult to evaluate, measure, or separate from drying shrinkage (Lyman 1934). The contribution of autogenous shrinkage was usually thought to be insignificant in normal-strength mixtures due to the dominant role of drying shrinkage. It used to account for about a tenth of the total drying shrinkage. In these earlier days, autogenous shrinkage was noted to occur only at very low W/C ratios and to increase dramatically with a reduction in the W/C ratio. Today, with the increasing demand for HPC, autogenous shrinkage has become increasingly important due to the excessive use of chemical and mineral admixtures leading to increased susceptibility of cracking in HPC (Holt 2005).

Self-desiccation or autogenous shrinkage is considered the driving cause of HPC cracking at early ages. Therefore, there is a general recognition among researchers that autogenous shrinkage is the most vigorous and prominent shrinkage resulting from internal reactions in HPC (An, *et al*. 2006; Bentur, *et al*. 1999; van Breugel and de Vries 1999). Furthermore, autogenous shrinkage endangers both early-age performance and long-time durability of HPC. It has been well documented at later ages, which is explained by self-desiccation, but autogenous shrinkage in the first days of concrete hardening has not been explained. Being of much greater concern than other types of shrinkage, it needs to be measured accurately.

The influence of autogenous shrinkage at early ages has been documented. Habel, *et al*. (2006) found high rates of autogenous shrinkage in the first 6 to 10 hours after initial concrete setting and hardening and 150 μm/m of shrinkage at 48 hours and 325 μm/m at seven days. They also found that autogenous shrinkage became virtually stable at 90 days.

Recently, it was found that water curing can reduce autogenous shrinkage up to 80%. During this curing procedure, most of the cement reacts with the residual water, which helps to avoid early-age tensile cracks by delaying shrinkage until the concrete gains sufficient tensile strength. Among the other benefits of the curing process are mechanical strength, low moisture permeability, and chemical and volumetric stability (Aitcin 1998).

### *2.3.3 Plastic Shrinkage*

Plastic shrinkage is a volumetric change. It occurs while concrete is in the plastic state. It is an outcome caused by the loss of moisture from fresh concrete after it is placed. It takes place during the first hours within the early-age chemical reactions, while the concrete is still liquid and forming a skeleton, and before it hardens or develops any strength.

Cohen and Olek (1989) concluded that plastic shrinkage appears in fresh concrete because of the increasing moisture loss rate. Once the rate of evaporation of water from the surface of concrete exceeds its bleeding, the drying rate at the concrete surface increases, causing high capillary stress development near the surface (Cohen and Olek 1989). Plastic shrinkage typically occurs when the surface of the concrete is exposed to direct sunlight, strong wind, or intensive drying conditions. This is generally attributed to high temperature, dry winds, and low ambient humidity. According to the ACI, plastic shrinkage may also be due to mixture ingredients, proportions, and admixtures (ACI 305). Plastic shrinkage in HPC mixtures is inconsistent according to the literature. Some researchers have found that plastic shrinkage cracking occurs as long as the specimen is restrained (Chang, *et al*. 2008). Other researchers state that concrete restraint is not sufficient; other conditions are required, such as dry winds (environmental effect) or high SCM content (constituent effect), for plastic shrinkage (Branch, *et al*. 2002). Cracks caused by this shrinkage can be quite wide on the upper surface of the concrete. They could reach 0.08 to 0.12 in. on the upper surface but typically does not exceed 0.39 in., and their width often decreases rapidly below the surface (TRB 2006).

It has been reported that the total shrinkage in HPC is increasingly autogenous shrinkage rather than drying shrinkage (Tazawa and Miyazawa 1995). This indicates that, at a low W/CM ratio, most shrinkage can be attributed to autogenous deformation rather than drying shrinkage, as seen in Figure 2-6, where autogenous shrinkage accounts for 40% of total shrinkage at a W/C ratio of 0.40 but almost 100% of total shrinkage at a W/C ratio of 0.17.

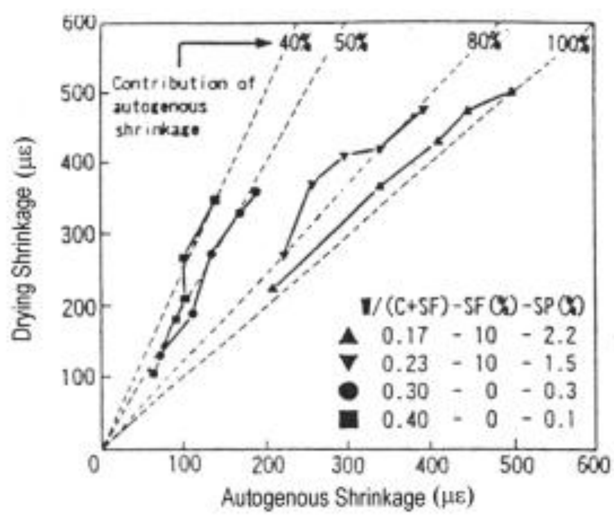


**Figure 2-6. Relationship between autogenous shrinkage and drying shrinkage (Holt 2005)**

### 2.4 Experiments

In the literature survey, the methods used to evaluate the restrained shrinkage of concrete are covered. During the last 30 years, considerable theoretical and experimental effort has been dedicated toward determining the behavior of concrete under mechanical loading or volumetric changes. Researchers have worked on understanding, predicting, and modeling various cracking behaviors. They have used field investigations, field-calibrated prediction models, laboratory investigations, and numerical modeling of the cracking patterns and concrete resistance. Since the first cracking in fresh concrete appears due to tensile stress, the conventional strength of material approaches were expected to successfully predicted the first age of cracking. However, tensile strength is difficult to assess using these methods. For this reason, there is a need for a non-mechanical loading test with a direct tension approach to assess the susceptibility of concrete cracking at early ages.

Different mechanisms and methodologies gathered from research are defined and compared. The experimental approaches and tools used in evaluating concrete cracking in a restrained manner present fundamental information for setting up a new device with enhanced potential. Several test methods have been used to evaluate the cracking potential of concrete. Each method has certain drawbacks. Most of these methods have encountered problems associated with load eccentricity and non-uniformity of stress and strain. These approaches have been concerned with outcome consistency and rationality rather than understanding concrete behavior at early ages. These tests and models provided a base for creating a device that has better performance than previous approaches.

Three main categories were identified in a study conducted by Carlswärd (2008) classifying the evaluation methods for early-age cracking of concrete. These categories are the end-restrained method, base restrained method, and ring tests, as seen in Figure 2-7. The most popular of these tests is the ring test, due to its simplicity and low cost. According to Carlswärd, the most favorable methods used are the end-restrained setups and ring tests, as both directly evaluate the shrinkage effect. This classification confirms a study conducted by Bentour (2003), in which he classified tests as ring tests with a restraining core; panel tests, in which the restraint is at the edge of the panel; and longitudinal tests, in which an external rigid frame is the restraint.

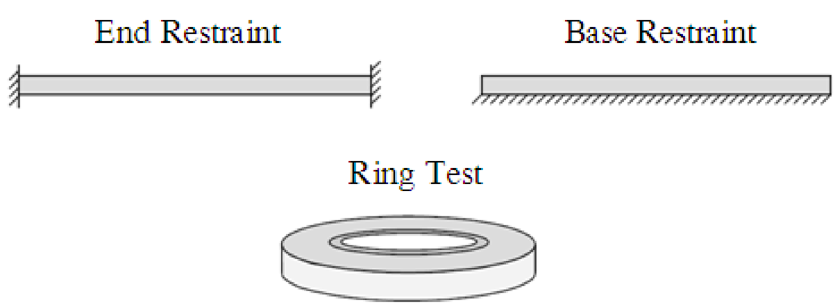


**Figure 2-7. The different test setups used to assess early-age shrinkage (Carlswärd 2008)**

Ring tests have been the most popular tests used to assess the cracking potential of fresh concrete mixtures. It is simple and easy to cast a test specimen, and the end effects are removed by providing axi-symmetric specimen geometry; these characteristics encourage researchers to use the ring method (Weiss, *et al*. 1998). The other test methods have not been widely used compared to the ring test, despite their higher quality results, due to the high costs and difficulties associated with providing sufficient end restraint and avoiding eccentricities. However, even with the widespread use of the ring test, there is still no standard test that is globally used to evaluate the shrinking behavior of fresh concrete.

### *2.4.1 Main Approaches*

*a) Ring Test*

Over the last decade, the ring test has become widely used to determine the time for fresh concrete specimens to crack. Numerous studies have been devoted toward understanding the performance of early-age concrete using the ring test. The ring test was first used by Carlson and Reading in 1939 (TRB 2006). In the ring test, shrinkage of an external concrete ring is restrained by an inner steel ring, as seen in Figure 2-8. It consists of a concrete ring cast around a smaller steel ring. As the concrete ring dries, it shrinks. The steel ring prevents this shrinkage, causing tensile stress to develop in the concrete. Tensile stresses generate and propagate. Once these stresses are large enough, cracking occurs. The strain is measured at the inner surface of the steel ring and is used to determine the interface pressure exerted by the shrinking concrete on the steel ring. Some studies have used the strain measured on the steel ring or simply the age of cracking to verify and compare the various materials used in each mixture.

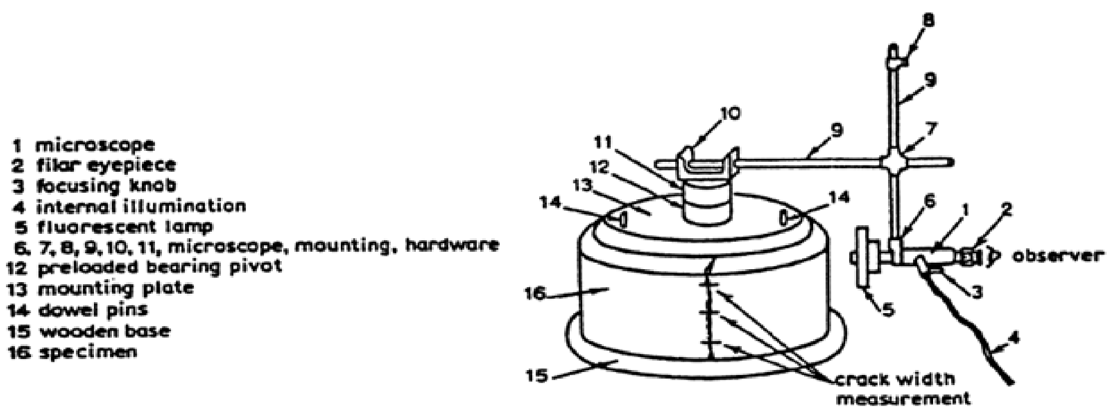


**Figure 2-8. The ring test apparatus (Hamanaga, *et al*. 2006)**

Various geometries of the ring test have been adopted by researchers. A large amount of analysis has been performed to understand how specimen geometry influences the results of the test. In a search for a universal format to assert the ring test, AASHTO offered a standardized form referred to as the *passive ring test* or *restrained ring test* (AASHTO PP34-99). This standardized model has been used in several studies; however, AASHTO did not provide an approach for quantifying stress development or for indicating how close a specimen may be to failure. Results in the literature indicated that a low degree of restraint was provided by the steel ring, resulting in a longer time before the first visible cracking was observed. As a result, alternative test geometry has been developed that was adopted by ASTM. The new geometry was referred to as the test method for determining age at cracking and induced tensile stress characteristics of mortar and concrete under restrained shrinkage (ASTM C1581-04). In this new approach a thicker steel ring was used. However, it became much harder to monitor the stress development due to the higher degree of restraint, which allows no measurable deformation to take place as the concrete shrinks.  Further research acquisition has led to a reduction in concrete wall thickness to 1.48 in.  This reduction was made to encourage cracking in the concrete ring at an earlier age.  Thus, the new restriction in specimen size made it more difficult to test concrete with larger aggregates or reinforcement.  In numerous papers, the speculations regarding the validity of the latest geometry in assessing the larger aggregate or fiber effect have been well documented (Moon, *et al*. 2006; Shah, *et al*. 2004).  As a result, this test method became applicable to mixtures only with a maximum nominal aggregate size of 0.5 in. (13 mm) or less, according to the latest ASTM standards.  More limitations have been placed on the ring test, where the concrete thickness is permitted to be three times the maximum aggregate size.  Many researchers also concluded that it is necessary to quantify and understand how the thickness of the steel ring changes the degree of restraint as well as the stress values.

Finally, though the ring test is an economic solution, it is an indirect tension test instrument, and sometimes it is not effective in assessing the concrete potential of cracking due to the non-linear stress distribution and the radial stresses that coexist.  It also does not simulate well the stresses caused by the restrained conditions in the concrete deck or pavement when cracking occurs.

*b) End Restraint*

Kovler (1994) proposes a modified uni-axial restrained shrinkage test to overcome the problems usually associated with uni-axial methods.  He uses a fully automated closed loop to increase the accuracy of the measurements and to control the loading.  The specimens in this experiment, fixed at one end and movable at the other end, are placed in a longitudinal testing device with end grips, where the change in length caused by the volumetric changes could be measured using an LVDT.  While positioned, the induced stresses in the restrained specimen can be measured with a load cell.  The basic idea was to expose a concrete dog-bone-shaped specimen to drying conditions.  The specimen shrinkage is restrained and the developing load and shrinkage deformation are measured.

Changes to the uni-axial restraint test have been adopted by researchers following an approach similar to Kovler's.  Hamanaga, *et al*. (2006) used a modified direct tensile strength testing device to evaluate the tensile stresses induced from the restrainment of concrete.  The experiment was performed on an axially restrained concrete specimen tested in the same manner as the direct tensile strength test; however, it was conducted by measuring the developing shrinkage load rather than loading it, using a testing machine with a capacity of 1000KN, in which the stress and strain are automatically controlled.  Similarly, another experiment was conducted by Yang, *et al*. (2004), where the specimens were axially restrained to carry out the static loading.  The differences between the last two experiments lie in the dimensions and the shape of the concrete specimen.  In the first method, it was a concrete rectangular specimen with the dimensions 12 in x 4 in x 4 in, while in the second method it was a cylindrical specimen with the dimensions 4 in x 8 in.  Both experiments had the same concept in which the concrete was be subjected to restrainment at the ends of the specimen; however, in the first method only a screw jack was used, while in the other approach, steel end plates were used in addition to rods.

Axially restrained specimens represent the field conditions better than the ring test due to the tolerance allowed by the testing device for the visco-elastic behavior to exhibit in the concrete; however, in the case of loading a concrete specimen for mechanical testing, the distribution of stress across the principal cross-section is usually not uniform, and it is difficult to determine precisely which mechanical property of the material is being measured by the test. It has been emphasized by researchers in fracture mechanics that experimental fracture strength of solid materials is 10 to 1000 times lower than theoretical strength values because tiny internal or external surface roughness or cracks can create higher stress. In addition, other major parameters came out as concerns in this category of experiments, such as the eccentricity of loading and the high risk of human errors, besides the lack of verification for some criteria chosen in the experiment, such as the rigidity of the restraining method, the cross-section of the specimen, and the effective specimen dimensions.

c) *Base Restraint*

Although it is the most representative of site conditions, base restraint is the least used method due to its high cost. No standardized model has been developed for this type of testing either. As described in Carlswärd's study, it was an experiment that consists of an overlay of concrete strips; each was 2 in x 6 in x 100 in cast onto large concrete bottom slabs. Similar to the ring test, it is used to determine shrinkage development and is measured at the upper and lower faces of the concrete strip as shrinkage takes place. The bottom concrete slab acts as a mold with a dimension of 12 in x 80 in x 120 in. Unlike the ring method, this method is solely expressed by the quantification of the existing cracks (Carlswärd 2008).

This method has a larger number of prerequisites. First, the bottom slabs have to be produced at least a year in advance to minimize the effect of remaining shrinkage. Second, sufficient restrainment and bond strength must be achieved between the strips and the large concrete bottoms. Third, an adequate simulation of the windy conditions must be plotted to allow the large exposed surface of the concrete strips to dry. Failure to achieve and maintain any of these prerequisites will produce unreliable results.

### *2.4.2 Other Approaches*

Over the years, engineers have developed or modified tests to achieve more reliable and consistent data and results. Weiss, *et al*. (1998) coupled the effect of end and base restraints in one device in which both rods and steel plates offer end restraint in addition to small steel strips for base restraint.

Carlswärd adopted three main categories, but several other methods have been adopted, such as ASTM's modified method for early-age shrinkage (ASTM C157), which attempts to directly measure strain development in the concrete using vibrating wire strain gauges. RILEM also offered another experiment called the RILEM TC 119 TCE 3, which is used to establish the cracking risk from thermal and autogenoues shrinkage (Burrows, *et al*. 2004).

### *2.4.3 Secondary Approaches*

Most restrained-approach experiments are performed along with the free shrinkage test. It has a testing methodology similar to the ASTM C157 test, where the LVDT is used to measure the change in diameter of each specimen and to conduct strain development. According to Moon, *et al*. (2006), free shrinkage alone is not sufficient to predict early-age cracking of concrete. While free-shrinkage tests can quantify length change, they may not always be sufficient for detecting materials that are prone to cracking. Because the concrete in bridge decks is restrained, there is a need to examine the behavior of HPC mixes under restrained conditions. Thus, test results from free drying shrinkage alone are not sufficient to fully understand the shrinkage behavior of HPC because it is influenced by a complex interaction of strength gain, stiffness development, creep, shrinkage, degree of restraint, and toughness (Yang, *et al*. 2004).

### *2.4.4 Conclusion*

According to the consolidated literature, the main conclusion that almost all researchers agree on is the urgent need to obtain a guiding model for each phase in the life of the concrete, especially the early ages. Following the gathered information, an attempt is conducted to construct a device that would assess early-age concrete cracking in a tensile manner. This device should be able to provide repeatable results with a low standard of deviation and low coefficient of variation within each test. These expectations are to be accomplished using the apparatus that is described later. The new device will provide pure tension cracking conditions for fresh concrete in such a way that the assessment of concrete volume changes is more precise.

# Section 3
# Methodology

This chapter describes the experimental setup and testing procedure conducted to evaluate concrete deformation using a testing device. The device is used to assess early-age cracking of HPC. These cracks occur due to the propagation of pure tensile stress in fresh concrete. It is based on a fundamental physical property of concrete: shrinkage. Restraining a volumetric change, such as shrinkage, is the reason for the formation of most early-age cracks in HPC mixtures. Shrinkage, coupled with HPC's higher tendency to crack, leads to early cracking problems in HPC. HPC's higher tendency to crack can be attributed to the combination of several factors, including higher shrinkage, higher initial strain, earlier initial set, and higher gain of stiffness. These factors work together to increase the probability of HPC tensile failure over time, as seen in Figure 3-1.

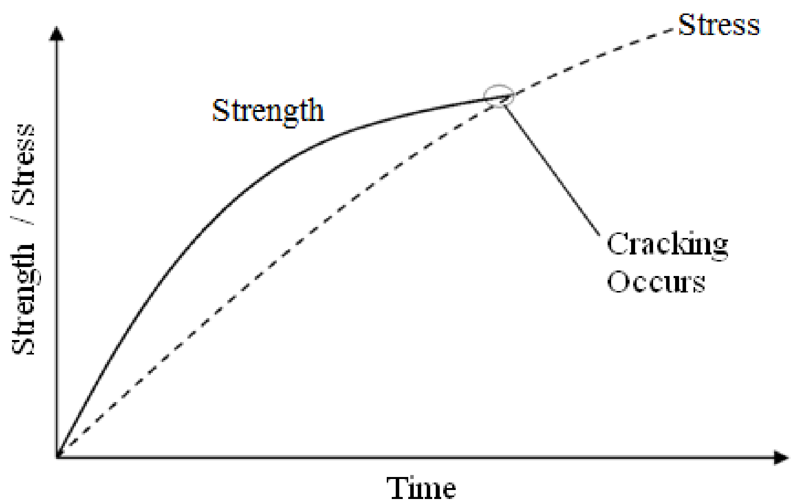


**Figure 3-1. Relationship between time and stress/strength development**

## 3.1 Need for Standard Test

Better understanding of shrinkage behavior and the cracking mechanism of concrete involves an in-depth analysis of its early-age deformations. Current design and test approaches to evaluating or measuring tensile stresses are indirect methods. To overcome these shortcomings, this new device is a pure-tension stress evaluation method that would enable the assessment of concrete cracking potential at early-age and the evaluation of restrained behavior in a direct tensile manner.

As stated by the TRB, there are several standard tests of concrete compression, such as ASTM C39 to determine peak strength and ASTM C469 to determine static elastic modulus. No standard test exists to assess direct tensile strength. However, the flexural strength ASTM C78 or splitting tensile strength test of concrete ASTM C496 can be used as an estimate of tensile strength. It is generally agreed that flexural strength is approximately 20% higher than direct tensile strength. Additionally, to assess the free shrinkage of concrete, ASTM C157 can be used for specimens made in the laboratory and ASTM C341 can be used for drilled or sawed specimens to measure the time-dependent length change of square prisms. However, free shrinkage alone is not sufficient to determine whether restrained cracking can be expected. But to assess the effect of restraint on the potential for cracking, several recent studies have been conducted in which the specimens were prevented from shrinking freely. Such studies have included a ring test, which is frequently used as a simple laboratory test because it removes difficulties associated with providing sufficient end restraint. Additionally, a non-contact laser length-change test and acoustic emission test were carried out. Recently, AASHTO provisionally offered a new standard test, AASHTO PP 34, which was developed to compare cracking ages for different materials. Similarly, ASTM C1581 has been developed with a slightly thinner concrete wall and higher degree of restraint than the AASHTO specimen (Mindess, *et al*. 2003). According to Mindess, *et al*. (2003), the need for an effective testing and analysis method to evaluate the tensile-cracking potential and resistance of concrete early on is essential. Several other researchers came to the same conclusion regarding the immediate need for a new method to assess and identify the tensile properties of different concrete mixtures, especially for HPC mixtures (Moon 2006; Hossain, *et al*. 2003; Yang, *et al*. 2004). Certainly there are factors besides the ones indicated in the TRB report for inventing a new pure tension cracking device, such as the following:

- Inconsistency in tensile tests results. For example, the direct tensile strength method always gives higher values than the splitting tensile strength test.
- Unreliability of the testing methods, which limits the scientific comparison and evaluation of studies.
- Differences in monitoring and evaluating strategies, resulting in a wide range of reports.
- Lack of information correlating field condition severity and laboratory restraint tests conducted.

### 3.2 Apparatus Setup and Description

The search for a practical means to evaluate the fresh mixture properties was done through evaluating the current methods and devices used, while considering the required improvements to produce a new experimental setup. An experimental investigation is being proposed, where the new standardized test should be competent in the following:

  - Assessing the early-age cracking potential of HPC due to restrainment and the propagation of pure tensile stresses.
  - Investigating the shrinkage behavior of HPC mixes.
  - Addressing the tensional behavior of HPC in a systematic and scientifically rigorous manner.

- Compiling performance data into a database and analyzing data using rigorous standards.
- Serving as a new selection tool for material engineers in different material and constructional fields in the future.

Concrete is normally restrained in construction conditions, where higher stresses develop from restraints and restrained elements usually experience a higher activity than free ones (Hossain, *et al*. 2003). Therefore, the proposed method must be restrained and capable of providing reasonable stress measurement in a more reliable and realistic way. The proposed device was based on rooting the occurrence of early-age cracks in concrete by restraining it through a reasonable human intervention represented by the rebars, as seen in Figure 3-2.

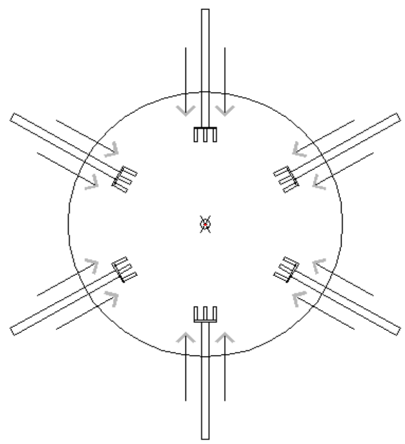

**Figure 3-2. Restraints provided by the embedded bars in the concrete specimen**

The apparatus is the core and backbone of this research, where restrained concrete shrinkage test will be performed on a pie-shaped concrete specimen. The mold within the apparatus will act as an illustrated instrument to prevent the pie specimen from shrinking, allowing premature cracking to occur, as described before, in which the rebars are used to cause physical restrainment to the volumetric changes of concrete. The rest of the apparatus consists of the following:

- One steel plate (plate dimensions: 28 in. x 28 in. x 1 in.)
- Two steel ring frames: The inner ring frame (thickness: 0.5 in., inner diameter: 18.5 in., outer diameter: 19.5 in.) and outer ring frame (thickness: 1 in., inner diameter: 23.5 in., outer diameter: 25.5 in.). Both are 4 in. in height, as seen in Figures 3-3 and 3-4.
- A thin rubber layer (thickness: 0.25 in.) will be connected to the inner diameter or circumference of the steel ring frame to accommodate the initial expansion of concrete during hydration, as seen in Figures 3-3 and 3-4.
- A set of six fork-shaped steel bars. Each is a #4 rebar welded by a small plate and finally connected by four steel bars 0.623 in. (6mm) thick and 1 in. (25mm) long; these bars and plates are welded according to the AWS as seen in Figure 3-5.
- Another set of six normally shaped rebars. Each is a #4 rebar; it will be used as a substitute for the fork-shaped ones.


| | | | |
|---|---|---|---|
| 1 | Steel Base Plate | 4 | Inner Steel Ring |
| 2 | Mold Handle | 5 | Rebars |
| 3 | Outer Steel Ring | 6 | Rubber Band |

**Figure 3-3.  Components that have been set togther to form the pie test apparatus**

There are two sets of rebars used in this experiment.  The two sets are implemented to simulate the effects induced by different types of restrainment imposed on fresh concrete.  Both provide a degree of restrainment to the concrete specimen that allows sufficient strain to develop.  A comparison is to be conducted experimentally between the normal-shaped rebars and the fork-shaped rebars to validate its theoretical basis, where according to the calculations, the fork-shaped rebars will have superior performance, as seen from the following calculations and Figures 3-6 and 3-7.

According to these analyses, the fork-shaped rebars restrain concrete to a slightly higher degree, so a higher measurable deformation can occur as the concrete shrinks.  This rebar usage was based on a methodology developed by Swaddiwudhipong, *et al.* (2003), who used a similar rebar to overcome the weak bond strength between the embedded bar and concrete and to avoid the stress concentration at the end of the embedded bars.

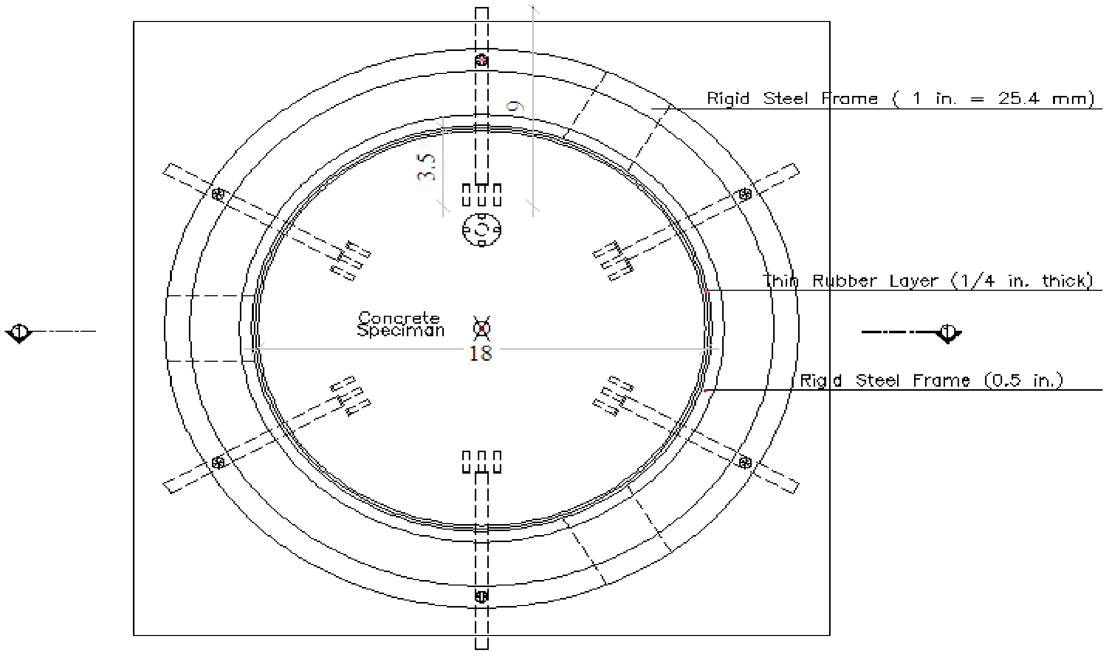


**Figure 3-4. Detailed drawing of the apparatus**

**Figure 3-5. Fork-shaped rebars placed symmetrically to avoid eccentricity**

**Figure 3-6. The normal-shaped rebars and the drilling tools used**

Stress is equal to force over area:

$$F_1 = \frac{\pi(D_1)}{4}, F_2 = \frac{n\pi(D_2)}{4} \tag{3-1}$$

Force continuity in the rebar:

$$F_1 = 4 \times F_2/4 \tag{3-2}$$

Assume $D_1$=1.3 cm and n=4. Then $D_2 = {}^{1.3}/_{4}$ = 0.65 cm (approx. 6 mm)

By comparing force continuity in the rebar ($F$ = 4×F/4)

$$\pi \times D_1 \times L : 4 \times \pi \times D_2 \times L$$
$$1.3 : 2.4$$

Therefore, using four smaller bars will increase the bonding by 50%.

**3-7. The fork-shaped rebars**

Next, the assembly and setup of the apparatus are described:

- The inner and the outer rings were connected as in Figure 3-8 to maintain a solid base with the steel plate.
- Three voids were created in the steel plate between the outer diameter of the inner ring and inner diameter of the outer ring (Figure 3-9). The parts removed will be welded to the inner and outer rings (Figure 3-8) to act as support "knees" of the apparatus. Between these three solid steel parts, a sufficient ventilation space is maintained to allow drying and shrinking of the concrete specimen from its downward surface.
- A plastic “polyester” sheet was placed underneath each specimen until the concrete mold started to harden (as a pre-test procedure for 12 hrs), as seen in Figure 3-10. It was in contact with the steel plate and the underside of the concrete specimen to ensure a frictionless surface between them.

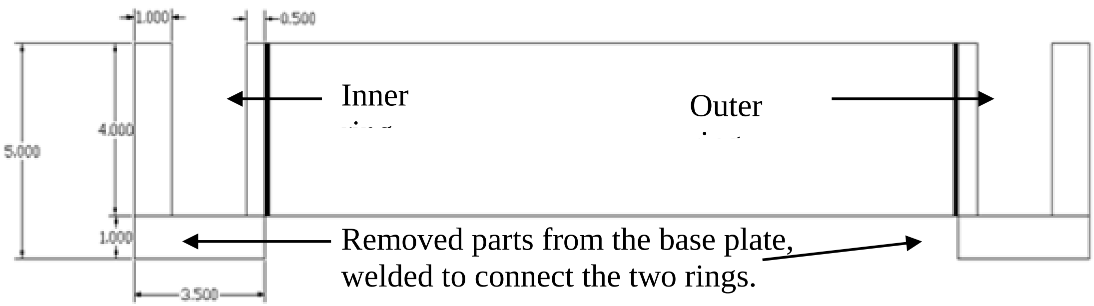

**Figure 3-8. Cross section of the mold**

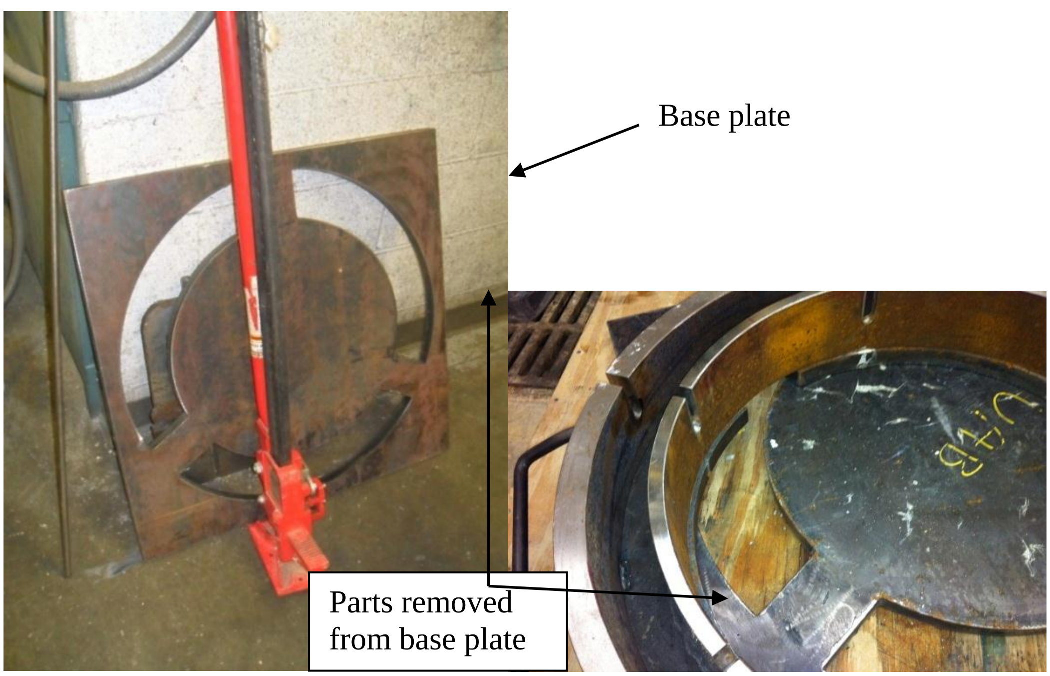

**Figure 3-9. Base plate and the three parts used to connect the inner and outer rings**

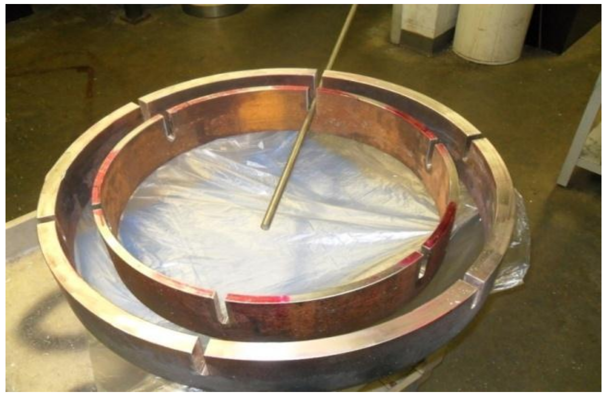

Figure 3-10. Low-friction polyester sheet on which concrete is cast

- The length of the steel bars embedded in the concrete will differ in their degree of restraint; thus, they are maintained at a constant length. The total length for each bar is 9 in. (7.9 in. the #4 rebar, 0.1 in. a small disk, and 1 in. each of the thin steel bars). The steel bar was embedded 3.5 in. (90 mm) into the concrete and extends 1.9 in. (48 mm) outside the outer steel ring frame to give stability to the embedded bars (Figure 3-11).
- A hole was drilled 2.35 in. from the end of the rebar, where the hole sizes are 0.197 in.; the purpose of these holes was to install the rebars on pins on the outer steel ring. These pins maintain a strong connection between the outer ring and the rebars while they hold the concrete during shrinkage. It also exhibited a constant restraint ratio during the experiment.

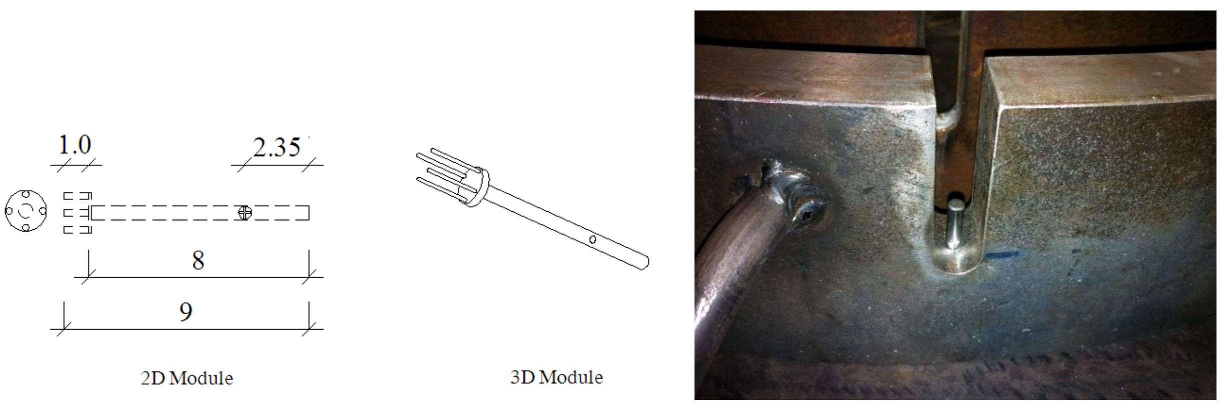


Figure 3-11. Detailed drawings of fork-shaped rebars and the holding pin

- Six small plates, 1.5 in. in diameter (small disk), were welded to the fork-shaped bars, as seen in Figure 3-12.

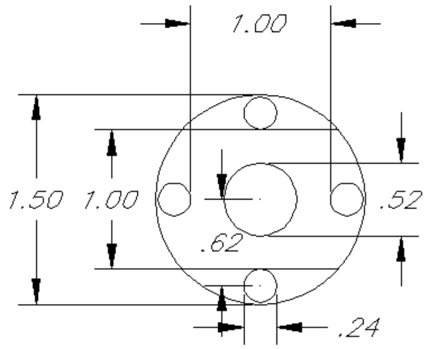


**Figure 3-12. Cross-section in the fork-shaped rebars**

Such a setup enables the preliminary assessment so the initial status of the concrete can be easily recorded. Further assessment in the experimental procedure can be classified on either how long it took the mixture to crack or the rate of stress development in the concrete specimen. Testing and analysis provide a rational basis for assessing the relative performance of concrete mixtures when subjected to shrinkage under strictly restrained conditions. The simplicity of this test enables it to compete with the ring test, the most commonly used device in early-age concrete assessment.

Based on these discussions, there are similarities and differences with the ring test:

- **Similarities:**

- Both tests are used as an early-age assessment tool for concrete mixtures.
- Both represent a simple testing procedure based on concrete restrainment, boundary conditions, and concrete shrinkage.
- Both are sufficient in detecting mixtures prone to cracking, since the potential for cracking is influenced by complex interactions of strength gain, stiffness development, shrinkage, and degree of restraint.

- **Differences:**

- Our method investigates cracking development in better-restrained conditions.
- Our method predicts the cracking age of concrete more precisely due to the development of cracks in a purely tensile mood.
- Our method has a higher surface-to-volume ratio, which better simulates site conditions.
- Our method improves the evaluation criteria, since the concrete is drying from two surface areas rather than one (as is the case in most ring-test methods).
- Our method handles tensile-stress formation more uniformly.
- The ring test does not allow any expansion, while ours allows it to a limit - mold boundaries.

The main purpose was to develop a tensile cracking assessment tool based on restraint in which simulating real site conditions for cracking is not the criterion but the condition that supports restrainment to propagate pure tensile stresses in the specimen, allowing the cracks to develop in a form similar to site conditions. This device primarily provides information about the age of visible crack development and secondarily indicates its development pattern. Because the forks are buried in the specimen, it is not feasible to establish a simple free-body diagram analysis. As such, the device is only purposed to compare concrete mixes.

Finally, the apparatus is a new approach toward understanding early-age concrete behavior, performance, deformation, cracking, and fracture. This apparatus will be useful in determining the relative likelihood of early-age cracking for cementitious mixtures and in aiding in the selection of cement-based materials that are less likely to crack under restrained shrinkage.

## 3.2 Testing Procedure

In concrete structures such as bridges, designers use HPC mixtures to overcome durability issues. This is in part because exposure to harsh environmental conditions is expected. In the last 20 years, the strength of concrete used in bridge construction has increased gradually. The mixtures for bridge decks are almost identical. This research attempts to compare the results of eight mixes, as seen in Table 3-1. Each mixture will be used to form a cylindrical specimen 18 in. in diameter and 4 in. deep.

**Table 3-1. Concrete composition**

| | |
|---|---|
| 8 Cylindrical pancake specimens | |
| Total Concrete Cubic Feet: 5.82 | (10066 cubic inches) |
| In 0.22 cubic yard, the concrete components decomposition is | |
| Cement | 853 lb |
| Fine Aggregate | 929 lb |
| Coarse Aggregate | 1731 lb |
| Water | 358 lb |

In bridges, a high-strength concrete of 6 ksi or more is normally requested. To optimize the mixture being used, it must be batched using different portions of carefully selected high-quality ingredients. Mixtures must be well-designed, batched, mixed, placed, compacted, and cured to the highest industry standards. This cannot be maintained without proper construction tools and procedures; curing must take place as soon as possible after construction to avoid propagation of stresses or formation of cracks. However, in this project, curing was not considered. To ensure project orientation toward the success of HPC in Alabama, it was highly valuable to conduct trial batches using local materials and production procedures. The proposed decks mixes for the state of Alabama can be seen in Table 3-2.

**Table 3-2. Proposed mixtures**

<table>
<tr><th></th><th>W/CM Ratio</th><th>Coarse Aggregate</th><th>Cement Type</th><th>SCM</th></tr>
<tr><td rowspan="3">Concrete Mix</td><td rowspan="3">0.42</td><td rowspan="2">River Gravel</td><td rowspan="3">Type I/II</td><td>Class C-Fly Ash</td></tr>
<tr><td>Class F-Fly Ash</td></tr>
<tr><td>Limestone</td><td>GGBF Slag</td></tr>
</table>

Mixtures used in one part of the country do not necessarily suit another region. However, Alabama's construction demands and HPC mix proportions are close to the rest of the southeastern U.S. The assessment and evaluation of the batched concrete mixtures is to be addressed according to the following considerations:

- Identifying performance objectives, based on the desired function of the mixture.
- Selecting high-quality local raw materials.
- Trial batching using possible combinations of raw materials.

The results of this experiment are assumed to be directly influenced by the variable parameters, which are included in this study. Uniquely, the effect of using different SCM types and different coarse aggregates are the only parameters addressed in this experimental study, as seen in Table 3-3.

Aktas indicated that the type and size of coarse aggregate will always have an influential effect on the cracking resistance of the fresh concrete (Kagan 2008). Therefore, the different coarse aggregate types are expected to influence the cracking pattern of concrete, as referred to in another research conducted by Einsfeld and Velasco (2006), where the results obtained using the standard compressive strength test indicated that the concrete strength was affected by the type and size of the coarse aggregate. Also, the effect of adding different SCM admixtures will also be addressed. The effect of different types of SCM on cracking is not completely understood, as demonstrated by the inconsistent results regarding its benefits, yet it is a recommended ingredient in HPC mixtures. Therefore, SCM has been chosen as a variable parameter in this experiment.

**Table 3-3. Variable and fixed parameters considered in this research**

| Variable Parameters | Fixed Parameters |
|---|---|
| Course aggregate type | Specimen size & boundary conditions<br>Surface-to-volume ratio (S/V)<br>Cement type "I/II"<br>W/CM ratio (0.42)<br>Fine aggregate type |
| SCM type | Curing conditions<br>Time constraints<br>Temperature<br>Humidity<br>Mixing procedure & degree of compaction |

Seeking consistency in the results, some parameters were set constant to limit the focus on the concrete's performance at early ages and to conduct the experiment in a uniform manner: cement type, W-CM ratio, fine aggregate type, temperature, humidity, and time constraints. One type of cement is used in this experiment: type I/II. However, all of the mixtures should contain binding materials other than cement, according to the needs of the mixture. The W-CM ratio is considered instead of the W/C ratio due to the inclusion of cementitious materials such as fly ash and GGBF slag in the mixture binding materials. The W-CM ratio is maintained at 0.42, which is usually used in bridge constructions all over the U.S., while the fine aggregate used is sand from Alabama. Finally, both temperature and humidity will be maintained in a controlled environment using the environmental chamber, where the temperature and humidity will remain constant as 23$^{o}$C (73$^{o}$F) and 50% RH respectively. Understanding these fixed parameters for evaluation is essential to enhancing the benefits of the performed test.

It should also be noted that there will be no curing techniques implemented in the testing despite its critical effect on the strength and durability of the concrete. These fixed constrains maintain an adequate base for evaluating and preserving the shrinking mechanism of concrete in a form similar to real site conditions.

Considering the overall quality of this project is a basic criterion for the precise evaluation of the test results and for ensuring the apparatus assesses the shrinkage that occurs in the 14 days after mixing. This includes the time when the concrete is in a liquid state; the transition period when it is forming a skeletal frame; and finally the initial hardening, after which the concrete is rigid. During the test, the specimen is sealed from top and bottom within the first 12 hours of its age as a pre-experimental procedure. The sealing will insulate the specimens to minimize the loss of water until the beginning of the experiment. Once it is placed in the environmental chamber, the seal is removed and the specimen left to dry and shrink. For HPC mixtures, initial hardening usually takes place 12 hours after mixing, when the early-age shrinkage rate is minimal. During this phase, no harmful shrinkage of concrete will occur since the material is still fluid and plastic. After the skeletal formation, shrinkage starts to play an integral role. At 14 hours, the concrete is expected to start gaining strength. The initial expansion will be accommodated by the rubber band surrounding the inner circumference of the mold, as seen in the apparatus in Figure 3-13. After 12 hours, the volume is continuously shrinking and shrinkage cracks occur only when the shrinkage stress becomes greater than the corresponding tensile strength of concrete (Chang, *et al*. 2008). Below are the steps for the testing procedure, including time constraints:

- Select the proportions of cementitious materials to achieve the desired strength at the 28th day. The final mix is expected to have high early-age strength (greater than 4 ksi at seven days).
- Mix the ingredients to form HPC mixtures. The concrete mixes are made using local materials and tap water.
- Immediately after mixing, the fresh concrete is placed in the steel mold, which consists of the inner ring (20 in. in diameter and 4 in. in height) in addition to the six fork-shaped rebars, as seen in Figure 3-13.
- The initial set is expected to take place two to six hours after mixing, while gaining sufficient early-age strength might take seven days.

- After the mixture is poured into the mold, it is covered and wrapped up the plastic sheet for 12 hours at room temperature.
- After 12 hours, the initial status of the concrete is recorded. The mixture should show no signs of cracking.
- Set the environmental chamber at 73$^{o}$F and 50% relative humidity.
- Strain and crack development is monitored under controlled environmental conditions.
- For each sample, inspection of the concrete's progress lasts for at least two weeks.
- Monitor the three phases of crack formation: crack initiation, crack propagation, and crack development.
- Record the final status and measure the change in diameter length.
- During the later stages of the experiment, standardized shrinkage measurements are taken before the concrete specimen is removed from the mold.
- For specimens that have not cracked, the rate of tensile stress development at the time of the test is determined to provide an adequate basis for comparison of specimens.
- Finally, set a new mixture for the experimental work, then follow the steps from the beginning once again.

In Figure 3-13, the steel mold and the steel plate fit together like Legos, which eases the placement of the concrete mixtures in the mold. It is essential to avoid segregation of the mixture components by placing them properly. The steel plate placed underneath the mold acts as a base plate, supporting the specimen during its first hours, when the concrete is still hardening.

### 3.3 Monitoring and Strain Gauges

Strain gauges are used to monitor strain development in the specimen while it is being placed in the steel mold. Monitoring and reporting HPC performance changes helps in developing a database. Comparing the results and conducting the data analysis are done once the experimental work and the collection of required data are accomplished.

Three types of strain gauge are used in this experiment to collect data. The first type is a circular rosette strain gauge for measuring strain development at the center of the pie specimen surface. The second type has a rectangular shape and is used to measure the development of surface strain at the center of the specimen. Both are placed at the center based on Saint-Venant's principle, which certifies that the center of the circular specimen should be under pure tension. Both gauges are placed on the concrete surface due to moisture diffusion at the concrete specimen surface because tensile stress is expected to occur on most of the exposed surface of concrete.

The third and final type of strain gauge used in this experiment will be a weldable strain gauge connected to the embedded rebars to quantify the strain development on those restraining rebars. According to research conducted by Kim and Lee (1998), the technique of using the strain gauges on the embedded rebars is suitable for measuring the internal shrinkage strain distribution. All three types of strain gauges are connected to an automatic data acquisition system, which is an intermediate step to saving the data on a computer for analysis.

**Figure 3-13. An overview of the pie test apparatus**

Such a setup has enabled stress development to be monitored precisely in addition to providing a simple procedure to easily quantify the restrained shrinkage characteristics of the concrete mixtures.

### 3.4 Expectations

When the concrete specimen deforms due to volumetric changes, the fork-shaped rebars oppose and hold back the potential movement. This opposition induces tensile stress in the specimen. Stress development can be monitored using the strain gauges suggested in this experimental setup, where it can be observed starting 12 hours after concrete placement. Such applications allow the determination of concrete cracking and the propagation of stresses as a function of time. It would also allow for accurate determination of tensile strength, the stress-strain relationship, and the elastic modulus.

The specimens are expected to dry from the concrete surface, allowing the cracks to initiate at the specimen surface and propagate toward the center. This is consistent with the idea of maximum tensile stress developing at the surface of the concrete due to moisture gradient. Hence, stress develops prior to visible cracking at early ages. Consequently, it is predicted that all specimens will show a drop in developing stresses corresponding to an age at which a visible crack developed in the concrete specimen.

Shrinkage is expected to start instantaneously. Once the initial setting time of concrete is achieved, it usually takes 3-6 hours (Hossain, *et al*. 2003). Within the first 12 hours after the concrete setting, a steep increase in total early-age shrinkage is expected, and then the rate of the total shrinkage will slow due to the relatively dense microstructure and a lower rate of propagating stresses (Ba, *et al*. 2008). Once shrinkage takes place, a typical change in length (diameter) is expected. It is hard to identify where the cracks will occur, but the test provides an approach for monitoring the strain and indicating how a specimen might fail.

Due to variation in the coarse aggregate used, it is expected that the use of large particles will reduce the specific area of aggregate, which might cause a lower bonding strength, resulting in a reduction in concrete strength. This would eventually cause wider and earlier cracks. Finally, the surface-to-volume ratio (S/V) of specimens has a significant influence on the rate of shrinkage, but due to its being maintained a constant in the test, its influence can be neglected.

## 3.5 Modeling

Further work should be done on defining the geometry and boundary conditions of this apparatus to simulate actual field applications. In the upcoming step of the research, a series of test-based calculations must be conducted using a finite element method (FEM). The finite element simulations will be performed using the commercial analysis code ANSYS to quantify the degree of restraint induced by the rebars, in addition to how material properties, geometry, and drying direction could influence the degree of restraint.

Numerous studies have been published discussing the importance of recording and evaluating the rate and degree of restraint. A study conducted by Hossain, *et al*. (2003) indicates that specimens with a higher level of restraint exhibit more cracking as a part of the stress relaxation process. However, stimulating the field condition severity and implementing it in laboratory testing is difficult to impose and control.

## 3.6 Next Step

Once the test method has been identified, it is possible to conduct the analysis investigating the chemical and mechanical phenomena causing shrinkage in the first hours of concrete structure formation. Laboratory experiments are performed, and stress-strain analysis is conducted. Thefinal task involves analyzing the information gathered, based on the mixture trial batches. Finally, this research is intended to be a report of reflection rather than an assemblage of information. Its purpose is to contribute to the literature used to avoid cracking in structures.

# Section 4
# Pilot Laboratory Study

This section describes the pilot study to verify the feasibility of the new device in evaluating the cracking potential of concrete mixtures.

## 4.1 Development of Embedded Concrete Strain Gauge

There are two types of embedded strain gauges to measure the deformation in concrete available in the market: the vibrating wire gauge and the embedded concrete strain gauge. However, because of the hard shell in the concrete gauge and the stiffness of vibrating wire gauge, they are not capable of measuring the deformation of fresh concrete before it has gained adequate strength. As such, we have developed a new way to embed strain gauge in concrete. Figure 4-1 shows the finished strain gauge.

**Figure 4-1. Strain gauge developed for measuring deformation inside concrete**

To verify the feasibility and accuracy of the embedded strain gauge, a mortar mix was prepared. The mortar had sand:cement:water mass proportions of 3:2:1. The strain gauge was buried 0.5 inches below the mortar surface. The strain reading was started once the specimen was finished. The strain reading was recorded by a Vishay P3 recorder. 48 hours after the mortar was cast, another strain gauge was glued to the specimen surface, as shown in Figure 4-2. The comparison of the two readings is shown in Table 4-1 below.

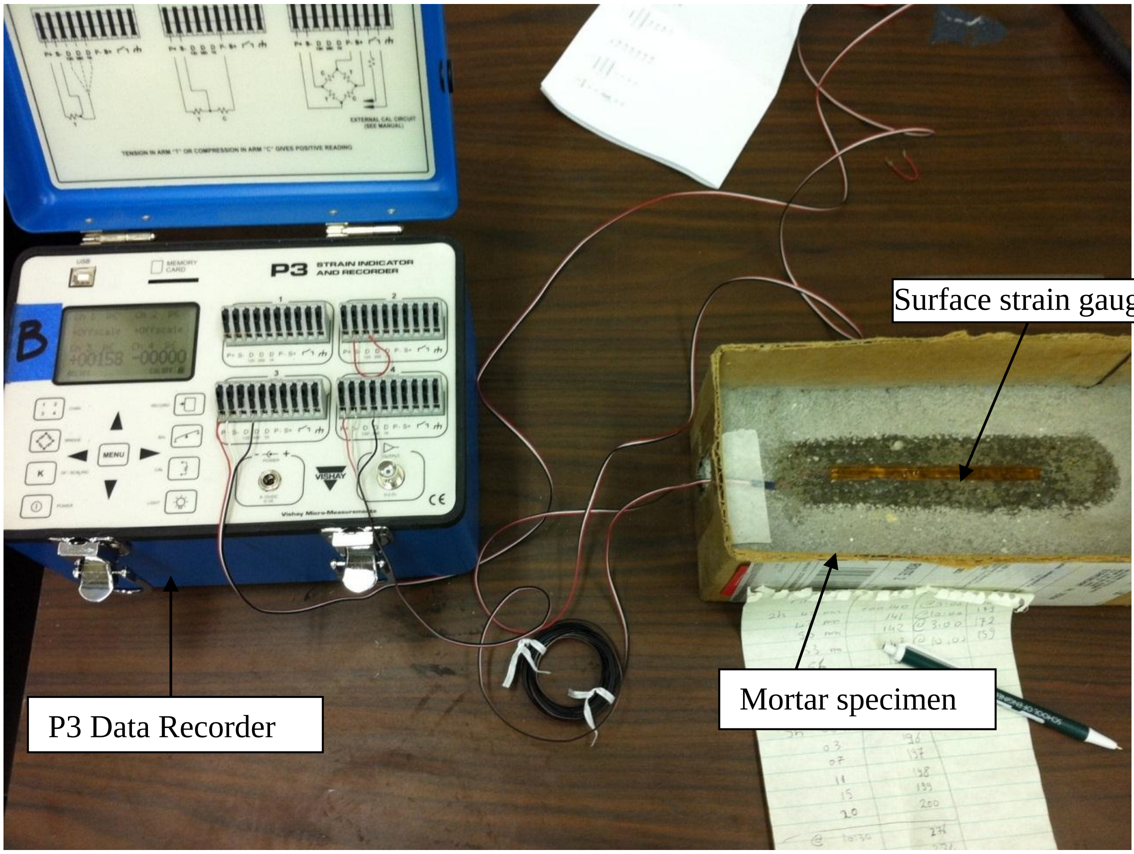


**Figure 4-2. Mortar specimen and P3 strain data recorder**

**Table 4-1. Strain reading of embedded and surface strain gauges**

| 7/9/11 (Time at) | | Embedded Strain | Strain on Surface | Difference |
|---|---|---|---|---|
| **Hour** | **Minute** | **με** | **με** | **με** |
| 10 | 00 | 159 | | |
| 10 | 30 | 158 | 0 | |
| **7/10/11 (Time at)** | | **Embedded Strain** | **Strain on Surface** | **Difference** |
| **Hour** | **Minute** | **με** | **με** | **με** |
| 10 | 00 | 143 | -9 | 6 |
| **7/11/11 (Time at)** | | **Embedded Strain** | **Strain on Surface** | **Difference** |
| **Hour** | **Minute** | **με** | **με** | **με** |
| 11 | 00 | 109 | -42 | 1 |
| 1 | 00 | 107 | -44 | 0 |
| 5 | 00 | 101 | -50 | 0 |

Clearly the measured shrinkage strain changes of the two readings were close and on the third day, there was no difference at all. This confirms the success of the developed embedded strain gauge, and the gauge was used in the concrete test.

The strain gauge was also glued to the steel bar holding the fork, as shown in Figure 4-3. For each test, only three bars were instrumented with strain gauges to measure stress development.

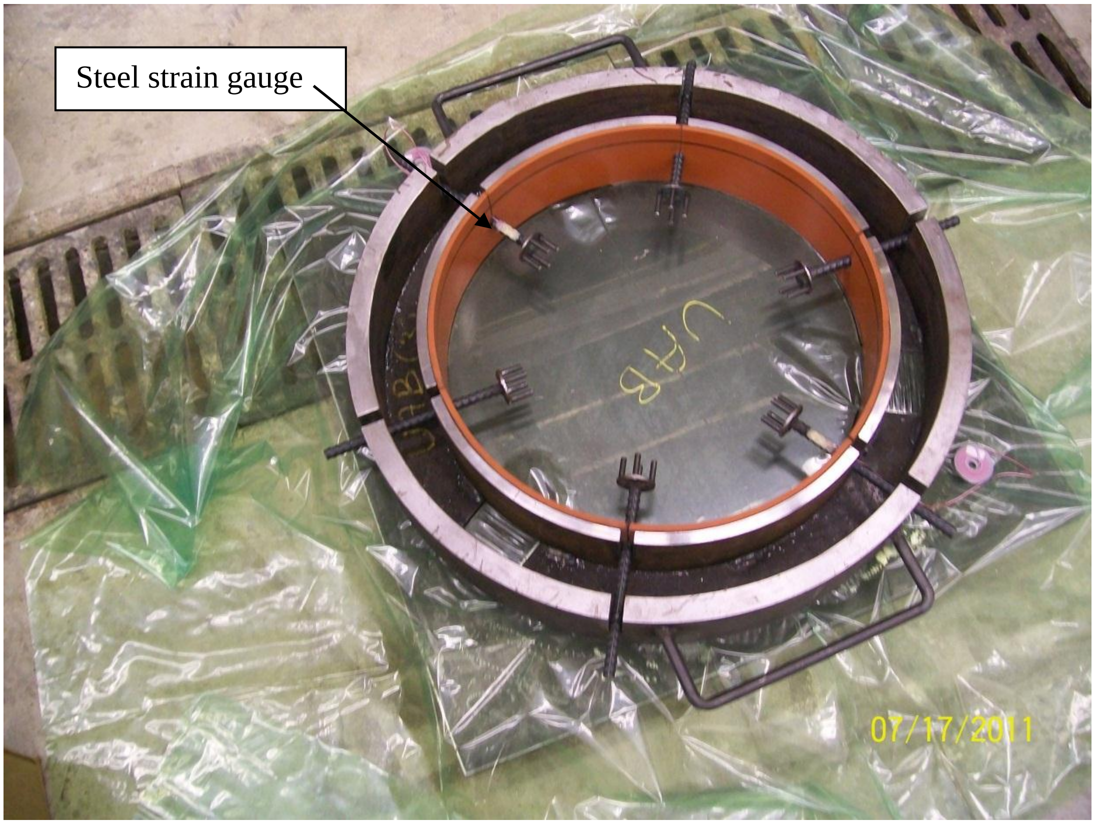

**Figure 4-3. Steel strain gauges attached to rebars**

## 4.2 Pilot Study on Concrete Mixes

### *4.2.1 Preparation of Specimen*

For this phase, pre-packaged concrete bags from home improvement store were used to prepare a concrete mix to test the device. The water was added as recommended by the producer. Figure 4-4 shows the mixing of concrete. The slump was measured as 7 inches.

The concrete was then transported to the place where the "pie test" device was positioned. The room temperature was held constant at $73^0$F. However, relative humidity was not controlled. The concrete was scooped into the mold, as shown in Figure 4-5. Care was taken to make sure the concrete was properly consolidated underneath the forks.

The next step was to prepare a flat surface to bury the strain gauge in concrete, as shown in Figure 4-6. Care was taken to ensure that the flat surface was 0.5 inches below the finished concrete specimen surface. After the surface was ready, the strain gauge was carefully placed on the surface as flatly as possible.

Figure 4-4.  Mixing and pouring out of concrete to be transported to the mold

Figure 4-5.  Casting of the concrete specimen


**Figure 4-6. Placing of embedded strain gauge in concrete specimen**

The last step was to add another layer of concrete to finish the specimen. Figure 4-7 shows the finished specimen and test setup. There was some bleeding water on the surface shortly after the concrete was finished.


**Figure 4-7. Finished concrete specimen and test setup**

### *4.2.2 Test Results and Discussion*

The strains were recorded with a frequency of every 10 seconds for a period of 59 hours. The recording was stopped because the strain of concrete and steel remained almost constant after 10 hours. The early recording was plotted in Figure 4-8 below.

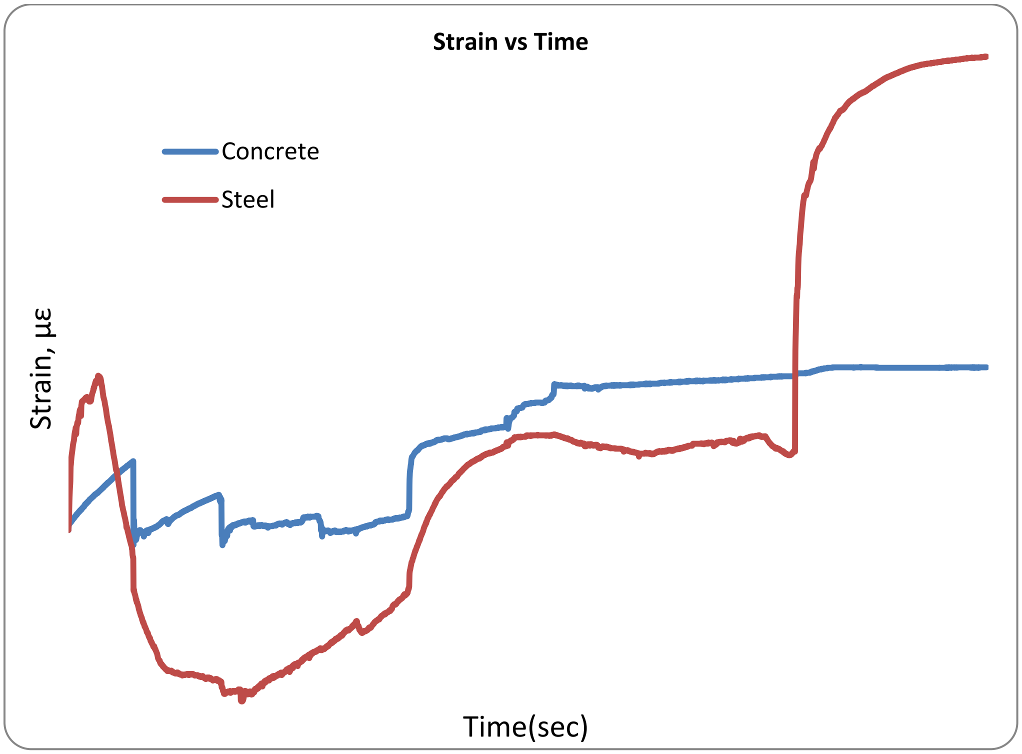


**Figure 4-8. Recorded concrete and steel strains at early age**

Note that the concrete and steel rebars all have expanded in the process. The concrete expansion can be attributed to the temperature rise due to cement hydration. After about 10 hours, the strain of concrete was almost constant. This indicates that the deformation—that is, shrinkage due to temperature drop and drying shrinkage—was totally restrained by the forks used in this study. The record of steel bar deformation is hard to explain and more study is needed. After about eight hours, the extension of steel bar suddenly greatly increased. This is probably due to the restraint due to the shrinking of concrete.

Figure 4-9 shows the specimen eight days before disposal. No visible cracks were found on the surface. The reason was probably the high relative humidity in the Birmingham area during those seven days. Another possible reason is that the concrete is not prone to cracking.

Even though the results are preliminary, the feasibility of the proposed device was established. The recorded strain for concrete is in the reasonable range. The fork can restrain the shrinkage of concrete.

**Figure 4-9. Uncracked concrete specimen at eight days**

# Section 5
# Conclusion

Increasing the service lifetime of concrete bridges and pavements is a concern for highway, structural, pavement, and construction engineers. Cracking is not a discrete event; it occurs over time. Therefore, controlling early-age cracks in HPC helps avoid deterioration and corrosion of concrete and reinforcement, in addition to setting back its catastrophic consequences. Thus, fewer bridge decks and concrete pavements will suffer cracking.

There is a global need to optimize overall performance of HPC to overcome its increased brittleness. Investigating the factors that influence HPC performance at early ages, in addition to assembling conditions for these cracks to develop, will directly influence its strength, durability, and long-term properties. Therefore, future interest and investigations of HPC as a construction material is essential. This ought to be done through experimental evaluation and testing of HPC.

The purpose of this project is to evaluate a newly developed and improved device for identifying early-age cracks in concrete mixtures. Accompanied by strain gauges, the stress-strain analysis for concrete mixtures can be examined and conducted. This method was set to determine the age of concrete cracking based on concrete restraint and endorsing the occurrence of early-age cracks in it. Ultimately, it is expected that the setup ensures the development of pure tensile stresses in the concrete. The pilot laboratory study verified that the device has the potential to accomplish these goals.

The findings and results using the new restrained concrete shrinkage test depend on the stress-strain analysis as well as the size and the number of cracks that develop. Thus, the results will help in defining the criteria proposed for each HPC mixture in a precise, accurate fashion by comparing the developed tensile stresses and cracking tendency at early ages. In addition, the results conducted will be compared with published studies on the different durability criteria for HPC.

Eventually, these goals will help establish a clearer understanding of the mechanism causing concrete cracking at early ages and offer valuable information regarding the use of HPC in bridges and pavements. Subsequently, increasing the cracking resistance of bridge-deck mixtures leads to an increase in its service lifetime.

Finally, beside the innovative apparatus offered that acts as a useful selection tool for engineers, this project is expected to serve as a reference for concrete-cracking evaluation methods in a purely tensile manner for both rehabilitated and newly constructed concrete bridges. It was based on recommendations to produce concrete mixtures that are more resistant to early-age cracking. It also supports efforts to construct HPC bridges, especially in Alabama.

In the long term, this project contributes to a better understanding of concrete behavior at early ages.

# Section 6
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