WORKBOOK FOR THE DETERMINATION OF STRENGTH AND DURABILITY PARAMETERS OF HIGH PERFORMANCE CONCRETE FOR BRIDGE STRUCTURES

INTRODUCTION

High performance concrete (HPC) is concrete that has performance characteristics exceeding those normally expected. The desired characteristics may be related to strength parameters (strength, elasticity, shrinkage, or creep) and to durability characteristics (resistance to freezing and thawing, scaling, abrasion resistance, or penetration of chlorides) or a combination of these (Goodspeed et al., 1996). The definition includes relationships between project exposure (i.e., climatic conditions, applied loads, and ambient conditions) and performance parameters. Different performance grades are recommended to address the needs of a project.

Strength is a measure of the amount of stress that causes failure. The materials in a structure must have the required strength to resist the stresses caused by the dead and live loads imposed. Stresses also cause deformations that are instantaneous (elastic behavior) and time-dependent (creep). Deformations also arise from changes in moisture content and temperature. Moisture content change may cause drying shrinkage. When a restrained body is subjected to deformations additional stresses would occur that can affect the overall load carrying capacity. In relation to durability, scaling and abrasion would affect the ride quality of roadways. Chloride induced corrosion of reinforcing steel would result in cracking and spalling that initially affects ride quality, but later the structural integrity. Similarly, cycles of freezing and thawing could cause cracking and scaling that can affect the ride quality and structural integrity of non-frost resistant concrete.

The improved performance characteristics of HPC are expected to result in cost savings, and reduced maintenance leading to reduced inconvenience and improved safety to the traveling public. The initial cost savings arise from using fewer beams; reduced labor, transportation, and construction; and increased span lengths necessitating fewer piers. The durability aspect is expected to lead to large cost savings because of longer service lives with minimal maintenance.

HPC is engineered concrete that addresses the needs of structures. Use of the proper ingredients and proportioning are essential in order to achieve the specified properties. Once concrete is produced, it must be tested to ensure that the desired properties are achieved.

Before the placement of concrete in the bridge structure, trial batches are recommended using the job material. Results will indicate if the materials and proportions selected can provide the desired properties. Testing in the field indicates if the concrete approved is delivered to the job. Samples prepared in the field can be brought to the lab and cured in the lab (lab-cured) for acceptance testing. They can also be kept at the job site (field-cured) to simulate the conditions the elements are exposed to. Lab-cured specimens would indicate the quality and uniformity of the concrete. Field-cured specimens would provide additional information on the adequacy of field curing. In either case, sampling and testing following standard procedures are needed. In case of dispute due to unexpected results, cores can be obtained from the structure and tested. Cores represent the concrete in-situ. In addition to quality of delivered concrete, it also includes construction practices (placement and curing), and the techniques for obtaining and testing the cores.

This workbook explains the eight standard tests that measure the durability and strength parameters of HPC. The significance of each test and a summary of the test procedures are presented.

FRESH CONCRETE

Sampling is an important part of testing. Before the explanation of the 8 standard test procedures on hardened specimens, sampling at the fresh state is described. The standard tests to determine the characteristics of freshly mixed concrete are briefly mentioned. Preparation of specimens for tests at the hardened state is also included.

Sampling

To ensure concrete meets the specifications, samples are obtained and tested to determine the physical and mechanical properties. Concrete being a mixture of different ingredients naturally exhibits variability. To establish specification limits, the amount of variability must be assessed. Concrete is delivered to the job site in a series of batches or loads. Batches and loads are parts of the total population. The lot is an estimation of the population. It is the quantity of material manufactured during a single condition of production that is considered to be homogeneous and in which the source and proportions of all major ingredients are similar. Testing randomly selected batches attempts to develop an unbiased measure of variation found in the lot. Variation occurs within the same batch as well as between batches. To reflect the variation from each load, samples from different stages of discharge of that load are taken and composited for a total sample. AASHTO T 141 (ASTM C172) explains sampling of freshly mixed concrete. It states that sample should be taken from at least two places in the middle third of the load.

Variability in concrete is a result of variability in ingredients, methods of preparation, curing procedures, and test sampling methods and conditions. To describe all of the variation that exists in a lot of a material, a large number of independent samples is typically required. However, economic and time restraints often limit the number of tests that can be made. Statistical procedures can provide information on the number of samples needed for a certain probability of accepting a lot. Statistical measures of a population or lot require that a mean and a standard deviation be calculated.

Standard Tests for Freshly Mixed Concrete

Generally, the concrete delivered to the job site is tested for air content (AASHTO T 152 [ASTM C231 pressure method] or AASHTO T 196 [ASTM C 173 volumetric method], slump (AASHTO T 119 [ASTM C 143], and concrete temperature (ASTM C 1064). At this state, characteristics of the mixture such as ease of placement and the ability to consolidate without segregation can be determined. Unit weight (AASHTO T 121 [ASTM C 138] is another useful test indicating air content, but is rarely tested in the field.

Preparation of Specimens

Making and curing concrete test specimens in the laboratory are given in AASHTO T 126 (ASTM C 192), and in the field AASHTO T 23(ASTM C 31).

Molds

The rigidity, water absorption, and expansion of mold material would affect the test results. Molds should be watertight. Reusable molds should be carefully checked to ensure that the shape does not change. Metal or rigid plastic molds are used in HPC.

Consolidation

Concrete with slumps above 3 in should be consolidated by rodding, slumps between 1 and 3 in either rodding or vibration, and slumps below 1 in by vibration in layers. For each upper layer, the rod should penetrate into the lower layer approximately 1 in. Different size rods are used for different size specimens. After rodding, the sides are tapped lightly with a mallet to close any holes left with rodding and to release any large air bubbles. These operations should be conducted in ways that minimize segregation.

Curing

Samples are maintained in a moist environment at 73 F $\pm$ 3 F in the laboratory. HPC generally has low water-cementitious material ratio (*w/cm*) and cannot afford to loose its moisture. In the field, after molding, the specimens are stored in a temperature range between 60 to 80F, and in a moist environment preventing any loss of moisture up to 48 hours. Then, they are transferred to the laboratory.

HARDENED CONCRETE

Freezing and Thawing

Structures exposed to cycles of freezing and thawing when saturated may exhibit surface scaling and disintegration if not properly protected. The use of chemicals to melt ice and snow accelerates the deterioration by subjecting the concrete to more cycles of freezing and thawing. The freezing and thawing damage can occur in both cement paste and aggregate in concrete. The freezing of water in the pores of aggregates or the cement paste is accompanied by an increase in volume, which can cause high hydraulic pressures (Cordon, 1966).

For resistance to freezing and thawing, water-saturated concretes must have sound aggregates, a proper air-void system, and have matured (developed a compressive strength of about 28 MPa) (Mather, 1990). With a proper air-void system, the paste contains air bubbles (most diameters less than 0.004 in) that are not more than 0.008 in from any point (Mather, 1990). To achieve this, air-entraining admixtures are added during mixing so the mortar fraction will contain about 9 percent air (ACI Committee 201).

Most rocks have pore sizes large enough to expel water, so hydraulic pressures in aggregates do not often occur. However, in some parts of the United States coarse aggregates are found to disintegrate in saturated concretes when exposed to cycles of freezing and thawing. One form of this distress, described as D-cracking, requires the presence of a sufficient quantity of susceptible aggregate, sufficient moisture and freezing, and cannot be prevented by optimizing the air-void system in the concrete (Janssen 1994). To minimize D-cracking, the maximum particle size of the susceptible aggregates is reduced.

The most commonly used test is AASHTO T 161 (ASTM C 666). There are 2 procedures. Procedure A involves rapid freezing and thawing in water. Procedure B requires rapid freezing in air and thawing in water. Specimens are subjected to 300 cycles of freezing and thawing and the internal soundness is determined by measuring the resonant frequency. It is optional that the length change is measured. Procedure B is not as severe as Procedure A since drying of specimen can occur during testing, and it is possible to accept concretes using Procedure B that may not have adequate resistance to freezing and thawing in the field. SHRP 20180 has offered another procedure, C. In Procedure C, the specimens are wrapped in towel and kept tightly wrapped except when measurements are taken.

Procedure A is a severe test. Concretes performing well in this test have done well in field applications. Concretes failing the test may also have satisfactory field performance, but such performance must be proven in the field.

Test Procedure (AASHTO T 161 [ASTM C 666] Procedure A)
Test specimens are cast or cut from hardened concrete.
Specimen width, depth or diameter is not less than 3 in nor more than 5 in, and length is between 11 and 16 in.
Cure molded specimens for 14 days in saturated lime water.
Surround the specimen by not less than 1/32 in nor more than 1/8 in of water at all times.
Freezing and thawing cycle consists of lowering the temperature of the center of the specimen from 40 to 0F (with $\pm$3F tolerance) and raising it from 0 to 40 F in not less than 2 nor more than 5 hour.
Not less than 25% of the time shall be used for thawing.

Remove the specimens from the freezing and thawing apparatus in a thawed condition at intervals not exceeding 36 cycles and test for fundamental transverse frequency and optionally for length change. Use fundamental transverse frequency to determine the relative dynamic modulus of elasticity indicative of the internal integrity of the concrete. Continue testing until 300 cycles or until the relative dynamic modulus of elasticity reaches 60% of initial modulus.

Scaling Resistance

Scaling is a freezing and thawing related deterioration. It is aggravated by the use of chemicals salts because of low cost and effectiveness. Scaling starts at the surface exposing coarse aggregate. It progresses into the concrete. Hydraulic and osmotic pressures cause high stresses that cause cracking of the concrete. Osmotic pressure is enhanced by the presence of chemicals. The deterioration is greater for intermediate concentrations of chemicals (3 to 4%) than for lower or higher concentrations (Newlon and Mitchell, 1994). Adequate air-void system is required to prevent or minimize distress. Over finishing should be avoided since loss of air at the surface is possible.

ASTM C 672 is the most widely used test to determine the resistance to scaling. Specimens are subjected to 4% calcium chloride and are rated from 0 to 5; 0 representing sound concrete with no scaling and 5 severe scaling with coarse aggregate visible over entire surface.

Test Procedure ([ASTM C 672])

Specimens have a surface area of at least 72 in^2 and at least 3 in in depth.

Place a dike about 1 in wide and ¾ in high along the perimeter of the top surface of the specimens.

Remove the specimens from moist storage at 14 days (can be dependent on strength level) and store in air for 14 days at 73.5 ± 3.5 F and 45 to 55% relative humidity.

Cover the surface of the concrete with 4% calcium chloride solution about ¼ in deep.

Place the specimen in a freezing environment for 16 to 18 hours, and then in laboratory air for 6 to 8 hours.

Flush the surface at the end of each 5 cycles. Make visual examination and replace the solution.

Test until 50 cycles.

Abrasion

Abrasion resistance is defined by ACI 116R as the ability of a surface to resist wear from rubbing and friction. This property is of great importance in transportation facilities. The travelled surfaces must have adequate skid resistance for proper vehicular control. Skid resistance is affected by both the microtexture provided by the aggregate particles and the macrotexture mainly provided by the grooves formed on freshly mixed concrete or the grooves cut in the hardened concrete (ACI 325.6R). Deep texture also enables the drainage of water, preventing loss of tire contact with the pavement surface (hydroplaning).

The abrasion resistance is improved by increasing the compressive strength, using hard and dense aggregates, proper finishing and curing methods (ACI 201, Liu, 1994).

Studded tires cause considerable wear even on quality concrete surfaces. An NCHRP report addresses pavement wear in the presence of studded tires (Bird, 1975). Abrasive materials such as sand have caused little damage to quality concrete surfaces.

ASTM has several standard test procedures to evaluate the abrasion resistance of concretes. In ASTM 418, the concrete surface is subjected to impingement of air-driven silica sand. In ASTM C 779, three procedures are given that simulate different abrasion conditions. In Procedure A, revolving steel disks in conjunction with abrasive grit abrade the surface. In Procedure B, steel dressing wheels riding in a circular path provide the abrasive action. In Procedure C, the abrasive action is caused by a rapidly rotating ball bearing under load on a wet concrete surface. ASTM C 944 is the standard test procedure used for HPC. A rotating cutter abrades the surface of the concrete under load. It has been successfully used in the quality control of highway and bridge concrete subjected to traffic (ASTM C 944). ASTM C 1138, determines the relative resistance of concrete to abrasion under water.

Test Procedure ([ASTM C 944])

Concrete specimen can be of any size and shape that can be accommodated by the abrasion device.

Weigh the specimen prior to testing.

Lower the rotating cutter with mounted dressing wheels into contact with the specimen for three, 2 minute, periods for a total of 6 min abrasion time at a location.

Maintain a load of 22 lb. For HPC that is highly resistant to abrasion, doubling the load, or the time, or both is recommended.

Determine the depth of abrasion in accordance with ASTM C 799 Procedure B.

Test the concrete at 3 different locations.

Chloride Penetration

The durability of concrete exposed outdoors depends largely on its ability to resist the penetration of water and aggressive solutions. There are four major types of environmental distress in reinforced concretes: corrosion of the reinforcement, alkali-aggregate reactivity, freezing and thawing deterioration, and attack by sulfates (Ozyildirim, 1993). Corrosion of the reinforcing steel is the most extensive of these. In each case, water or solutions penetrating into the concrete initiates or accelerates the distress, making costly repairs necessary. Air-entrained concretes that have low permeability are required to resist infiltration of aggressive liquids and provide the necessary resistance to freezing and thawing when exposed to the environment.

Reinforcing steel is normally protected against corrosion by a protective oxide layer that forms in the alkaline environment provided by the concrete (pH > 12.5) (ACI 222R). Within the service life of the structure, sufficient chlorides can penetrate into concrete to destroy the protective layer, leading to electrochemical reactions that result in rust formation. This corrosion threshold value is approximately 1.3 lb/yd^3 (0.8 kg/m^3) (Clear, 1976). The presence of cracks or voids in members resulting from inadequate curing, consolidation, loading, or other means, and poor drainage can facilitate the penetration of chlorides.

The chloride penetration is a function of the amount and quality of the paste and aggregate, and the interface between the paste and the aggregate. Concretes with pozzolans or slag and low *w/cm* exhibit high resistance to penetration.

Two common tests for determining the resistance of concrete to penetration are AASHTO T 259 and AASHTO T 277 (ASTM C 1202) tests. AASHTO T 259 (Resistance of Concrete to Chloride Ion Penetration), is known as the ponding test. In this test, slabs are ponded for 90 days with sodium chloride solution and the chloride content at different depths in the concrete is determined. However, discerning between concretes generally requires longer ponding times, a year or more. In 1981, a rapid and convenient electrical test was developed for the Federal Highway Administration (Whiting, 1981). AASHTO has adopted it as AASHTO T 277 (ASTM C 1202). This is the recommended test for HPC. In this test, the charge passed in coulombs through a saturated specimen 2-in thick in diameter and subjected to 60 V dc in a 6-hour period is determined. Low values indicate high resistance to penetration by solutions. This test gives a good indication of permeability with proper testing (in the absence of interferences) and proper interpretation.

Both tests provide a good indication of the resistance of concretes to the penetration of aggressive solutions (Ozyildirim, 1993, Ozyildirim, 1994). Quantitative relationships between the coulomb values obtained from the rapid permeability test and the chloride contents from the ponding test have been sought. For comparisons, it is important that similar concretes should be tested at similar ages. All concretes exposed outdoors or cured in a moist room exhibit a reduction in coulomb values with time, and different concretes have different rates of reduction (Ozyildirim, 1998). However, specimens air-dried in the laboratory do not exhibit the expected reduction (Ozyildirim, 1994, Ozyildirim, and Halstead, 1988). Hence, different curing methods or different test ages can easily give the appearance of a lack of any relationship.

In an ongoing FHWA study, the actual penetration of chlorides is measured. The chlorides are driven into the concrete using a direct voltage similar to the AASHTO T 277. Then sample is split open and treated with $AgNO_3$. Reaction of $AgNO_3$ with Chlorides forms a black AgCl which can be detected.

Air and water permeability tests are also available. SHRP Product 2031 developed an air permeability test that measures the flow rate of air flow out of a concrete surface under a fixed vacuum. The greater the flow rate the more permeable is concrete. It is a convenient test. The entire test takes about a minute.

Test Procedure (AASHTO T 277 [ASTM C 1202])
Cylinders or cores can be tested.
Cut the top 2 in of a 4 in cylindrical specimen and coat the sides with epoxy.
Saturate the specimen under vacuum and keep in water for 18 hours.
Apply a 60 v DC across the specimen for 6 hours. Measure the current.
Product of current and time gives the charge passed in coulombs.

Strength

It has been a common practice to assess concrete quality only in terms of concrete strength (Mindess and Young, 1981). It is generally accepted that increase in strength improves other properties of concrete as well. This is misleading. For example, more cement to increase strength may also increase shrinkage; accelerated curing increase early strength but may reduce the permeability of concrete.

The factors that affect strength can be categorized as constituent materials, methods of preparation, curing procedures, and test conditions. Attention should be paid to all the factors to attain strengths representative of the elements.

Specified design strength value is expected to enable the structure to carry the intended loads without appreciable internal damage. Considering the variability in materials and testing, a larger value is desired in developing the mixtures to ensure that a large number of tests will exceed the design strength.

In the industry, the standard cylinder size for test specimens has been 6x12 in. Usually two cylinders are prepared for a test value. However, most machines do not have the capacity to test high-strength concrete (HSC) with 6x12 in. Smaller 4x8 in cylinders are prepared and tested for convenience. Generally three 4x8-in cylinders are used for a test result. AASHTO T22 explains the strength testing. ASTM C 39 also covers strength testing. ASTM C 31 requires testing with large cylinders whereas AASHTO T23 permits the use of smaller (4x8 in) cylinders when the nominal maximum size does not exceed 1 in.

Plane, parallel ends are important; otherwise, improper end conditions will adversely affect the strength values (Richardson, 1991). Plane, parallel ends can be obtained by grinding or capping. Grinding ends is a very good way to prepare the ends. However, it requires equipment and takes time. Neoprene caps in extrusion rings are widely used with success. In case of doubt, comparative tests with cylinders having ground ends can be made. Capping material should be used with caution since in HSC strength may approach or exceed that of the capping material.

Most highway agencies specify strengths at an age of 28 days. If high strengths are required in HPC, it may be difficult to achieve them at 28 days. In general, structures are put to service at a later date making it possible to extend the test age to 56 days or even 90 days. In case strengths need to be determined at earlier age to provide a level of comfort, maturity method can be used to predict long term strengths from earlier ages.

Test Procedure (AASHTO T22[ASTM C39])

High strength cylinders exhibit explosive behavior at failure. Follow all safety guidelines including a protective device around the specimen and safety goggles.

Testing machine should have the sufficient capacity and capable of providing the prescribed rates of loading.

Testing machine must have two plane steel bearing blocks, one of which is a spherically seated block.

Specimen diameters do not vary by more than 2 percent.

Prepare the ends of the specimen and ensure they are plane.

Test specimens as soon as practical after removal from moist storage.

Align the specimen with the center of the spherically seated block.

Apply the load continuously and without shock.

Follow the loading rate specified except in the first half of the anticipated loading a higher rate is permitted.

Make no adjustment to rate of loading as the specimen is yielding rapidly before failure.

Record the type of failure.

Elasticity

Concrete deforms under the applied load. The amount of deformation depends upon the magnitude of the load, the rate of application, and the elapsed time after the load is applied (Philleo, 1994). Instantaneous effect of loading is considered as elastic properties, and the time dependent effect as creep. To be elastic, a body returns to its original dimensions after the release of load. Elasticity is measured as the ratio of stress to corresponding strain. The ratio is known as the modulus of elasticity, and for many materials is fairly constant over a wide range of stress. The terms that describe the limits of elastic behavior are the proportional limit and the elastic limit. Concrete does not have a definite proportional or the elastic limit. Therefore, the modulus of elasticity is defined arbitrarily as the initial tangent modulus, tangent modulus, secant modulus, or chord modulus.

In concrete, the modulus of elasticity is related to compressive strength and density. The volume fraction and the density of the principal constituents, and the characteristics of the transition zone between the paste and the aggregates determine the elastic behavior. Aggregate amount, porosity, grading, size, shape, texture, and mineralogical composition influence the modulus.

Modulus of elasticity can be measured under both tension and compression.

Concrete elements are expected to resist compressive stresses; therefore, modulus of elasticity is determined from compressive loading. When a stress is applied in a given direction, dimensional change occurs in that direction and also in a direction perpendicular to the applied load. The absolute ratio of the lateral strains to the longitudinal strain is known as the Poisson's ratio. Poisson's ratio is a constant for a given material below the proportional limit. Elastic modulus and the Poisson's ratio together describe the elastic behavior of a material. For concrete, below 40% of its ultimate strength Poisson's ratio is essentially constant and varies between 0.15 and 0.20 (Philleo, 1994). For most design computations of concrete elements, Poisson's ratio is not needed (Mehta, 1986).

ASTM C 469 provides the test method for measuring the modulus of elasticity of concrete and the Poisson's ratio.

Test Procedure (ASTM C469)
Place the specimen with the strain measuring equipment attached.
Load the specimen more than once. Do not record data during the first loading. At least two subsequent loadings are recommended.
Determine the load corresponding to a strain of 50 millionth.
Load the specimen until 40% of the ultimate load is obtained. Determine the strain at that load.
Calculate the elastic modulus from the slope of the line using the two points.

Shrinkage

Shrinkage is a volumetric decrease with time; however, it is generally expressed as a linear strain since the majority of concrete elements have one or two dimensions much smaller than the third (Aïtcin et al., 1997). Shrinkage includes plastic shrinkage, drying shrinkage, autogeneous shrinkage, and carbonation shrinkage. At early ages, when concrete is unhardened, the shrinkage due to loss of moisture is known as plastic shrinkage. It occurs when the rate of evaporation exceeds the rate of bleeding (Lerch, 1957). Moisture loss in hardened concrete is known as drying shrinkage. It takes place over several weeks and months. Autogenous shrinkage is caused by the hydration of cement (Aïtcin, 1999). Carbonation shrinkage results as the various cement hydration products are carbonated in the presence of CO_2.

Shrinkage is influenced by the moisture content, *w/cm*, internal restraint provided by the aggregate, admixtures, humidity and temperature environments (Kosmatka and Panarese, 1988). In concrete specimens, the loss of water depends on the size of the specimen (Neville, 1996). The shrinkage values generally quoted are for free shrinkage. The specimen is not restrained internally or externally. In structures reinforcing steel, moisture gradients, and external constraints restrains shrinkage. Tensile stresses develop because of the restraint. When tensile stresses exceed the tensile strength of concrete, cracking occurs. When strains develop over a long period of time creep takes place. Creep reduces the stress induced by the sustained strain. Cracking can be avoided if stress caused by shrinkage, and reduced by creep, is smaller than the tensile strength of concrete (Neville, 1996). The effect of creep on elastic strain capacity is expressed by the extensibility of the concrete. Extensibility is defined as the maximum tensile strain that hardened concrete can sustain before cracking occurs (ACI 116). A high extensibility enables concrete to withstand a greater volume change.

AASHTO T 160 determines the unrestrained free-shrinkage. Another test being standardized by AASHTO is PP34 for estimating the cracking tendency of concrete. It is commonly referred to as the ring test. The test method measures the strain in a steel ring as the surrounding concrete shrinks. It can provide information on volumetric changes and can include the creep effect (Burrows, 1988).

Test Procedure (AASHTO T160 [ASTM C157])

Test specimen is 4x4 in by 11.25 in long prism. The cross section can be 3x3 in if the maximum size is 1 in.

Three specimens are used for each test condition.

Remove specimens from the molds at an age of 23.5 ± 0.5 hours.

Soak in lime saturated water for 30 min. Measure the length.

Store the specimens in lime saturated water at 73.4 ± 3F until an age of 28 days. Measure the length.

Store the specimens in a room maintained at a relative humidity of 50 ± 4% and at a temperature of 73.4 ± 3F.

Creep

ACI 116 defines creep as the time-dependent deformation due to sustained load. Creep deformation can be several times as large as the strain on loading (Neville, 1996). In structures, creep and shrinkage occur simultaneously. Creep caused by drying is known as drying creep and that without the migration of moisture to and from the concrete as basic creep. Total creep strain is the sum of the two. However, in common practice, creep is considered as deformation under load in excess of the sum of the elastic strain and unrestrained shrinkage strain (Mehta, 1986).

Creep is associated primarily with the cement paste and is approximately a linear function of stress up to 35 to 40% of its strength (Philleo, 1994). The load can be applied by a controlled hydraulic system or by springs. It is required that companion unloaded specimens be prepared and tested. Length changes of unloaded specimens are subtracted from the loaded specimens to determine creep due to load eliminating the effect of shrinkage.

Creep and shrinkage characteristics are influenced by water and cement content (paste volume fraction), aggregate characteristics, age at time of loading, type of curing, and applied stress to strength ratio (Holmes, 1994). Creep and shrinkage affect deflections, loss of prestress, reduction in stress concentrations, and changes in camber.

Test Procedure (ASTM C512)

Use a loading frame capable of applying and maintaining the required load on the specimen. The load should not vary by more than 2% of the intended value.

Between the steel bearing block and the specimen place another cylinder having a diameter equal to the test cylinder and length at least half of its diameter.
ASTM C512 requires large cylinders, 6 in diameter and length at least 11.5 in.
Prepare the ends of test specimens to ensure they are plane.
Moist cure the specimens for 28 days. Then keep at room temperature and $50 \pm 4\%$ relative humidity. At 28 days load the specimens to no more than 40% of the compressive strength. Take strain readings immediately before and after loading, then daily for 1 week, weekly until the end of 1 month, and monthly until the end of 180 days. Measure the longitudinal strain in the specimen to the nearest 10 millionths.

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