

Field Materials Manual Series:

Concrete Materials & Mix Design for Highway Infrastructure

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The organizational adaptation is provided for educational purposes only.

Course Overview

Course Description

Concrete is one of the most versatile and widely used construction materials. It is composed of hydraulic cement, fine and coarse aggregates, water, and sometimes admixtures. Concrete is used extensively in highway construction for pavements, bridges, tunnels, culverts, and other structures.

This course covers the materials, proportioning, and verification of concrete for highway applications. It examines how to specify cement and admixtures for durability in harsh environments, understand mix design procedures for strength and performance, evaluate material certifications, and verify fresh concrete properties on site. The course draws from the Federal Lands Highway Field Materials Manual and is part of a series on highway materials acceptance and testing.

Learning Objectives

Upon successful completion of this course, participants will be able to:

- Specify hydraulic cement types and mineral/chemical admixtures for concrete durability
- Design concrete mixes for strength and durability using ACI procedures
- Understand exposure categories (freeze-thaw, sulfates, corrosion) and their material requirements
- Evaluate concrete material certifications and perform acceptance testing
- Verify fresh concrete properties before placement (slump, air content, temperature, unit weight)

Intended Audience

This course is intended for concrete and structural engineers, as well as construction managers, project engineers, quality assurance personnel, and inspectors responsible for concrete specification, design, materials verification, and acceptance on highway infrastructure projects.

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Acronym Reference Guide

This glossary lists the acronyms and abbreviations used in this course.

Acronym	Full Name	Context/Usage
AASHTO	American Association of State Highway and Transportation Officials	Sets test methods (T 11, T 99, etc.)
ACI	American Concrete Institute	Concrete design standards (ACI 211.1, etc.)
ASR	Alkali-Silica Reactivity	Durability problem in harsh climates
ASTM	ASTM International	Sets test standards
DEF	Delayed Ettringite Formation	Durability problem from high sulfates
f_c	Compressive Strength of Concrete	Design strength (psi)
f_{cr}	Required Average Compressive Strength	Must exceed this in testing
FHWA	Federal Highway Administration	U.S. Department of Transportation agency
FLH	Federal Lands Highway	Oversees highway projects on federal lands; issues the Field Materials Manual
FP	Federal Highway Projects	Projects funded and managed under Federal Highway Administration authority; subject to FLH Field Materials Manual requirements
NETTCP	Northeast Transportation Training and Certification Program	Nationally accepted certification for sampling and testing personnel; regional certification standard
NICET	National Institute for Certification in Engineering Technologies	Technician certifications (Level II)
ppm	Parts Per Million	Concentration unit
QL-PAY	Quality Level/Payment Statistical Analysis Software	FLH software for comparing contractor vs. inspector test results and determining pay factors
SHA	State Highway Agency	State-level transportation agency; coordinates with FHWA on highway projects
w/c	Water-to-Cement Ratio	Controls concrete strength and durability
WAQTC	Western Alliance for Quality Transportation Construction	Regional testing standards

Chapter 1

Introduction & Role of Concrete in Highway Infrastructure



1.1 Introduction

Concrete is the most widely used structural material in highway infrastructure. It forms bridge decks, barrier walls, pavements, culverts, and foundations. The performance of these structures depends critically on proper material selection, mix design, and field quality control.

This course covers the materials, proportioning, and verification of concrete for highway applications. Engineers will learn how to specify cement and admixtures for durability in harsh environments (freeze-thaw, sulfates, corrosion), understand mix design procedures for both strength and performance, evaluate material certifications, and verify fresh concrete properties on site. The course emphasizes the link between exposure conditions and material selection, a bridge deck in Pennsylvania requires different materials and proportioning than one in Arizona.

The content draws from the Federal Lands Highway Field Materials Manual and reflects standard practices across US highway construction. Throughout, the guiding principle is: durability first, strength second. A concrete structure that meets strength requirements but fails prematurely due to environmental attack represents a design failure, regardless of strength test results.

1.2 Summary and Description

Concrete is one of the most widely used building materials in the world and a primary component of many highway structures. It is used in many highway applications such as roadway surfacing, bridges, retaining walls, head walls, culverts, guardrails, anchors, and posts. Concrete is a composite material that consists of a binding medium within which are embedded particles or fragments of aggregate, usually a combination of fine and coarse aggregate. In Portland cement concrete, the binder is a mixture of Portland cement and water, with or without admixtures.

The material presented herein will focus primarily on structural concrete and minor concrete as denoted in the Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP). Generally, structural concrete is specified in a contract when load analysis (i.e. bridges, culverts, wall and foundations) is required and the total concrete mixture quantity is greater than or equal to 50 yd³ (38 m³). Minor concrete is typically specified when load analysis is not required (i.e. headwalls, curb and gutter, sidewalks, waterways) and the total concrete mixture quantity is less than 50 yd³ (38 m³). The FP provides requirements for quality construction and materials that include:

- Material Component Requirements
- Concrete Composition, Mixture Proportioning and Mix Design Approval
- Construction and Materials Acceptance

1.3 Mix Design and Durability Overview

Concrete mix design encompasses two distinct but related goals: achieving adequate strength to carry loads, and ensuring durability to withstand environmental exposure.

Traditional concrete mix design (ACI 211 methods) focused primarily on strength. Water-to-cement (w/c) ratio was selected to achieve the required compressive strength; other considerations were secondary. Modern practice recognizes that durability requirements often drive mix design more stringently than strength.

For example, a highway bridge deck in Minnesota experiences freeze-thaw cycles and deicing salt exposure. The durability requirements dictate a low w/c ratio, specific air entrainment, and often a limit on cement content or requirement for supplementary materials. These durability constraints might produce concrete stronger than strictly required for strength alone, but this over-design is intentional and necessary.

The course that follows first addresses materials (cement types, admixtures, aggregates, water), then covers durability requirements for different exposure conditions, and finally addresses strength design. This sequence reflects the professional judgment that durability must be specified first; strength follows naturally when durability requirements are met.

1.4 Concrete Materials Specifications

Concrete is typically composed of the following basic materials:

- Hydraulic cement
- Mineral admixtures (i.e. fly ash, silica fume, ground granulated blast furnace slag)
- Water
- Aggregates (coarse and fine)
- Chemical admixtures (i.e. air entraining, water reducing, set retarding, etc.)
- Fibers

The standard specifications typically used for each of these basic materials are shown in Table 1. Both AASHTO and ASTM standards have been developed for most concrete materials. Table 1 shows both the AASHTO and ASTM materials standards. Although both standards have been listed for ready reference and comparative purposes, their individual requirements may differ in some circumstances. It should be noted that contract specifications will state the standards that are applicable for a given construction project and also may provide additional requirements which supplement the AASHTO/ASTM specifications.

Table 1: Concrete Material Specifications.

Material Component	Test Method
Hydraulic Cement: Portland Cement Blended Hydraulic Cement	AASHTO M 85 AASHTO M 240
Pozzolans and Mineral Admixtures: Fly Ash Ground granulated blast furnace slag Silica Fume (microsilica)	AASHTO M 295, Class C or F AASHTO M 302, Grade 100 or 120 AASHTO M 307
Water	AASHTO M 157
Aggregates: Coarse Aggregates Fine Aggregates	AASHTO M 80, Class A with amendments AASHTO M 6, Class B with amendments
Chemical Admixtures: Air-entraining Water-reducing and set-controlling Concrete Coloring	AASHTO M 154 AASHTO M 194 ASTM C979

Fibers	
Fibrillated polyolefin	ASTM D7508
Steel	ASTM A820

The basic material types used to proportion a concrete mixture are hereafter discussed on an individual basis in association with their materials standards. The benefits of using each of these material types as well as the potential constructability issues are also addressed.

Chapter 2

Hydraulic Cement & Cement Types



2.1 Hydraulic Cement

Hydraulic cement is defined as cement that sets and hardens by chemical interaction with water and is capable of doing so underwater. Both Portland cement and blended cement are considered hydraulic cements, however, the physical and chemical properties of each are governed by different materials specifications indicated in Table 1.

2.1.1 Portland Cement

Portland cement is hydraulic cement produced by pulverizing Portland-cement clinker, usually in combination with calcium sulfate. It exhibits a specific gravity of about 3.15. The typical material standard used for Portland cement is AASHTO M 85. There are eight types of Portland cement that are currently specified, namely types I, IA, II, IIA, III, IIIA, IV and V. Typically only types I, II or V are used; however, special contracts requirements may specify others (i.e. type III cement for prestressed concrete applications).

Type I cement is the most common and is known as general use cement. Type II is also general use cement that provides moderate sulfate resistance and moderate heat of hydration. Type V cement provides high sulfate resistance. The “A” suffix after the type designation denotes air entraining cement so type I cement is non air entraining whereas type IA cement is air entraining. In lieu of utilizing air-entraining cement, a concrete mixture can be air entrained by use of a chemical admixture (i.e. air entraining agent).

AASHTO M 85 details standard chemical composition and physical properties requirements for each cement type as well as the applicable test methods used for evaluation. In addition, allowable optional provisions and their associated chemical and physical requirements are also included. The contract specifications will state any optional provisions that have been included as part of the material requirement. Consult the Division Materials Engineer for additional information.

2.1.2 Blended Cement

Blended cement is a hydraulic cement consisting essentially of a uniform blend of:

- Granulated blast-furnace slag and hydrated lime
- Portland cement and granulated blast-furnace slag
- Portland cement and pozzolan
- Portland blast-furnace slag cement and pozzolan.

It is produced by:

- Intergrading Portland cement clinker with blast furnace slag, fly ash or silica fume
- Blending Portland cement with finely ground blast furnace slag, fly ash or silica fume
- By a combination of intergrinding and blending.

AASHTO M 240 is the standard specification for blended hydraulic cement. It is used in a fashion similar to Portland cement. There are four general types of blended hydraulic cements:

- Type IS – Portland blast-furnace slag cement,
- Type IP – Portland-pozzolan cement,
- Type IL – Portland-limestone cement,
- Type IT – Ternary blended cement.

The physical and chemical requirements for various compositions of blended hydraulic cement are covered in AASHTO M 240. Special properties can be specified by adding various suffixes to the blended cement selected. Special properties are denoted as:

- (A) – Air-entraining
- (LH) – Low heat of hydration
- (MH) – Moderate head of hydration
- (MS) – Moderate sulfate resistance

- (HS) – High sulfate resistance
- (R) – Resistance to alkali-silica reaction

AASHTO M 240 details standard chemical composition and physical properties requirements for each blended cement type as well as the applicable test methods used for evaluation. In addition, allowable optional provisions and their associated chemical and physical requirements are also included. As was the case with Portland cement, contract specifications will include references to optional provisions should they apply. Consult the Division Materials Engineer for additional information.

Blended cements can be used as the only cementing material in concrete or they can be used in combination with other supplementary mineral admixtures, which are added at the batch plant. If the blend consists of a proportion of fly ash or slag, blended cements can develop lower early compressive strength, up to 28 days, when compared to an equivalent weight of Portland cement alone. If the blend consists of a proportion of silica fume, blended cements can develop higher compressive strengths, up to 28 days, when compared to an equivalent weight of Portland cement. A comparison of Portland cement types and their associated options is shown in Table 2.

Table 2: Portland and Blended Hydraulic Cement Comparison.

Cement Specification	General Use	Moderate Sulfate Resistance	Moderate Heat of Hydration	High Early Strength	Low Heat of Hydration	High Sulfate Resistance	ASR Resistance
AASHTO M 85 Portland Cement	I	II	II(MH)	III	IV	V	Low Alkali Option

2.1.3 Hydraulic Cement Constructability Issues

When hydraulic cement and water are mixed, a series of chemical reactions begin that result in slump loss, setting, hardening, evolution of the heat of hydration and strength development. This overall process is referred to as cement hydration. The quantity of mixing water required to completely hydrate Portland cement is a water-cementitious materials ratio of about 0.40 by weight. When chemical admixtures are used the water-cementitious materials ratio can be halved to as low as about 0.20. Cement fineness and chemical composition are the major characteristics of cement that influence rate of reaction and strength development.

Hydration of cement, however, is a temperature dependent process. When cured at room temperature about 70 °F (21°C), the final set of concrete is typically achieved in about 2 1/2 to 4 1/2 hours and the specified compressive strength is

normally reached in 28 days. Environmental conditions, which affect the temperature of the concrete mixture, therefore influence the behavior of cement. Since the time of set, the strength development and the temperature rise of concrete are all related to the hydration rate, these fresh and hardened concrete properties are influenced by the ambient temperature conditions present at the project site. Hydration rate proceeds very slowly below 40° F (4 °C) but increases rapidly with increasing temperature. As a rule of thumb, the rate of hydration doubles for each 18 °F (10 °C) increase in temperature and, conversely, is halved for each 18 °F (10 °C) decrease. It is of paramount importance that concrete is cured properly at the project site in conjunction with cold or hot weather conditions in order to achieve specified concrete strengths in a timely fashion. In this manner, construction processes which are dependent upon concrete strength (i.e. form removal, etc.) may also proceed.

Premature stiffening in fresh concrete and/or mortar is another issue of concern. Premature stiffening can occur as a result of false set or flash set. False set occurs as a significant loss of plasticity or slump without the generation of heat shortly after mixing. False set is caused by rapid crystallization of excess gypsum from the cement mill. Concrete that has undergone false set can be handled and placed without difficulty. Additional mixing breaks up the crystals and restores workability. It is not necessary or acceptable to add water to the mixture in this process. Flash set occurs as a rapid loss of workability with considerable generation of heat shortly after mixing. The plasticity cannot be regained by further mixing; only with the addition of water. Flash set is caused by a chemical imbalance in the cement. Concrete experiencing flash set should be rejected and the cement should be tested for conformance to specification requirements. A cement sample should be obtained and the Division Materials Engineer should be contacted for consultation and appropriate testing.

2.2 Cement Type Selection Based on Exposure

Portland cement type selection is the first material decision in concrete mix design. Six types exist, each suited to different conditions.

- Type I (General Purpose) is suitable for structures with no special sulfate exposure, no heat of hydration concerns, and no alkali-silica reactivity risk. Most building concrete uses Type I.
- Type II moderates heat of hydration and provides moderate sulfate resistance. It suits large mass concrete structures (thick footings, dam concrete) where heat buildup could cause thermal cracking.
- Type V provides maximum sulfate resistance and suits concrete in sulfate-bearing soils or seawater exposure. Many western states require Type V for structures on sulfate-bearing soils.

Blended cements (Type IS, IP, IL) incorporate fly ash or slag, reducing heat of hydration and improving long-term strength. They are increasingly specified for sustainability and durability in harsh climates.

The exposure category identified in durability analysis directly determines acceptable cement types. The contract specifications for the project will indicate which types are permitted.

Chapter 3

Mineral & Chemical Admixtures



3.1 Mineral Admixtures / Pozzolans

Mineral admixtures, otherwise known as pozzolans, are siliceous or siliceous and aluminous materials that in themselves possess little or no cementitious value that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Pozzolans are both artificial and natural. Materials such as fly ash, ground granulated blast furnace slag and silica fume are artificial pozzolans. Raw or calcinated materials that possess pozzolanic properties such as volcanic tuffs or pumicites, opaline cherts, shales and clays are natural pozzolans. These mineral admixtures are finely divided inorganic materials that may be added to concrete to modify its performance and/or cost.

3.1.1 Fly Ash

Fly ash is a product from coal burning. It is defined as the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gases from the combustion zone to the particle removal zone. It consists of solid and hollow, silt-sized glass spheres that are typically finer than Portland cement or lime. Fly ash exhibits a tan to dark gray color and its specific gravity ranges from 1.9 to 2.8.

AASHTO M 295 is the standard specification for fly ash and details standard chemical composition and physical properties requirements for each fly ash type as well as the applicable test methods used for evaluation. Fly ash is categorized into three classes based on its chemical composition as follows:

- Class N is a raw or calcinated pozzolan that is not allowed by FP specifications.
- Class C or high calcium fly ash is derived from sub-bituminous coals. It possesses a free lime (CaO) content in excess of 20 percent and as such has some cementitious (i.e. strength gaining) properties in and of itself.
- Class F or low calcium ash is derived from bituminous and anthracite coals. It possesses less than 10 percent free lime (CaO) and as such has very little cementitious properties in and of itself. Class F fly ash must be mixed with Portland cement to serve as a cementing material.

Concrete made with class F fly ash and Portland cement will typically gain compressive strength at a slower rate than concrete made with an equivalent weight of Portland cement up to 28 days age. However, at later ages, the strength of concrete made with the class F fly ash will be greater. Concrete made with class C fly ash wherein the Portland cement is replaced at a proportion of one part fly ash to one part cement typically exhibits a 28 day strength equal to or greater than concrete containing an equivalent weight of Portland cement without fly ash. However, concrete made with class C fly ash will likely not show the later age strength gain typical of concrete made with class F fly ash, although strength gain will continue to occur over that of Portland cement alone.

The FP limits the amount of fly ash that can be used in concrete mixtures. Not more than 25 percent of the total cementitious materials can be fly ash or other pozzolans.

3.1.1.1 Fly Ash Benefits

The benefits of incorporating fly ash into a concrete mixture include:

- Increased workability – Spherical shaped particles act as ball bearings and produce a lubricating effect providing improved pumping, reduced bleeding and enhanced flat work finishing.
- Decreased water demand – Replacement of Portland cement with fly ash reduces the water demand. When 20 percent of the cement weight is replaced with fly ash, the water demand is reduced about 10 percent. Reductions of 5 to 10 percent are normal.
- Reduced heat of hydration – Replacing Portland cement with fly ash typically reduces the overall temperature rise of concrete and the associated potential for temperature cracking.
- Increased long term strength.
- Reduced permeability and increased corrosion resistance.
- Improved resistance to sulfate attack – Class F fly ash is very effective. Class C ash is less effective.

- **Improved resistance to Alkali-Silica Reactivity (ASR)** – At least 15 percent of the cementitious material should be fly ash. Lower amounts may increase ASR.

3.1.1.1 Fly Ash Constructability Issues

Constructability issues which may arise as a result of using fly ash in a concrete mixture include:

- **Lower early compressive strength** – Strength gain of concrete containing fly ash is minimal in the colder months. Below 40°F (4° C) strength gain occurs at a very slow rate. Chemical admixtures may be used to partially offset this effect.
- **Air entrainment** – The use of fly ash in concrete usually requires a higher dose of air entraining agent to meet air requirements if the loss on ignition of the fly ash is greater than 3 percent. Use of Class F fly ash with high loss on ignition can cause difficulty in consistent air entrainment. Additionally, entrained air is lost more rapidly in conjunction with prolonged mixing or agitation. There can also be problems with fly ash compatibility with certain types of chemical admixtures.
- **Time of set** – Replacement of Portland cement with fly ash will usually extend the concrete set time. Longer set times increase the potential for plastic shrinkage cracking and premature finishing (i.e. sealing bleed water under the top surface of the concrete thereby causing a plane of weakness).

3.1.2 Ground Granulated Blast-furnace Slag (GGBFS)

Blast-furnace slag is a product from iron and steelmaking. It is defined as the non-metallic product consisting essentially of silicates and aluminosilicates of calcium and other bases that is developed in molten condition simultaneously with iron in a blast furnace. Ground granulated blast-furnace slag (GGBFS) is granulated blast-furnace slag that has been finely ground and is hydraulic cement. It is lighter in color than conventional concrete and exhibits a specific gravity ranging from 2.85 to 2.95. AASHTO M 302 is the standard specification for ground granulated blast-furnace slag. GGBFS is classified by performance in the slag activity test in three grades including grade 80, grade 100 and grade 120. The slag activity test compares the ratio of the compressive strength of slag and Portland-cement mortar samples made with 50-50 weight combinations to equivalent weight samples made with Portland cement only. This AASHTO standard details the chemical composition and physical properties requirements for each GGBFS grade as well as the applicable test methods used for evaluation. There are no supplementary optional provisions.

When using a blend of 50 percent GGBFS and 50 percent Portland cement by weight, grade 100 GGBFS typically exhibits a 28-day compressive strength equivalent to concrete made with an equivalent weight of Portland cement only. Grade 120 GGBFS, however, normally shows reduced strength at early ages but increased strength at later ages (i.e. 7 days and beyond).

The FP allows the use of grades 100 and 120 GGBFS only. It further restricts the amount of GGBFS to no more than 50 percent of the total weight of the cementitious materials. Blends less than 50 percent of the total weight of cementitious materials may be desirable when higher early concrete strengths are required to facilitate quick form removal or when thin sections are placed at low temperatures. However, some of the GGBFS benefits noted below may be sacrificed.

3.1.2.1 GGBFS Benefits

The benefits of incorporating GGBFS into a concrete mixture include:

- Increased workability.
- Decreased water demand – Reductions of 1 to 10 percent are common.
- Reduced permeability and increased corrosion resistance.
- Improved resistance to sulfate attack.
- Improved resistance to Alkali-Silica Reactivity (ASR).

3.1.2.1 GGBFS Constructability Issues

Constructability issues which may arise as a result of the using GGBFS in a concrete mixture include:

- Concrete color change – During the second to fourth days after casting, a blue-green surface color may appear which diminishes with age as oxidation occurs.

3.1.3 Silica Fume

Silica fume is a product from silicon metal refining. It is defined as very fine non-crystalline silica produced in electric arc furnaces as a byproduct of the production of elemental silicon or alloys containing silicon. Silica fume ranges from light to dark gray in color and generally exhibits a specific gravity ranging from 2.2 to 2.25; although its specific gravity can be as high as 2.5. In raw powdered form, silica fume is a very fine material, on the order of 100 times finer than Portland cement. As such, it presents unique handling and safety concerns. Silica fume is therefore available in four different forms, some of which are

designed to minimize clogging of batch plant equipment and dust generation. The four forms are as follows:

As produced silica fume – Available in bulk or bags as collected in raw powder form.

- Slurried silica fume – Available in slurry form, typically in a 50-50 blend of water and silica fume by weight. The water portion of the slurry counts as mixing water and should be compensated for in the water-cementitious materials ratio calculation. The slurry is available with and without chemical admixtures.
- Densified (compacted) silica fume – Available in compacted form where raw powder has been densified by mechanical means or by compressed air. The densified silica fume is available with and without chemical admixtures.
- Pelletized silica fume – Available in pellet form where raw powder has been mixed with a small portion of water. Pellets should not be used as a mineral admixture in concrete because they do not break down sufficiently or disperse properly.

AASHTO M 307 is the standard specification for silica fume. It details standard chemical composition and physical properties requirements as well as the applicable test methods used for evaluation. In the cases of slurried or densified silica fume, tests are performed on the raw material from which these products have been made.

Concrete in which a percentage of the weight of Portland cement has been replaced with silica fume will exhibit 28-day compressive strengths higher, sometimes substantially higher, than concrete made with an equivalent weight of Portland cement. However, the contribution of silica fume to strength development after 28 days is minimal.

The FP limits the amount of cementitious materials that may be replaced with silica fume. Not more than 10 percent of the total cementitious materials may be replaced with silica fume.

3.1.3.1 Silica Fume Benefits

The benefits of incorporating silica fume into a concrete mixture include:

- Substantially increased compressive strength up to 28 days age.
- Improved scaling resistance – At least 5 percent of the cementitious material should be silica fume.
- Excellent abrasion resistance
- Reduced permeability and increased corrosion resistance.

- Slightly improved resistance to sulfate attack.
- Improved resistance to Alkali-Silica Reactivity (ASR).
- Reduced heat of hydration

3.1.3.2 Silica Fume Constructability Issues

Constructability issues which may arise as a result of the using silica fume in a concrete mixture include:

- Increased water demand – Water demand increases in proportion to the amount of silica fume used. In order to achieve the desired workability, permeability and strength, silica fume concrete must always be made with chemical admixtures consisting of a water reducing admixture, a high range water-reducing admixture or both.
- Increased air entrainment admixture dosage requirements – In order to obtain the desired air content, admixture dosages must be increased in proportion to the amount of silica fume used.
- High slump – Due to the use of chemical admixtures, silica fume concrete typically exhibits a much higher slump than conventional concrete. Slumps on the order of 8 inches (200 mm) are common and acceptable.
- Workability loss – Due to the use of chemical admixtures, the slump loss of silica fume concrete will occur much more rapidly than conventional concrete.
- High susceptibility to plastic shrinkage cracking – Bleeding does not occur for silica fume concrete. Therefore, when the surface water evaporates, it is not replenished by bleed water and the silica fume concrete is highly susceptible to plastic shrinkage cracking. The surfaces of freshly placed silica fume concrete must be protected from rapid water evaporation by proper curing as soon as is practicable after placement.
- Color – The color of silica fume concrete will be darker than conventional concrete.

3.1.4 Collective Mineral Admixture Limitation

As previously noted, the FP stipulates individual material limits regarding the maximum amount of Portland cement that may be replaced with mineral admixtures of fly ash, ground granulated blast furnace slag and silica fume. In addition, when more than one mineral admixture is used in combination with Portland cement, inclusive of blended cements, the collective combination of materials is also limited. These collective material limitations are applicable in very severe circumstances for concrete exposed to freezing and thawing and in continuous contact with moisture and exposed to de-icing chemicals.

The FP has limitations on the individual and collective amount of supplemental cementitious materials for structural concrete and minor concrete and are summarized in Table 3.

Table 3: Maximum Cementitious Material Requirements.

Supplemental Cementitious Materials	Maximum Percent of Total Cementitious Material by Weight
Fly ash or other pozzolans, AASHTO M 295	25
Slag (GGBFS), AASHTO M 302	50
Silica Fume, AASHTO M 307	10
Total of fly ash or other pozzolans, slag, and silica fume	50(1)
Total fly ash or other pozzolans and silica fume	35(1)
(1) Limit fly ash or other pozzolans to no more than 25 percent of the total mass of cementitious material and limit silica fume to no more than 10 percent of the total mass of cementitious material.	

3.2 Mineral Admixtures: Benefits and Limitations

Fly ash, GGBFS, and silica fume are mineral admixtures that partially replace Portland cement. They offer significant benefits:

- Reduced heat of hydration — Prevents cracking in thick sections
- Improved long-term strength — Pozzolanic reactions strengthen concrete over time
- Lower permeability — Reduces water intrusion and corrosion risk
- Sustainability — Reuses industrial byproducts; reduces carbon footprint

However, mineral admixtures have limitations. They slow early strength gain, which can delay form removal and opening to traffic. Maximum replacement levels are specified (typically 25% for fly ash, 50% for slag) to ensure performance. Chloride and sulfate exposure also limit maximum levels.

Selection depends on project requirements. High early strength needs favor lower admixture content or Type III cement. Sustainability and long-term durability goals favor higher levels. The mix design process balances these competing objectives.

3.3 Chemical Admixtures

An admixture is a material other than water, aggregates, hydraulic cement, and fiber reinforcement, used as an ingredient of a cementitious mixture to modify

freshly mixed, setting, or hardened properties and that is added before or during mixing. They are provided in liquid, suspension, or water-soluble solid forms. Chemical admixtures are used to reduce the cost of the concrete mixture, to increase the efficiency of cementitious materials, to achieve desirable fresh and hardened concrete properties, to maintain concrete quality during mixing, transporting, placing and curing and to overcome construction emergencies (i.e. slump loss).

When admixtures are employed in a concrete mix design, it is imperative that trial mixtures be conducted to evaluate their compatibility with one another as well as their compatibility with mixture materials. Admixture effects on fresh and hardened concrete properties should be determined. The trial mixtures should be conducted at temperatures and humidity levels as close as possible to conditions anticipated at the project site. Admixture dosage rates should be within the ranges recommended by the admixture manufacturer and at the optimums determined by trial mixture evaluations.

3.3.1 Air-entraining Admixtures

Air-entraining admixtures are used to develop a system of uniformly dispersed microscopic air bubbles in the cement paste. These bubbles serve to improve freeze-thaw and deicer scaling resistance as well as to enhance concrete workability, reduce water demand and minimize segregation and bleeding. AASHTO M 154 is the standard specification for air entraining admixture. It details physical properties requirements as well as applicable test methods used for evaluation. In addition, allowable optional provisions for uniformity are also included. Air-entrainment in a concrete mixture is produced by liquid admixture during mixing, by use of air-entraining cements or by a combination of both methods. Too little air will result in minimal benefits whereas too much air can have detrimental effects on other concrete properties.

3.3.2 Water-reducing and Set-controlling Admixtures

AASHTO M 194 is the standard specification for water-reducing, set-controlling, and hydration stabilizing admixtures. It details physical properties requirements as well as applicable test methods used for evaluation. It further defines seven different types of admixtures consisting of the following:

- Type A – water-reducing
- Type B – set retarding
- Type C – set accelerating
- Type D – water-reducing and set retarding
- Type E – water-reducing and set accelerating
- Type F – water-reducing, high range
- Type G – water-reducing, high range, and set retarding

As the names and types imply, water-reducing and set controlling admixtures reduce the water requirements of a concrete mixture for a given slump and/or modify the time of setting or both. Set retarding admixtures, inclusive of types B, D and G, are used to delay the effects of high ambient temperatures in accelerating concrete set time such that the mixture is kept workable during placement.

Extended set-control admixtures or hydration stabilizers meet the technical requirements for types B and D admixtures although they differ from conventional set-retarding admixtures in that they stop the cement hydration process altogether. Thus, they are specified separately in the FP but will typically meet the requirements of AASHTO M 194. Hydration stabilizers are used to maintain concrete in a stabilized, non-hardened state during long hauls. The stabilizer is added during or immediately after initial batching and is adjusted so that the setting time of the concrete is extended for the duration of the haul. If the concrete remains in a stabilized state after arrival at the job site, an activator can be added to facilitate normal hydration and setting. When hydration stabilizers are used, the FP limits the maximum allowable discharge time to 3 1/2 hours. The design discharge limit and associated admixture dosage should be included in the concrete mix design submittal.

Set accelerating admixtures, inclusive of types C and E, are used to accelerate the rate of set and strength development of concrete at an early age. Calcium chloride can be used in this admixture which can cause corrosion of reinforcement steel. For this reason, chloride accelerators are prohibited by the FP. Set accelerating admixtures are also prohibited for use with class P (prestressed) concrete.

Water-reducing admixtures are used to reduce the water to cementitious materials ratio and consequently produce higher strengths at lower cement contents. They are also used to provide workability by increasing slump without increasing water content. Normal water reducing admixtures, inclusive of types A, D and E, typically reduce the water content about 5 to 10 percent.

Concrete made with these admixtures commonly exhibits a slump around 4 inches (100 mm) with a slump loss of about 3 inches (75 mm) in 2 hours. High range water reducing admixtures or superplasticizers, inclusive of types F and G, reduce the water content from 10 to 30 percent. Concrete exhibiting slumps of 6 to 7 inches (150 to 175 mm) can be produced with water content reductions ranging from 10 to 15 percent. Flowing concrete, which exhibits a slump greater than 7 1/2 inches (190 mm) while remaining self leveling and cohesive, is also typically made with the aid of high range water reducing admixtures. Slump loss of concrete made with these admixtures can be very rapid and occur at a rate of about 3 to 4 inches (75 to 100 mm) per hour. Some admixtures are marketed as midrange water reducing admixtures, although there is no such classification.

These admixtures typically meet type A requirements and provide up to 12 percent water reduction without delaying the setting time of concrete.

3.3.3 Concrete Coloring Admixtures

Concrete coloring admixtures are used to color concrete for aesthetic and safety purposes. ASTM C 979 is the standard specification. Coloring pigments should normally not exceed 10 percent by weight of cementitious material. Before a coloring admixture is used on a project, its historical performance should be checked for color fastness in sunlight, chemical stability in cement and non-detrimental effects on concrete properties.

3.3.4 Miscellaneous Admixtures

Many miscellaneous admixtures are available for use in concrete. They include corrosion inhibitors, shrinkage reducers, alkali-silica reactivity inhibitors and pumping aids to name a few. As is the case for all admixtures, they must be compatible with other ingredients of the concrete mixture and pre-approved prior to use.

3.4 Chemical Admixtures: Achieving Workability and Air Entrainment

Chemical admixtures modify concrete properties without changing the fundamental composition. Air-entraining agents are essential in freeze-thaw climates; they entrain small air bubbles that provide relief for ice expansion. Water-reducing admixtures allow lower water content at constant slump, which improves strength and durability. Retarders delay setting in hot weather; accelerators speed setting in cold weather or when early strength is needed.

The contract specifications and mix design requirements determine which admixtures are used. Air entrainment for freeze-thaw exposure is mandatory in cold climates; it is prohibited in some pavements where surface friction is critical.

Chapter 4

Water & Aggregate Specifications



4.1 Water

Mixing water is defined as the water in freshly mixed sand-cement grout, mortar, or concrete, exclusive of any previously absorbed by the aggregate (for example, water considered in the computation of the net water-cement ratio). Almost any water that is drinkable can be used for mixing concrete. The standard specification for Ready-Mix Concrete is AASHTO M 157. This AASHTO standard listed as part of the requirements in the FP covers mixing and curing water requirements for concrete, irrespective of whether or not it is ready-mix concrete.

Although AASHTO M 157 stipulates that the quality of water to be used in concrete must be tested, the FP allows potable water of known quality to be used without testing. The definition applied to “potable water that is safe for human consumption” is noted in the FP as being provided by the public health authority having local jurisdiction.

Water of questionable quality can be used for making concrete if it meets established requirements for sulfate content, alkali content, and total solids. In addition, fabricated mortar specimens made with this water must pass tests for compressive strength, time of set, and chloride content. The water and mortar tests that are used to evaluate these parameters as well as the parameter limitations are provided in AASHTO M 157. The component tested, the test methodology and the limits are summarized in Table 4..

Table 4: Water and Mortar Requirements for Questionable Water Source.

Component	Test Method	Limits
Compressive strength	AASHTO T 106*	90% min of control at 7 days
Time of set	AASHTO T 131*	From 1:00 earlier to 1:30 later deviation from control
Chloride as $\text{Cl}^{(-1)}$	ASTM D512	Prestressed concrete – 0.06% Conventionally reinforced concrete in a moist, chloride exposed environment – 0.10% Conventionally reinforced concrete in a moist environment, but not exposed to chloride – 0.15% Above ground building construction where the concrete will stay dry – no limit
Sulfate as SO_4^{**}	AASHTO T 290	3000 ppm
Alkalis as $(\text{Na}_2\text{O} + 0.658 \text{ K}_2\text{O})$	AASHTO T 105	600 ppm
Total solids	ASTM C1603	50,000 ppm
* Comparison shall be based on fixed proportions and the same volume of test water compared to control mix using water or distilled water. ** Wash water reused as mixing water in concrete may exceed listed concentrations of sulfate if it can be shown that the concentration calculated in the total mixing water, including mixing water on the aggregate and other sources, does not exceed the stated limits.		

4.2 Concrete Aggregates

Aggregates are granular materials, such as sand, gravel, crushed stone, crushed hydraulic cement concrete or iron blast-furnace slag, used with a hydraulic cementing medium to produce either concrete or mortar. Fine and coarse aggregates occupy about 60 to 70 percent of concrete by volume and about 70 to 80 percent by weight.

4.2.1 Concrete Aggregate Gradation

Gradation is a measure of aggregate source quality, uniformity and consistency. The combined gradation from the fine and coarse aggregate is determined by a sieve analysis detailed in AASHTO T 27 and AASHTO T 11. The aggregate particle size is determined by using wire-mesh sieves with square openings. A laboratory sieve shaker is used to perform the analysis. Grading limits are specified to control aggregate proportions as well as cement and water requirements and overall concrete workability, durability and economy. Variations in grading can adversely affect the uniformity and quality of concrete

from batch to batch. Very fine sands are often uneconomical in that they require high water contents to sustain mixture workability. Very coarse sands can produce harsh, non-workable mixtures. Aggregates that do not have a large deficiency or excess of any size produce the most satisfactory concrete.

4.2.2 Concrete Fine Aggregate

Concrete fine aggregate generally consists of natural sand or crushed stone (manufactured sand) or a combination of the two with particles smaller than the No. 4 (4.75 mm) sieve. Technically, fine aggregate is defined as almost entirely passing the No. 4 (4.75 mm) sieve while being predominantly retained on the No. 200 (75 μ m) sieve.

The FP requires fine aggregate source quality verification testing and states that fine aggregate must conform to AASHTO M 6, class B, including the reactive aggregate supplementary requirement as well as additional supplemental FP requirements. AASHTO M 6 is a very comprehensive material standard. It provides requirements for gradation, aggregate quality and uniformity of grading (fineness modulus). To provide guidance in the submittal of fine aggregate quality test data, the requirements for the aggregate are shown on form FHWA 1608. Aggregates not meeting all of the gradation requirements may still be used based on a satisfactory service record. If the gradation criteria are not met, consult the Division Materials Engineer for additional review to determine if acceptable performance can be documented.

The test used to assess the uniformity of the fine aggregate grading is the fineness modulus. The fineness modulus is determined by summing the cumulative percent retained for each sieve size, excluding the No. 200 (75 μ m) sieve, and dividing the summation by 100. The list of sieves used for this calculation can be found in AASHTO T 27.

The required fine aggregate source quality tests, test methods and aggregate characteristics have been summarized in Table 5.

Table 5: Fine Aggregate Source Quality Characteristics.

Aggregate Test	Test Method	Aggregate Characteristic
Clay lumps and friable particles (Deleterious substance)	AASHTO T 112	Injurious to workability and durability, may cause pop-outs. Increases water demand
Coal and Lignite (Deleterious substance)	AASHTO T 113	Affects durability, may cause stains and pop-outs

Materials finer than No. 200 (75 µm) sieve (Deleterious substance)	AASHTO T 11	Injurious to bond, causes large increases in water demand
Organic Impurities (Deleterious substance)	AASHTO T 21	Injurious to setting and hardening, may cause deterioration
Sodium Sulfate Soundness, 5-cycles	AASHTO T 104	Measure of weathering resistance
Alkali-Silica Reactivity (ASR)	ASTM C1260 ASTM C1567 ASTM C1293 ASTM C295 ASTM C856	Measure of ASR potential as well as effectiveness of mineral admixtures in ASR mitigation

4.2.3 Concrete Coarse Aggregate

Concrete coarse aggregate generally consists of gravel, crushed stone, crushed blast-furnace slag, crushed concrete or a combination of any of these materials with particles larger than the No. 4 (4.75 mm) sieve and mostly between 3/8 and 1 1/2 inches (9.5 and 37.5 mm). Technically, coarse aggregate is defined as being predominantly retained on the No. 4 (4.75 mm). The standard specification for coarse aggregate quality is AASHTO M 80 and the gradation requirements can be found in AASHTO M 43. The FP allows all AASHTO M 43 standard sizes except numbers 8, 89, 9 or 10.

The FP requires coarse aggregate source quality verification testing and states that coarse aggregate must conform to AASHTO M 80, class A, including the reactive aggregate supplementary requirement as well as additional supplemental FP requirements. To provide guidance in the submittal of coarse aggregate quality test data, the requirements for the aggregate are shown on form FHWA 1608.

The required coarse aggregate source quality tests, test methods, and aggregate characteristics have been summarized in Table 6.

Table 6: Coarse Aggregate Source Quality Characteristics.

Aggregate Test	Test Method	Aggregate Characteristic
Clay lumps and friable particles (Deleterious substance)	AASHTO T 112	Injurious to workability and durability, may cause pop-outs. Increases water demand
Chert (lightweight pieces less than 2.4 specific gravity SSD) (Deleterious substance)	AASHTO T 113	Injurious to durability, may cause pop-outs

Materials finer than No. 200 (75 µm) sieve (Deleterious substance)	AASHTO T 11	Injurious to bond, large increases water demand
Coal and Lignite (Deleterious substance)	AASHTO T 113	Affects durability, may cause stains and pop-outs
Los Angeles Abrasion	AASHTO T 96	Measure of wear resistance and index of aggregate quality
Sodium Sulfate Soundness, 5-cycles	AASHTO T 104	Measure of weathering resistance
Mass of Insoluble Residue for Bridge Decks and Surface Courses Only	ASTM D3042	Measure of wearing resistance of carbonate aggregates
Alkali-Silica Reactivity (ASR)	ASTM C1260 ASTM C1567 ASTM C1293 ASTM C295 ASTM C856	Measure of ASR potential as well as effectiveness of mineral admixtures in ASR mitigation

4.2.4 Aggregate Tests Used During Concrete Mixture Proportioning

In order to meet the water requirement of the approved concrete mixture (i.e. to maintain the water-cementitious materials ratio), the FP requires the amount of water to be adjusted at the mixing plant on an ongoing basis to account for the existing moisture conditions of the aggregates. The fine and coarse aggregate tests needed to perform mixture proportioning adjustments as well as the definitions of the parameters measured are shown in Table 7. Since these tests are performed to gather information for mixture adjustments only, testing limitation requirements are typically not specified.

Table 7: Aggregate Tests Used During Concrete Mixture Proportioning.

Parameter Measured	Test method	Definition
Bulk specific gravity	AASHTO T 19	The ratio of the weight of dry aggregate to the weight of water having a volume equal to the volume of the aggregate including both its permeable and impermeable pores.
Dry-rodded unit weight	AASHTO T 19	Mass per unit volume of dry aggregate compacted by rodding under standardized conditions. Used to measure density of aggregate including aggregate and voids between aggregate particles.

Absorption	AASHTO T 85 (Coarse) AASHTO T 84 (Fine)	The increase in the weight of aggregate due to water in the pores of the material, but not including water adhering to the outside of the particles, expressed as a percentage of the dry weight.
Bulk SSD specific gravity	AASHTO T 85 (Coarse) AASHTO T 84 (Fine)	The ratio of the weight of aggregate, including the weight of water it contains when its permeable voids are saturated, to the weight of an equal volume of water.
Moisture content	AASHTO T 255	The ratio of the weight of water lost in drying to the oven dry weight expressed as a percentage.

4.3 Aggregate Selection for Durability

Aggregates are the skeleton of concrete. Fine aggregates (sand) fill voids; coarse aggregates provide volume and wear resistance. Aggregate quality determines concrete's resistance to freeze-thaw, abrasion, and chemical attack.

In freeze-thaw climates, coarse aggregates must pass soundness testing (AASHTO T 104) to ensure resistance to salt weathering. Aggregates that fail soundness testing will break apart over years of freeze-thaw cycling, causing spalling and deterioration.

In sulfate-bearing soils, aggregates must not contain reactive sulfides that can oxidize and damage concrete. Fine aggregate must not contain deleterious substances (coal, shale, mica) that can affect durability.

Durability requirements constrain aggregate selection. Not all available quarry sources meet project needs; aggregate testing and approval occur before large-scale use.

4.4 Fibers

Fibers are long and slender filaments with lengths typically ranging from 1/4 inch to 6 inches (6 to 150 mm) and thicknesses ranging from 0.001 to 0.2 inches (0.025 to 5 mm). Fibers are added to the concrete during mixing to provide resistance to tensile and flexural stresses in the concrete. They do not affect drying shrinkage but increase the resistance to cracking as well as decrease crack width. Fibers are typically added in low volume dosages ranging from less than one to 2 percent. The standard specification covering fiber reinforced concrete is ASTM C1116. It allows three types of fibers including steel, glass and synthetic.

- **Steel fibers** may be stainless, alloy, or carbon steel in composition. Steel fibers only slightly affect concrete compressive strength but can

dramatically increase tensile and flexural strengths. Steel fibers are used in airport and highway pavements, bridge decks and floors.

- **Glass fibers** are designed to be alkali-resistant in that they have the potential to react with alkalis in the cement paste when exposed to humid or moist environments. Such a reaction can cause reductions in concrete properties including strength, toughness and impact with age. They have been primarily used in the exterior panels of buildings.
- **Synthetic fibers** are man-made products such as polyolefins (polypropylene and polyethylene) as well as acrylic, aramid, carbon, nylon and polyester. They are used to reduce plastic shrinkage and subsidence cracking. Polypropylene fibers have been used in bridge decks, pavements, low water crossing and other applications where plastic shrinkage cracking may be a concern.

The use of fibers and the requirements for the mixture will typically be stated in the special contract requirements for a project.

Chapter 5

Material Certification & Acceptance Testing



5.1 Materials Certification Acceptance

Proper materials certifications pertaining to each applicable material type and source must be obtained by the Project Engineer and retained in project files. As part of the process for approving a Contractor's mix design, representative certifications should be submitted to the Division Materials Engineer for review and recommendation for approval along with the concrete mix design, form FHWA 1608. The FP requires hydraulic cement production certifications for structural concrete, prestressed concrete, shotcrete and minor concrete. Also, individual materials standards that have been specified in the contract should be referenced. They set forth additional detail pertaining to Contractor submittal of valid manufacturer certifications including required statements, test data and frequency. Certifications must be signed and dated as well as certify that the specified requirements of applicable standards and project specific special contracts requirements have been met. Table 8 summarizes individual concrete materials requiring manufacturer certifications as required in the FP in conjunction with the applicable materials standard to which they must be certified.

Table 8: Required Concrete Material Certifications.

Material	Test Method	Frequency
Hydraulic Cement: Portland Cement Blended Cement	AASHTO M 85 AASHTO M 240	1 per shipment 1 per shipment
Mineral Admixtures: Fly Ash Ground granulated blast furnace slag Silica Fume (microsilica)	AASHTO M 295 AASHTO M 302 AASHTO M 307	1 per shipment 1 per shipment 1 per shipment
Water	AASHTO M 157	1 for each source
Coloring Agents	ASTM C979	1 per type
Chemical Admixtures: Air-entraining Water-reducing, Set-controlling, Hydration stabilizing	AASHTO M 154 AASHTO M 194	1 per shipment 1 per shipment per admixture used

The FP further notes that material accepted by certification may be sampled and tested at any time to verify the properties stated as part of the certification. Sampling of concrete materials should be in accordance with the procedures and sample sizes noted in Table 9.

In general, it is good practice to obtain one sample with each shipment of material. These samples should be retained on the project until final project acceptance or provided to the Division Materials Engineer when required for the purpose of Government testing to verify conformance to the contract specifications.

Table 9: Material Sampling Specifications and Sample Sizes.

Material Component	Test Method	Sample Size
Hydraulic Cement:		
Portland Cement	AASHTO R 71	Representative of not more than 100 tons (90 Mg): Two grab samples at ≥ 10 lb (5 kg) each
Blended Hydraulic Cement	AASHTO R 71	Representative of not more than 100 tons (90 Mg): Two grab samples at ≥ 10 lb (5 kg) each
Mineral Admixtures:		
Fly Ash	ASTM C311	Representative of not more than 400 tons (360 Mg): One grab sample at ≥ 4 lb (2 kg) each
Ground granulated blast-furnace slag	AASHTO M 302	Representative of not more than 125 tons (115 Mg): Two grab samples at ≥ 5 lb (2 kg) each. Remove a 12-in. (300 mm) layer of slag in a hole before sampling.
Silica Fume (microsilica)	AASHTO M 307	Representative of not more than 110 tons (100 Mg): 2 grab samples at ≥ 2 lb (1 kg) each.
Water:		
Compressive strength	AASHTO M 157	As required for pertinent tests: liquid grab samples at ≥ 1 pt (0.5 L) each.
Time of set	AASHTO T 106	
Chloride as Cl	AASHTO T 131	
Sulfate as SO_4	ASTM D512	
Alkalis	AASHTO T 290	
Total Solids	AASHTO T 105	
	ASTM C1603	
Aggregates	AASHTO R 90	Coarse Aggregate: 150 lb (75 kg)
(Coarse and Fine)		Fine Aggregate: 100 lb (50 kg)
Aggregate Sample Splitting	AASHTO R 76	Samples are properly split and reduced in size by use of sample splitters or quartering

Chemical Admixtures:		
Air-entraining	AASHTO M 154	Representative of not more than 2500 gal (9500 L): 3 liquid grab samples at $\geq$ qt (1 L) each Representative of not more than 2 tons (2 metric tons): 4 non-liquid tube samples at $\geq$ lb (1 kg) each
Water-reducing, Set-controlling	AASHTO M 194	Representative of a unit shipment or a single production lot: 3 liquid grab samples at $\geq$ 1 pt (0.5 L) each Representative of not more than 2 tons (2 Mg): 4 non-liquid tube samples at $\geq$ 2 lb (1 kg) each

As always, special contract requirements should be reviewed to ascertain if additional materials certifications and samples are required on a project-specific basis.

5.2 Water Acceptance

The FP allows potable water of known quality to be used without testing and certification. Water of questionable quality, however, must be tested in accordance with AASHTO M 157 as summarized in Table 4 and certified thereto. The Contractor must submit the certification, including test results, to the Project Engineer. In turn, the Project Engineer must submit the certification to the Division Materials Engineer for approval with the concrete mix design.

5.3 Material Certification and Verification

Contractor-provided material certifications (mill test reports, supplier certifications) serve as the first line of acceptance. The Project Engineer reviews certifications to verify that materials match the approved mix design and contract specifications.

However, certification alone is insufficient. Inspector verification testing is essential, particularly for aggregates and water from new sources. Testing confirms that field materials match their certifications and will produce concrete meeting specifications.

The balance between certification and testing varies by contract. Experienced suppliers with proven track records may satisfy requirements primarily through certification plus occasional spot-check testing. New sources or questionable materials require extensive testing. Professional judgment guides this decision.

Chapter 6

Concrete Mix Design Philosophy & Procedures

6.1 Mix Design Philosophy and Selection Process

Concrete mix design is a structured process that balances strength, durability, workability, and economy. The American Concrete Institute (ACI) publishes standardized procedures (ACI 211.1 for normal-weight concrete, ACI 211.2 for lightweight concrete) that engineers follow to proportion materials.

The process begins with exposure category determination. Exposure categories define the environmental conditions the concrete will face: freeze-thaw cycling, sulfate attack, corrosion, air entrainment requirements, and water-cement ratio limits. The exposure category drives material selection and forms the foundation of the entire mix design.

Next, strength requirements are determined from structural analysis. The required compressive strength (f'_c) drives the w/c ratio and cement content.

Durability requirements and strength requirements are then balanced. In many cases, durability requirements impose a lower w/c ratio or material restrictions that produce concrete stronger than strictly necessary for load-bearing. This over-design is intentional and required.

Finally, workability is addressed to ensure the concrete can be placed and consolidated effectively in the field.

6.2 Concrete Mixture Composition and Proportioning Requirements

For structural concrete, the FP denotes mixture composition requirements for various classes of concrete and specifies nominal maximum aggregate sizes and minimum air contents. Concrete and/or exposure classes, which dictate mixture proportioning, specified compressive strength and other durability requirements, are usually specified in the plans on contract drawings or in project specific special contract requirements. Similar requirements are stipulated in the minor concrete section of the FP; however, only one mixture composition is specified in conjunction with a specified concrete compressive strength. Classes are typically not utilized.

The FP requires concrete mixtures to be proportioned in accordance with specific ACI practices and guides as applicable. The ACI practices and guides and the definitions associated thereto are discussed below. Applications and use on FLH projects are also addressed in association with each definition and practice.

6.2.1 ACI 211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete

Normal concrete – Concrete having a density of approximately 150 lb/ft³ (2400 kg/m³) made with normal-density aggregates. Normal concrete is used in the majority of construction applications including typical FLH project applications (i.e. pavements, bridges, culverts, walls, foundations).

Heavyweight concrete – Concrete of substantially higher density than that made using normal-density aggregates (i.e. up to 350 lb/ft³ (5600 kg/m³)), usually obtained by use of high-density aggregates. Heavyweight concrete is used in radiation shielding, counterbalancing, ballasting and sound attenuation applications. As such, it has not been employed on FLH projects.

Mass Concrete – Any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change, to minimize cracking. Mass concrete is used in thick-section applications for structures such as dams, mat foundations, pile caps, bridge piers, walls and tunnel linings. It has been used on FLH projects in rare occasions when the size of structural member (i.e. bridge piers) has necessitated measures to prevent temperature dependent cracking.

6.2.2 ACI 211.2 Standard Practice for Selecting Proportions for Structural Lightweight Concrete

Lightweight concrete – Concrete of substantially lower density than that made using aggregates of normal density. The concrete is made with lightweight aggregates with a concrete compressive strength exceeding 2500 psi (17 MPa) at 28 days of age and an air dry density not exceeding 115 lb/ft³ (1840 kg/m³). Lightweight concrete is used in applications where normal density aggregates (exhibiting specific gravities from 1.6 to 3.2) are not locally available and light density aggregates are used in whole or in part in the concrete mixture. When compared to normal concrete, proportioning and control procedures for lightweight concrete are modified to account for greater absorptions and rates of absorptions. Lightweight concrete has been used on rare occasions on FLH projects for standard applications such as headwalls or foundations.

6.2.3 ACI 211.3 Guide for Selecting Proportions for No-Slump Concrete

No Slump Concrete – Freshly mixed concrete exhibiting a slump of less than 1/4 inch (6 mm). No slump concrete is used in applications where normal workability impairs constructability. These applications have historically included four types of concrete including roller compacted concrete (RCC), roof tiles, concrete masonry units and pervious concrete. Roller compacted concrete has been employed for dams, pavements and horizontal construction. When compared to normal concrete, proportioning and control procedures for no slump concrete are modified in accordance with specific procedures for each concrete type to account for lower water contents and other factors. No slump concrete has been used on rare occasions on FLH projects in applications such as RCC grade control structures within washes for the purposes of dissipating erosion and bridge scour.

6.2.4 ACI 211.4 Guide for Selecting Proportions for High-Strength Concrete using Portland Cement and other Cementitious Materials

High Strength Concrete – Concrete that has a specified compressive strength for design of 6000 psi (41 Mpa) or greater. High strength concrete is used in applications where superior strength is needed in the design and performance of structural members. Optimization of mixture proportioning and attainment of a low water-cementitious materials ratio is critical to achieving high strength. Select mineral and chemical admixture combinations and aggregate sizes are typically specified in this process. Typical applications for high strength concrete include bridges and pavement overlays although these structures can be designed with normal concrete. Both of these applications have been used on FLH projects on a limited basis.

High Performance Concrete – Concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing and curing practices. High performance concrete (HPC) differs from high strength concrete in that superior performance in a particular application is required. The application may or may not require higher compressive strength. In addition to compressive strength, specialized testing and performance requirements are typically specified to address one or more desirable durability characteristics including freeze-thaw, scaling, abrasion, chloride penetration, ASR and sulfate resistance. Testing and performance requirements related to structural integrity may also be specified for rigidity, shrinkage and creep as well as place ability (i.e. flow). As such, examples of HPC when compared to normal concrete include high-ultimate strength, high early strength, high rigidity, high durability, increased workability, pumpability and finish ability and increased place ability in hot and cold weather. HPC has been applied on FLH projects in a fashion similar to high strength concrete. Its use is expected to increase in the future.

A properly proportioned concrete mixture must be designed for strength, durability, workability (i.e., placeability, pumpability, finishability), economy and appearance. The water-cement ratio determines the strength and durability properties. When mineral admixtures are used, the water cement ratio becomes the water-cementitious materials ratio. In other words, the cementitious materials portion is calculated by summing the weight of the cement plus the weights of the mineral additives (i.e. cement + fly ash + silica fume + ground granulated blast furnace slag). The weight of the water is then divided by the weight of the cementitious materials. The water-cement and water-cementitious ratio are denoted as w/c in the FP.

For structural concrete, the FP requires the concrete mixture to be proportioned to meet durability requirements for maximum water-cementitious materials ratio, minimum specified compressive strength (f'_c) and may include additional

criteria for durability as stated in ACI 301. Durability is discussed in Section 6.3 below.

For structural concrete, the FP also requires the concrete mixture to be proportioned to meet the required average compressive strength requirements (f'_{cr}) stipulated in ACI 301. These strength requirements are discussed in Section 6.5 below.

6.3 Concrete Mixture Durability Requirements

Durability is the ability of concrete to resist weathering action, chemical attack, abrasion and other conditions while retaining its engineering properties. To provide adequate durability, structural concrete must be proportioned by the Contractor to meet FP requirements.

Durability requirements pertaining to the maximum water-cementitious materials ratio and minimum compressive strength (f'_c) are dependent upon designated exposure categories and classes. ACI 301 defines four different exposure categories and their individual applications as follows:

- Exposure Category F (Freezing and thawing) – applied to exterior concrete that is exposed to moisture and cycles of freezing and thawing with or without deicing chemicals.
- Exposure Category S (Sulfates) – applied to concrete in contact with soil or water containing deleterious amounts of water-soluble sulfate ions.
- Exposure Category W (Permeability) – applied to concrete in contact with water requiring low permeability.
- Exposure Category C (Corrosion) – applied to reinforced and prestressed concrete exposed to conditions that require additional protection against corrosion of reinforcement

The severity of exposure within each category is further subdivided into exposure classes. Increasing numerical values are used to represent increasingly severe exposure class conditions. A classification of “0” indicates that the exposure severity has negligible effect or does not apply to the structural member.

Specific and applicable exposure classes are assigned to structural members by the Division Materials Engineer on a project-by-project basis in conjunction with the severity of exposure conditions anticipated at the project site. When a structural concrete member is assigned more than one exposure class (i.e. F3, SO, W1 and C2), the concrete mixture must be proportioned by the Contractor to meet the most restrictive requirements for maximum water-cementitious materials ratio and minimum specified compressive strength (f'_c).

The mixture proportioning durability requirements for maximum water-cementitious materials ratio and minimum specified compressive strength (f'_c)

are specified in the FP and special contract requirements. Other durability requirements are also specified in association with each assigned exposure category and class (with the exception of Exposure Category W (Permeability), which has no additional durability requirements). Exposure class categories F, S and C will be hereafter discussed with respect to the attack method, the corresponding deterioration appearance and specifications pertaining to concrete mix design mitigation measures. Thereafter, other FP durability requirements will be addressed.

6.3.1 Exposure Category F (Freezing and thawing)

Freeze-thaw attack occurs in climates of repeated freezing and thawing. When temperatures drop below freezing, ice starts to form in concrete pores. Water increases in volume on freezing. Water confined in pores between freezing bodies is under compression and pores dilate causing the cement paste to rupture or crack. When concrete contains porous aggregate, the aggregate itself is prone to freeze-thaw damage even when the concrete contains air entrainment (see Figure 1).

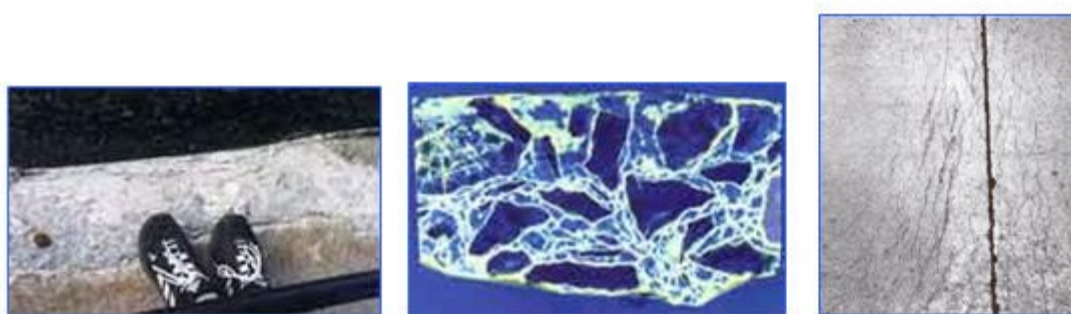


Figure 1: Concrete freeze-thaw damage (1) on the surface in the form of de-icer scaling; (2) throughout the thickness in the form of cracks in paste around aggregate; and (3) at pavement joints in the form of D-cracking.

Freeze-thaw deterioration is manifested on the exposed concrete surface by deicer scaling, crumbling and delamination. It is manifested throughout the thickness of the concrete by parallel surface cracks in paste and cracks in paste around aggregate. In pavements, freeze-thaw deterioration sometimes takes the form of D-cracking. D-cracking consists of closely spaced cracks that form parallel to pavement joints and progressively move outward. D-cracks are caused by porous aggregates. As water accumulates under pavements, the porous aggregates become saturated. When freezing and thawing cycles occur, cracking of the concrete typically starts in the saturated aggregate at the bottom of the slab and progresses upward to the wearing surface.

Freeze-thaw damage may be avoided by proper air entrainment of fresh concrete and use of nonporous aggregate. A good air void system provides free

space to which water can diffuse and freeze without damaging the concrete. From a microscopic standpoint, air bubbles should be spaced no more than 230 μm apart and 10 to 1000 μm in size. Concrete air content requirements are based on the maximum aggregate size used.

In addition to specifying mixture proportioning requirements for maximum water-cementitious materials ratio and minimum specified compressive strength (f'_c) for each freezing and thawing exposure class (F0, F1, F2 or F3), the FP and special contract requirements further mandate allowable air content ranges. To provide protection against freeze-thaw attack, the concrete mixture must be designed by the Contractor to meet air content requirements of the assigned freeze-thaw exposure class. It is noted that too much entrained air will result in detrimental strength loss. As a rule of thumb, the compressive strength loss is about 5 percent for each 1 percent of air content.

It is further noted that the FP limits the maximum total cementitious materials content pertaining to collective combinations of mineral admixtures (i.e. for concrete exposed to freezing and thawing and in continuous contact with moisture and exposed to deicing chemicals or the F3 exposure class). The requirements have been previously discussed and are shown in Table 3.

6.3.2 Exposure Category S (Sulfates)

Naturally occurring sodium, potassium, calcium or magnesium sulfates found in soil, dissolved in groundwater or from deicing chemicals can enter concrete and attack the cementing materials. Wetting and drying can replenish and concentrate salts on the concrete surface leading to continual attack. Sulfate attack disrupts the cement paste through one of two mechanisms: (1) formation of additional ettringite or (2) formation of additional gypsum. The formation of ettringite results in an increase in solid volume leading to expansion and cracking of paste. The formation of gypsum leads to paste softening and loss of strength. The presence of ettringite and gypsum in concrete, in and of itself, is not an indication of sulfate attack as these components are present in all concrete. In addition to chemical analysis, petrographic examination (ASTM C856) of hardened concrete samples is necessary to verify sulfate attack.

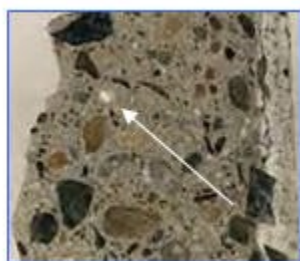


Figure 2: At the microstructure level, salt deposits (i.e. the formation of ettringite) are shown on a hardened concrete sample as well as cracking in the paste due to the formation and expansion of ettringite.

When in-service concrete will be exposed to soil or solutions (groundwater or deicing solutions) containing sulfates, a sulfate condition must be determined and the concrete mixture designed with the appropriate sulfate resisting cementitious materials types. Soil and/or water testing to determine the sulfate condition is accomplished as part of the project development with test results typically being included in Geotechnical reports. Measured test results are used by the Division Materials Engineer to assign an applicable sulfate exposure class which in turn is specified in special contract requirements on a project-by-project basis.

In addition to specifying mixture proportioning requirements for maximum water-cementitious materials ratio and minimum specified compressive strength (f'_c) for each sulfate exposure class (S0, S1, S2 and S3), the FP and special contract requirements further mandate the use of sulfate resisting cementitious materials types. To provide protection against sulfate attack, the concrete mixture must be designed by the Contractor to meet the required cementitious materials type of the assigned sulfate exposure class. Alternatively, combinations of cementitious materials proposed for use in the mix design may be tested by mortar bar expansion in a sulfate solution. Mortar bar samples must be fabricated and tested in accordance with the procedure designated in the contract and meet the expansion limitation requirement of the assigned sulfate exposure class. The Contractor is further required to submit valid hydraulic cement materials certifications with the concrete mix design as part of form FHWA 1608. These certifications must include pertinent chemical and physical properties test data, including mortar bar expansion data when applicable, allowing verification of the use of appropriate sulfate resisting cement on the project (See Section 9.5).

6.3.3 Exposure Category C (Corrosion)

Concrete protects reinforcing steel because it provides a high pH environment around it. The pH of concrete, including that of the pore solution, is about 12.5. At a pH of 11.5 and higher, a passivating oxide film will form on the steel surface in contact with the concrete which protects the steel from corrosion. As long as the passivating oxide film forms and the high pH environment is maintained, the reinforcing steel will be protected from corrosion.

Reinforcement in concrete corrodes as a result of the failure to establish an initial passivating environment or by loss of an established passivating environment over time. The passivating environment may not initially form if

the concrete exhibits excessive voids throughout its depth and at or near steel reinforcement if the concrete is porous. The passivating environment may be lost over time by concrete carbonation which lowers the pH pore solution near reinforcement steel to about 8.5. All concrete carbonates as a result of exposure to carbon dioxide in the atmosphere. The passivating environment may also be lost over time by ingress of the chloride ion into concrete which destroys the passive oxide film surrounding the steel.

As reinforcement corrodes, it increases substantially in volume resulting in delamination of overlying concrete and further structural deterioration. The effective load carrying area of the reinforcement is also reduced.

In addition to specifying mixture proportioning requirements for maximum water-cementitious materials ratio and minimum specified compressive strength (f'_c) for each corrosion exposure class (C0, C1 and C2), the FP and special contract requirements further mandate limitations on the water soluble chloride ion (Cl^-) of the concrete mix ingredients when concrete is placed over reinforcing steel. To provide protection against reinforcement corrosion, the concrete mixture must be designed by the Contractor to meet the maximum water soluble chloride ion (Cl^-) content by weight of cement for the assigned corrosion exposure class and structural member type. The Contractor is further required to submit water soluble chloride ion (Cl^-) data on hardened concrete with the concrete mix design on form FHWA 1608. The data must verify that the maximum water soluble chloride ion (Cl^-) content of the mix ingredients has not been exceeded at the designated test age and that the concrete has been tested in accordance with the procedure designated in the contract.

Finally, for proper corrosion protection of the reinforcing steel, it is imperative that minimum concrete cover requirements stipulated by contract drawings be provided. Concrete cover over reinforcing steel should be checked in the field by the Project Engineer. Reinforcement steel cover can best be assessed in the forms prior to concrete placement.

6.3.4 Delayed Ettringite Formation (DEF)

Delayed Ettringite Formation (DEF), also known as internal sulfate attack, results in the formation of ettringite and associated expansion after heat curing at too high of a temperature. Many experiments have shown that pastes, mortars and concretes exposed to excessive temperatures during the hardening process exhibit expansion and cracking when subsequently exposed to moist conditions. The critical temperature for DEF is related to cement alkali content. Cements containing higher alkali contents (i.e. type III cements) exhibit lower critical temperatures. The FP limits elevated curing temperature to a maximum of 160 °F (71 °C).

The temperature of reinforced and prestressed concrete subjected to elevated temperature curing must be monitored by the Contractor and the maximum

curing temperature recorded. It must be submitted with the concrete mix design (see FHWA form 1608).

6.3.5 Alkali-Silica Reactivity (ASR)

Alkali aggregate reactivity is the chemical reaction in either mortar or concrete between alkalis (sodium and potassium) from portland cement or other sources and certain constituents of some aggregates; under certain conditions, deleterious expansion of concrete or mortar may result. ASR is a type of alkali aggregate reactivity which involves reactions of the alkalis in portland cement and certain siliceous rocks or minerals (i.e. opaline, chert, strained quartz, volcanic glass).

In order for ASR to be operative, three components are required including reactive silica, sufficient alkalis and sufficient moisture. Eliminating any one of these components will stop ASR reactivity and subsequent concrete damage.

Reactive silica refers to aggregates that tend to breakdown under exposure to highly alkaline pore solution in concrete and thereafter react with the alkalis to form an expansive ASR gel. Not all siliceous aggregates are reactive. Reactivity depends on aggregate mineralogy, crystalline structure and solubility of silica in the pore solution of concrete.

Sufficient alkalis refer to the alkalis predominately contributed by the sodium and potassium in portland cement but also from other constituent materials and/or external sources. Such alkali sources include supplementary cementitious materials (fly ash, slag and silica fume), aggregates, chemical admixtures, deicing salts, seawater and wash water. The alkalis serve to raise the pH of the pore solution which in turn increases the solubility of the reactive silica.

Sufficient moisture refers to the moisture that is necessary to promote ASR expansion. If the internal relative humidity of the concrete exceeds 80 percent, sufficient moisture is present to allow ASR expansion. Such moisture is typically inherently present within concrete structures that are exposed to the environment or in contact with the ground (i.e. pavements, bridges, canals).

ASR occurs as the alkali and silica react to form a gel reaction product. The gel reaction product absorbs water and subsequently swells. When the volume of the reaction product is greater than the volume of the individual reacted materials, expansive tensile stress are exerted on the concrete and cracking occurs. The only indisputable evidence that ASR has developed in concrete is the detection of ASR reaction products. In the early stages of reactivity or under conditions where only small quantities are produced, ASR gel is virtually undetectable by the unaided eye. Final confirmation of the ASR mechanism must be performed at the microstructure level by a skilled petrographer.

A characteristic and advanced ASR cracking pattern is known as map or pattern cracking. The crack pattern resembles that which develops on dried mud flats.

On concrete pavement surfaces, ASR cracks are typically more prominent in the wheel paths in the longitudinal direction. Below the pavement surface, ASR can be manifested by a predominance of vertical cracks in the upper 1 to 2 inches of pavement as well as cracks with sub-horizontal orientation. ASR cracks can extend completely through the pavement thickness.

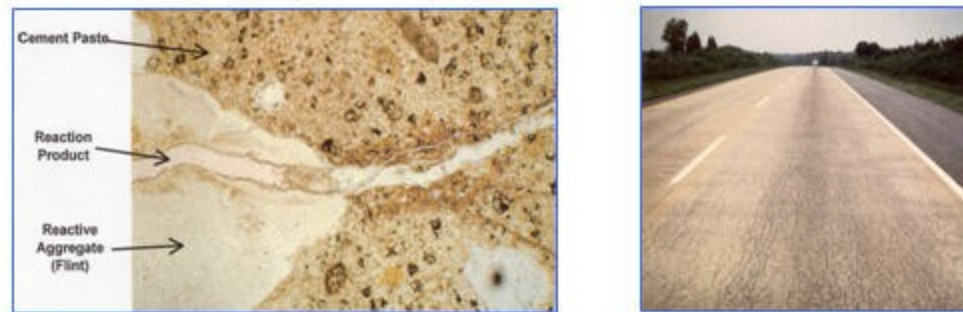


Figure 3: At the microstructure level, the characteristic ASR gel is shown within cracks that have formed through and around aggregate and into the surrounding paste. At the macrostructure level, an advanced and characteristic ASR cracking pattern known as map or pattern cracking is shown.

To prevent ASR in new concrete, the concrete mixture is designed to (1) control and limit the availability of alkalis in cement and/or (2) the type and amount of reactive aggregate.

Lowering of alkalis in the concrete mixture is accomplished by specifying the optional low alkali cement requirement found in portland cement specifications in AASHTO M 85. The low alkali content serves to lower the pH of the concrete pore fluid which in turn decreases the solubility of the reactive silica. The optional low alkali-cement provision may be specified in the special contract requirements as a secondary, but not stand alone, means of ASR mitigation. If the low alkali option is allowed, the Contractor must submit valid hydraulic cement materials certifications with the concrete mix design which includes pertinent chemical and physical properties test data verifying the use of low-alkali cement on the project (See Section 9.5).

Limiting the type and amount of reactive aggregate in the concrete mixture is accomplished by one or more of the following:

- Testing aggregate sources to determine whether or not they contain reactive aggregates.
- Testing reactive sources to determine if the reactivity can be effectively mitigated by use of supplementary cementitious materials (i.e. fly ash, silica fume ground granulated blast furnace slag).

The FP and special contract requirements will specify reactive aggregate supplemental requirements for fine and coarse aggregates. Limiting the type

and amount of reactive aggregate is the preferred and primary means of ASR mitigation.

The reactive aggregate supplemental requirements call for the use of non-reactive aggregates in the concrete mixture. Aggregate producers should be able to provide test results demonstrating the reactivity level of their product. The reactive aggregate supplemental requirements do allow for the use of reactive aggregates if supplementary mineral admixtures are added that demonstrably show prevention of harmful expansion by subsequent testing.

The Contractor is required to submit data from aggregate producers for both fine and coarse aggregate which documents aggregate reactivity levels as well as the test methodology used for measurement. If reactive aggregate is proposed for use, then test data must be included which shows that harmful expansion has been effectively mitigated by use of supplementary cementitious materials. However, the proportions of supplementary materials proposed for use in the concrete mix design must be similar to those showing effective mitigation by testing. The mix design proportions must also meet the maximum cementitious material requirements shown in Table 3. ASR testing as well as expansion criteria which is accepted by Federal Lands Highway is shown in Table 10.

Table 10: FLH Accepted ASR Testing.

Test Name	ASR Test Type and Application*	Sample Type and Size	Test Duration	Expansion Criteria
ASTM C1260	Immersion of mortar bars in NaOH solution at 80° C. (Evaluates aggregates only)	At least 3 mortar bars 1 x 1 x 10 inches long 25 x 25 x 250 mm long)	16 days total – 14 days from zero measurement. Cannot be used to evaluate SCMs or Lithium	0.10% max at 16 days after casting
ASTM C1293	Concrete prisms stored at 38°C and 100% humidity. (Evaluates aggregate, SCMs and Lithium)	Three prisms per cement-aggregate combination not less than 3 x 3 x 10- inches long (75 x 75 x 250 mm long)	Measure after 1, 2, 4, 8, 13, 18, 26, 39 and 52 weeks. Every 6 months thereafter as necessary	0.04% max at one year
ASTM C1567	Immersion of mortar bars in alkaline solution at 80°C. (Evaluates SCMs)	At least 3 mortar bars 1 x 1 x 10 inches long (25 x 25 x 250 mm long)	16 days total – 14 days from zero measurement. Cannot be used to evaluate Lithium	0.10% max at 16 days after casting

ASTM C295	Petrographic examination of aggregates	Varies; quarry samples of fine and coarse aggregate	Short term: visual and microscopic to assess reactive aggregate types	Used with ASTM C1260
ASTM C856	Petrographic examination of hardened concrete	One core specimen 6 inch diameter x 12 inches long (150 mm diameter x 300 mm long) or mortar bar sample	Short term: visual and microscopic to assess reactivity, cracks etc.	Used with ASTM C1260
* SCM stands for supplementary cementitious materials such as fly ash, silica fume or ground granulated blast furnace slag or a combination thereof.				

It is emphasized that ASR testing is included as part of the aggregate source quality testing shown in Tables 5 and 6. The Contractor should ensure that aggregate samples are submitted to the Government far in advance of the submittal of the concrete mix design in that some aggregate ASR tests take weeks to perform. As a minimum, ASTM C1260, which is used to ascertain whether or not aggregate is reactive, takes 16 days to perform after receipt and casting of test samples. Additional time will be necessary if supplementary petrographic analysis is required. Also, if reactive aggregate is employed in the concrete mix design, ASTM C1567, which is used to ascertain whether or not the use of supplementary cementitious materials has been effective in mitigating ASR expansion, takes another 16 days after receipt and casting of test samples. It is important to recognize and plan sufficient time for the Government verification testing for contract compliance with ASR requirements.

6.4 Connecting Exposure Category to Material Limits

The durability section (Section 6.3) details five exposure categories and the material limits associated with each. Understanding this connection is essential to professional practice.

- Exposure Category C1 (Dry Interior) — No special durability concerns; normal Type I cement, no air entrainment required.
- Exposure Category C2 (Wet, No Freezing) — Marine environments or constant moisture; sulfate-resistant cement, lower w/c ratio.
- Exposure Category C3 (Wet, Freezing & Thawing) — Northern climates with deicing salt; air entrainment mandatory, w/c ≤ 0.45 , cement limits apply.
- Exposure Category C4 (Very Severe) — Heavy marine exposure or intense salt and freeze-thaw; maximum air entrainment, minimum w/c ratio, maximum cement content, supplementary materials required.

These are not guidelines; they are minimum requirements. A structure designed for Category C1 but exposed to Category C3 conditions will deteriorate prematurely. Proper exposure classification is critical. Engineers must verify the contract exposure category and ensure the mix design complies with all associated limits.

6.5 Concrete Mixture Strength Requirements

In addition to the durability requirements discussed in Section 6.3, the FP also requires structural concrete to be proportioned to meet the required average compressive strength requirements (f'_{cr}) stipulated in ACI 301.

Compressive strength is the measured maximum resistance of a concrete specimen to axial compressive loading or the specified resistance used in design calculations. Compressive strength requirement notation is as follows:

- f'_c = specified compressive strength of concrete, psi (MPa)
- f'_{cr} = required average compressive strength of concrete used as the basis for selection of concrete proportions, psi (MPa)
- ss = sample standard deviation, psi (MPa)
- k = factor used for the increase in standard deviation if the total number of tests is less than 30.

To account for variability that will occur in the field during construction and placement, a suitable concrete mixture must be designed for an average strength (f'_{cr}) appreciably higher than the specified compressive strength (f'_c). In order for a concrete mix design to be approved, proper strength documentation and calculations must be provided by the Contractor. The data should be supplied as part of the mix design submittal on form FHWA 1608. The process for establishing and documenting a suitable concrete mixture consists of three basic steps:

- Step 1: Determine a sample standard deviation from suitable test records (strength tests).
- Step 2: Determine a required average compressive strength (f'_{cr}) from formulas which consider the sample standard deviation or suitable supplemental information documenting average strength potential.
- Step 3: Select mixture proportions that produce an average compressive strength at least as great as the required average compressive strength and also meet durability requirements for the applicable exposure categories noted in Section 6.3.

6.5.1 Determine a Sample Standard Deviation from Suitable Test Records (Strength Tests)

Concrete strength is assessed by strength tests. One strength test (X_i) is defined as the average of the strengths of at least two 6 by 12-inch (150 by 300 mm) cylinders or three 4 by 8-inch (100 by 200 mm) cylinders made from the same sample of concrete and tested at 28 days, or at the test age designated in the contract, for f'_c . The average of all the strength tests is calculated and used to determine a sample standard deviation. The sample standard deviation is in turn used to determine the required average compressive strength (f'_{cr}).

Suitable test records not more than 12 months old must be used or developed to establish a sample standard deviation. When a concrete production facility is presenting strength test records from which a sample standard deviation is calculated, it is required to represent materials, quality control procedures and conditions similar to those expected on the project. For instance, the same mineral and chemical admixtures should be employed in the concrete mix design as will be used on the project. Changes in materials and proportions within test records are not to be more restricted than those proposed for the work. Additionally, the production facility is required to present test records which represent concrete that meets a specified compressive strength or strengths (f'_c) within 1000 psi (7 MPa) of that specified for the proposed work. Where different materials are used for different portions of proposed work (i.e. different classes of concrete), each mix design combination must be evaluated separately by use of strength tests and approved. The Division Materials Engineer can assist in evaluation of the mixtures and recommendation for their use.

The formulas used for the computation of the sample standard deviation are dependent upon the number of suitable test records. There are three different cases of test records.

Case 1

When a concrete production facility has one test record of at least 30 consecutive tests of similar materials and conditions expected, the sample standard deviation (s_s) is calculated from those results in accordance with the following formula:

$$s_s = \sqrt{\frac{\sum(X_i - \bar{X})^2}{(n - 1)}}$$

Where:

s_s = sample standard deviation, psi (MPa)

X_i = individual strength tests

$\bar{X}$ = average of n strength test results

n = number of consecutive strength tests.

If two groups of consecutive tests or two test records are used to obtain at least 30 tests, the sample standard deviation ($\bar{S}_s$) is the statistical average of the values calculated from each test record in accordance with the following formula:

$$\bar{S}_s = \sqrt{\frac{(n_1 - 1)(s_{s1})^2 + (n_2 - 1)(s_{s2})^2}{(n_1 + n_2 - 2)}}$$

Where:

$\bar{S}_s$ = statistical average standard deviation where two test records are used to estimate the sample standard deviation

s_{s1} , s_{s2} = sample standard deviations calculated from two test records, 1 and 2, respectively

n_1 , n_2 = number of tests in each test record, respectively.

Case 2

When a concrete production facility has one test record of 15 to 29 consecutive strength tests, the sample standard deviation is established as the product of the calculated sample standard deviation (s_s) above and the k-modification factor shown in Table 12 below. The test record must represent only a single record of consecutive tests that span a period of not less than 45 calendar days.

Case 3

When less than 15 consecutive strength tests are available, there is insufficient data to establish a sample standard deviation and additional supplemental information must be submitted as discussed in Section 6.5.2 below in order to document average strength potential and to establish mixture proportions.

6.5.2 Determine a Required Average Strength (f'_{cr})

The determination of the required average strength is hereafter addressed for the same three cases of test records previously discussed in Section 6.5.1.

Case 1

When suitable test records from 30 or more consecutive tests are available to establish a standard deviation, the required average compressive strength is determined from the equations shown in Table 11. The required average compressive strength (f'_{cr}) is based on the specified compressive strength (f'_c) which is either (1) less than or equal to 5000 psi (35 MPa) or (2) greater than 5000 psi (35 MPa).

Table 11: Required Average Compressive Strength with Test Records of 30 or More Consecutive Tests.

Specified Compressive Strength, f'_c , psi (MPa)	Required Average Compressive Strength* f'_{cr} , psi (MPa)
$f'_c \leq 5000$ psi (35 MPa)	Use the larger value computed from the following equations: $f'_{cr} = f'_c + 1.34ks_s$ (1) $f'_{cr} = f'_c + 2.33ks_s - 500$ psi (2) $(f'_c + 2.33ks_s - 3.45$ MPa)
Over 5000 psi (35 MPa)	Use the larger value computed from the following equations: $f'_{cr} = f'_c + 1.34ks_s$ (1) $f'_{cr} = 0.90f'_c + 2.33ks_s$ (3)
* k is equal to 1 if the total number of tests are greater than or equal to 30	

In the first instance ($f'_c \leq 5000$ psi (35 MPa)), two computations are made using equations 1 and 2. In the second instance ($f'_c > 5000$ psi (35 MPa)), two computations are again made using equations 1 and 3.

Since the total number of tests are greater than or equal to 30, the sample standard deviation does not have to be modified and $k = 1$ in equations 1, 2 and 3. As was discussed in Step 1 above, either the calculated sample standard deviation, ss , for one test record or the calculated statistical average standard deviation, $S\bar{s}$, for two test records is actually used in the required average compressive strength formula calculations (f'_{cr}). The largest f'_{cr} value computed from equations 1 and 2 for $f'_c \leq 5000$ psi (35 MPa) or equations 1 and 3 for $f'_c > 5000$ psi (35 MPa) in Table 11 is ultimately used as the required average compressive strength (f'_{cr}).

Case 2

When test records from 15 to 29 consecutive strength tests are available, the sample standard deviation is established as the product of the calculated sample standard deviation (ss) for one test record and the k -modification factor shown in Tables 11 and 12. The procedure results in a more conservative or increased required average compressive strength (f'_{cr}) and is statistically equivalent to that of a 30-test record.

Table 12: Required Average Compressive Strength with Test Records of 15 to 29 Consecutive Tests.

Number of Tests*	k-modification Factor for Sample Standard Deviation*
Less than 15	Use Table 13
15	1.16
20	1.08
25	1.03
30 or more	1.00
*Interpolate for intermediate numbers of tests	
+k-modified standard deviation used to determine required average strength f'_{cr} in Table 11	

After applying the appropriate k-modification factor, the largest f'_{cr} value computed from equations 1 and 2 for $f'_c \leq 5000$ psi (35 MPa) or equations 1 and 3 for $f'_c > 5000$ psi (35 MPa) in Table 11 is ultimately used as the required average compressive strength (f'_{cr}).

Case 3

When less than 15 consecutive strength tests are available, there is insufficient data to establish a sample standard deviation. The required average compressive strength is therefore established by a predetermined increase in the specified compressive strength in accordance with Table 13 provided suitable supplemental information is submitted documenting average strength potential. Suitable supplemental information includes strength test records and associated trial mixture proportions.

Table 13: Required Average Compressive Strength with Test Records less than 15 Consecutive Tests.

Specified Compressive Strength, f'_c , psi (MPa)	Required Average Compressive Strength f'_{cr} , psi (MPa)
$f'_c < 3000$ psi (21 MPa)	$f'_{cr} = f'_c + 1000$ psi (7 MPa)
3000 psi (21 MPa) $\leq f'_c \leq 5000$ psi (35 MPa)	$f'_{cr} = f'_c + 1200$ psi (8.5 MPa)
$f'_c > 5000$ psi (35 MPa)	$f'_{cr} = 1.10f'_c + 700$ psi (5 MPa)

When strength test records and associated trial mixture proportions are submitted to document average strength potential, test records consisting of less than 30 but not less than 10 consecutive tests are acceptable provided test records encompass a period of time not less than 45 days. Required concrete proportions may be established by interpolation between the strengths and proportions of two or more test records.

When test records are not available, concrete proportions established from trial mixtures may be used to develop test records for cases 1, 2 or 3. As noted in ACI 301 the trial mixtures must meet the following requirements:

- Materials shall be those for proposed work.
- Trial mixtures with a range of proportions that will produce a range of compressive strengths encompassing f'_{cr} and meet the durability requirements for applicable exposure categories noted in Section 6.3.
- Trial mixtures shall have slumps within the range specified for the proposed work; for air-entrained concrete, air content shall be within the tolerance specified for the proposed work.
- For each trial mixture, at least two 6 by 12 inch (150 by 300 mm) or three 4 by 8 inch (100 by 200 mm) cylinders shall be made and cured in accordance with ASTM C192. Cylinders shall be tested at 28 days or at the test age designated for f'_c .
- The compressive strength results, at designated test age, from the trial mixtures shall be used to establish the composition of the concrete mixture proposed for the work. The proposed concrete mixture shall achieve an average compressive strength as required in Tables 11 or 5-13 and meet the durability requirements for applicable exposure categories noted in Section 6.3.

When no suitable test records or trial mixture data is available, other experience and information may be submitted and used if approved by the Division Materials Engineer.

6.5.3 Select Mixture Proportions

Select mixture proportions that produce an average compressive strength at least as great as the required average compressive strength and also meet durability requirements for the applicable exposure categories in Section 6.3. In order for a concrete mix design to be approved, proper strength documentation and calculations must be submitted by the Contractor which demonstrate that the proposed concrete mixture produces an average compressive strength equal to or greater than the required average compressive strength for the applicable case. As noted above, such documentation consists of a field test record, strength test records, trial mixtures or other information approved by the Division Materials Engineer. The data should be supplied as part of the mix

design submittal on form FHWA 1608. The Division Materials Engineer may be contacted for assistance and direction in the compressive strength evaluation.

6.5 Strength Requirements and the Water-Cement Ratio

Concrete strength depends on the water-to-cement (w/c) ratio: lower w/c produces stronger concrete. Durability requirements often impose a maximum w/c ratio that produces concrete stronger than strictly required for design loads.

For example, a bridge deck might have a structural design requirement of $f'_c = 4,000$ psi, which could be achieved with $w/c = 0.50$. However, freeze-thaw and salt exposure requirements might limit w/c to 0.45, producing concrete capable of 4,500+ psi strength. The engineer intentionally over-designs for strength to meet durability constraints.

This relationship is fundamental to concrete engineering. Durability drives the w/c ratio; strength follows naturally.

Chapter 7

Mix Design Submittal, Approval & Fresh Concrete Testing



7.1 Concrete Mix Design Submittal

The concrete mix design for structural concrete must be recorded and submitted on form FHWA 1608. The form should be submitted to the Project Engineer at least 36 days before concrete production. All forms require documentation of individual mix constituents, specific gravities, weights, and absolute volumes expressed in the proper units indicated on the form. Mix designs should be reported such that the total volume of mix constituents equals one cubic yard (27 cubic feet) or one cubic meter inclusive of design air contents. However, it is acceptable practice to design a concrete mixture with a total volume that is slightly higher (i.e. a few tenths) to allow for some variation in the as-produced air content. Admixture dosages in fluid ounces per cubic yard or liters per cubic meter must also be recorded. In addition, design fresh and hardened concrete properties and other information must be provided as indicated on the forms.

7.2 Concrete Mix Design Approval

The FP requires concrete mix designs be submitted for approval. The Contractor should submit the required forms to the Project Engineer who in turn will submit them to the Division Materials Engineer for review and recommendation for approval. Prior to submitting the forms, the Contractor should review to verify all data and information has been provided according to the contract.

The Division Materials Engineer will review the submitted forms and documentation to ensure compliance with contract requirements.

7.3 Pre-Placement Coordination and Contractor Quality Control Plan

Before the first load of concrete is delivered to the project, a pre-placement coordination meeting must occur. This meeting confirms that all materials, personnel, equipment, and procedures are ready for concrete placement.

During this meeting, the following items must be verified:

- The approved mix design and water-cement ratio limits are posted and understood
- All material certifications (cement, admixtures, aggregates, water) are on file and current
- Contractor's quality control plan is reviewed and approved
- Laboratory equipment is calibrated and ready for fresh concrete testing
- Sampling frequencies, locations, and witness procedures are established
- Curing procedures and timeline for strength testing are confirmed
- Traffic control and placement schedule are coordinated

The pre-placement meeting agenda (detailed in Appendix C) provides a comprehensive checklist. The Project Engineer should not authorize placement until all items are verified and documented.

7.4 Concrete Batch Verification and Construction Phase Testing

The following sections discuss the testing and inspection of concrete during the construction phase once the concrete mix design and materials submittals have been approved.

In addition, the contractor should supply a complete concrete batch ticket with every batch delivered to the project. The Project Engineer should verify that the proportions shown on the ticket match the concrete mix design that was approved for the project. An example of a concrete batch ticket is shown in Figure 4.

CONCRETE BATCH TICKET

KEY NO. _____ PROJECT NO. IDPFH-94-1 (1) DATE 10-24-07

CONTRACT ITEM NO. _____ SUPPLIER BFRedi-Mix CONCRETE CLASS C-AE

COARSE AGG. SIZE NO. 2B MIX DESIGN NO. 060700 TIME BATCHED: 7:05 AM TRUCK NO. 4 TICKET NO. 27351

MATERIAL	S.S.D. MIX DESIGN 1 CY	ACTUAL BATCHED MASS (A)	TOTAL MOISTURE % (B)	ABSORPTION MOISTURE % (C)	FREE WATER % (D) (B-C)	FREE WATER (E)
COARSE AGG 1	1718 LBS	13765 LBS	1.2	0.8	0.4	55 LBS
COARSE AGG 2	LBS	LBS				LBS
FINE AGG	1281 LBS	10240 LBS	4.0	1.2	2.8	279 LBS
FINE AGG	LBS	LBS				LBS
WATER	263 LBS	1584 LBS				334 LBS
CEMENT	658 LBS	5275 LBS				
FLY ASH	LBS	LBS				
TOTAL MASS (P)	3920 LBS	30864 LBS				

WATER WITHHELD 192 (LB) 230 (GAL) AT THE BATCH PLANT W/C RATIO @ PLANT _____ (optional)

ADDMIXTURE	BRAND	OZ/BATCH
AIR ENTRAINMENT	MB AE 90	36
WATER REDUCER	322 N	315
SET RETARDER		
SUPER PLASTICIZER		
OTHER		

CEMENT BRAND Ashgrove FLY ASH _____
 TYPE I II
 MIXING REVOLUTIONS (PLANT) 30
 REMARKS _____

BATCH INSPECTOR: HS CHECKED BY: _____

CONCRETE PLACED (LOCATION): Dock

TIME EMPTY _____ TOTAL TIME _____ TODAY'S TOTAL CY _____ TOTAL CY TO DATE _____

WATER ADDED 10 (GAL) X 8.34 = _____ (LB) ADDED TO TOTAL MASS (G) _____ NEW TOTAL MASS (MI) _____

MIXING REVOLUTIONS (PLANT) _____ MIXING REVS. (FIELD) _____ TOTAL MIXING/AGITATING REVOLUTIONS _____

TESTS: AIR TEMP. 39 CONC. TEMP. 62 SLUMP 284 AIR% 5.2 MINUS AGG. CORRECTION FACTOR _____

CYLINDERS Set 2 A, B DENSITY: 144.2 lb/cf

CALCULATED ACTUAL CY BATCHED = $\frac{(Q) \text{TOTAL MASS OF BATCHED MATERIALS}}{(P) \text{TOTAL MASS OF MIX DESIGN}}$ = _____ (R) CY ROUNDED TO TENTHS _____

RELATIVE YIELD: $\frac{\text{New Total Mass (Mi)}}{(R) \text{Actual CY Batched}}$ = _____

CEMENT FACTOR: $\frac{\text{LBS. Cement}}{\text{New Total Mass (Mi)} / (\text{density (lb/cf)} \times 27)}$ = _____

ACTUAL WATER/CEMENT RATIO = $\frac{(S) \text{Total mixing water (LBS.)}}{\text{Cement} + \text{Fly Ash (LBS.)}}$ = _____

REMARKS: _____

PLACING INSPECTOR: Chris Morgan CHECKED BY: _____

Figure 4: Example of Concrete Batch Ticket.

As part of the construction phase of the work, a pre-concreting meeting should be held to discuss various aspects of concrete placement. A sample pre-concreting meeting agenda is included in Appendix C of this course.

7.5 Aggregate Testing for Uniformity and Water Content Adjustment of Concrete Mixtures

Aggregate source and concrete mix design approval do not constitute final acceptance. If the approved source(s) do not continue to supply acceptable aggregates during the construction process, further use of the source(s) will be denied and a new mix design will be required using another source. For structural concrete, the FP requires that the concrete as well as the as produced

aggregate used in the concrete be sampled, tested and evaluated. Aggregate tests are required to be performed on a daily basis to verify the uniformity of the supply as well as to determine properties necessary for adjustment of the water content of the concrete mixture.

Uniformity of aggregate supply is verified by gradation and fineness modulus tests. A new concrete mix design is required if there is a change in source of material or when the fineness modulus of the fine aggregate changes by more than 0.20.

The water content needs to be monitored and adjusted in accordance with moisture condition of the aggregate, which fluctuates in accordance with environmental conditions at the mixing plant site. The moisture condition is tested on a daily basis and used in conjunction with the aggregate absorption to adjust the batch water amount to meet the water-cementitious materials ratio requirement of the approved mix design. If the water-cementitious materials ratio is not kept constant, the compressive strength, workability and other properties will vary from batch to batch. For example, an increase in the fine aggregate moisture content of one percent will increase the slump of the concrete as much as 1 1/2 inches (40 mm) and decrease the compressive strength by as much as 300 psi (2.1 MPa).

In order to adjust batch water contents, it is necessary to understand the moisture conditions of an aggregate particle. Each aggregate particle is made up of internal voids which may or may not contain water. Four potential moisture conditions are depicted in Figure 5.

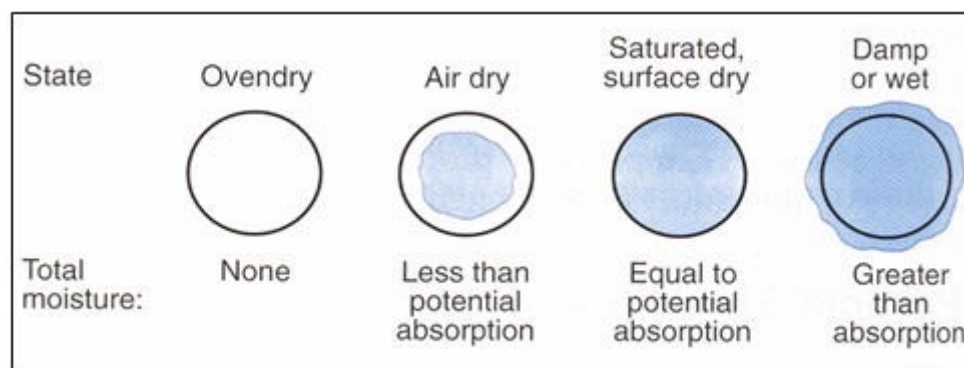


Figure 5: The four moisture conditions of an aggregate particle.

These moisture conditions are defined as follows:

- **Oven Dry** – Particle is completely dry and fully absorbent.
- **Air Dry** – Particle is dry at the surface but contains some interior moisture and is still partially absorbent.

- **Saturated Surface Dry (SSD)** – Particle is fully absorbent and neither absorbs water from nor contributes water to the concrete mixture.
- **Damp or wet** – Particle contains excess moisture on the surface known as free water.

Concrete mix designs are based on a saturated surface dry aggregate condition. Therefore, the existing moisture condition of the aggregate must be determined to properly apply aggregate moisture corrections. Existing moisture conditions are found by determining absorption and moisture contents. Provided the quality of the aggregate remains the same, the aggregate absorption should remain constant. However, since the moisture content reflects the environmental condition of the stored aggregate and since these conditions continually change as a normal course of the daily temperature and humidity cycles, new moisture contents need to be periodically determined. It is a good idea to conduct moisture contents tests at least two times daily, in the morning and afternoon.

The moisture condition of any aggregate and its effect on the concrete mix water can be found by subtracting the existing moisture content of the aggregate, determined according to AASHTO T 255 from the aggregate absorption determined according to AASHTO T 84 and T 85. If the existing moisture content is less than the absorption, as in the case of air dry aggregate, the result will be negative and the aggregate will absorb some of the mixing water. If the existing moisture content is greater than the absorption, as in the case of the wet aggregate, the result will be positive and the aggregate will provide excess mixing water. In both cases, the amount of water added at the batch plant needs to be adjusted to account for the moisture condition of the aggregates such that the water requirement of the approved mix design can be maintained. Form FHWA 1638, Worksheet for Determining Concrete Batch Moisture/Absorption Corrections, can be used as a means of checking that adjustments have been properly calculated and performed. In this manner, the Project Engineer can verify that water content of the approved mix design has not been exceeded.

7.6 Fresh Concrete Properties

For structural concrete and minor concrete, fresh concrete properties inclusive of slump, air content, unit mass and temperature must be measured and evaluated for acceptance. The specific sampling, testing and properties requirements are included in the contract specifications. They define the frequency, methods for evaluation and allowable tolerances. The importance of proper sampling and testing cannot be over emphasized. Only by following proper procedures for fresh concrete sampling and testing can the quality of the delivered product be evaluated. The Project Engineer should witness fresh concrete properties testing for acceptance and take possession of the Governments portion of the concrete cylinders for future hardened concrete

properties testing. Typical fresh concrete testing includes methods shown in Table 14.

Table 14: Fresh Concrete Test Methods.

Concrete Test	Test Method	Concrete Characteristics
Sampling Fresh Concrete	AASHTO R 60	Proper method for obtaining fresh concrete sample
Slump	AASHTO T 119	Concrete consistency and uniformity
Air content	AASHTO T 152 AASHTO T 196	Freeze / thaw resistance
Temperature	AASHTO T 309	Temperature of mixture for proper placement
Unit Weight	AASHTO T 121	Yield
Making Test Specimen	AASHTO T 23	Proper method for making, curing and transporting cylinders

The frequency of sampling is established in the contract and is typically one sample per 30 cubic yards (25 cubic meters) but not less than one per day. The truck loads or batches of concrete to be tested must be selected on a random basis by the Project Engineer before commencement of the concrete placement.

7.6.1 Sampling

Fresh concrete is sampled in accordance with AASHTO R 60. Samples are acquired from the discharge stream at the point of placement. They should be taken between the 10 and 90 percent points of the discharge. Concrete should be collected in two or more portions at regularly spaced intervals throughout the discharge stream. The elapsed time should not exceed 15 minutes between taking the first and final portions of the sample. The samples should be transported to a place where fresh concrete property tests are to be conducted and remixed with a shovel. Slump, temperature and air content tests should be started within five minutes after sampling whereas molding specimens for compressive strength testing should initiate within 15 minutes after sampling.

7.6.2 Concrete Slump

The slump test is conducted in accordance with AASHTO T 119. It is a measure of concrete consistency or uniformity. The standard slump cone is filled in three layers of approximate equal volume and each layer is rodded 25 times with a standard rod. The top layer of concrete is horizontally struck off to a flat surface and the slump cone is vertically raised to allow the concrete to slump. The slump cone is placed next to the slumped concrete and the slump rod is placed horizontally on top of the slump cone. Concrete slump is measured as the

vertical distance from the displaced original center of the top surface of the fresh concrete to the bottom of the rod. Slump is measured to the nearest $\frac{1}{4}$ inch (5 mm) and recorded.

7.6.3 Air Content

Air content can be measured by use of a pressure air meter (AASHTO T 152) or a volumetric air meter (AASHTO T 196). Pressure air meters are calibrated to read air content directly as pressure is applied. Since the measured air content includes air that is trapped in aggregates, a small aggregate correction factor must be subtracted from the pressure meter gauge reading to obtain the correct air content. Pressure type meters cannot be used with porous or lightweight aggregate. Type A pressure meters must be calibrated at the elevation at which they are used since changes in barometric pressure will affect the function of the meter. Volumetric air meters can be used with concrete containing any type of aggregate. They can be used at different elevations and do not require an aggregate correction factor. Volumetric air meters utilize isopropyl alcohol to accelerate air removal and dispel foam. Concrete is placed in the air meter container in three equal layers and rodded in a fashion similar to that of the slump test. After each layer is rodded, the sides of the air meter container are tapped with a rubber or rawhide mallet to close any voids left by the rod and to release any trapped air. Air content is measured to the nearest 0.1 percent and recorded.

7.6.4 Concrete Temperature

Concrete temperature is measured in accordance with AASHTO T 309 to assess whether the concrete is too hot or too cold at the time of placement. When performing a temperature measurement, the sensor should be placed within the fresh concrete at a location that allows it to be completely immersed and surrounded by at least three inches (75 mm). The temperature measuring device is left in place and monitored for at least two minutes or until the concrete temperature stabilizes before a reading is acquired. Temperature is measured to the nearest 1°F (0.5°C) and recorded.

7.6.5 Concrete Unit Weight

AASHTO T 121 is used to verify batch weights, to determine yield and to measure gravimetric air content. The test requires knowledge of mixture proportions in order to calculate yield and air content. The size of the unit weight container used for measurement varies with the maximum aggregate size of the mixture being tested. The air meter container is typically used to measure unit weight.

7.7 Hardened Concrete Properties

Compressive strength is the main hardened concrete property that is tested and evaluated. It is important to fabricate, cure, and handle the specimens appropriately. AASHTO T 22 provides the method for testing concrete specimens

for compressive strength. Compressive strength concrete cylinders are made and cured on a construction project in accordance with AASHTO T 23. Cylinder molds must be made of watertight, non-absorbing material that is capable of holding its dimensions and shape under use. Cylinder length must be twice the diameter. Cylinder diameter must be at least three times the nominal maximum size of the coarse aggregate. Standard 6 by 12-inch (150 by 300 mm) cylinders are typically used when the nominal maximum size of the coarse aggregate does not exceed 2-inches (50 mm). However, AASHTO T 23 does allow the use of 4 by 8-inch (100 by 200 mm) cylinders when the nominal maximum size of the coarse aggregate does not exceed 1-inch (25 mm).

For concrete slumps greater than 1-inch (25 mm), cylinders may be consolidated by rodding or internal vibration. The number of required layers as well as the roddings or vibrator insertions per layer varies in conjunction with the cylinder size. After consolidation, the top surfaces are finished with a wood float or trowel to produce a flat even surface that is level with the mold edge.

Cylinder specimens may be either field cured or standard cured. Field cured cylinders are marked for identification, stored near the point of deposit of the concrete and subjected to the same temperature and environment as the structural work. They are tested in the moisture condition resulting from the specified curing treatment.

Standard cured cylinders are subjected to a twofold process consisting of initial and final curing. During initial curing, cylinders are marked for identification and placed within a level, protected and controlled on-site storage area immediately after molding and finishing. They are initially cured for up to 48 hours in a controlled environment that provides temperatures between 60 to 80°F (16 to 27°C) and prevents moisture loss. For concrete mixtures with a specified strength of 6000 psi (40 MPa) or greater, the initial curing temperatures must be controlled between 68 and 78°F (20 and 26°C).

Cylinders must not be transported for final curing until at least 8 hours after final set. During transportation, cylinders must be protected from moisture loss, freezing and jarring. After arrival at the testing laboratory, the molds are removed. Cylinders are then final cured with free water maintained on their surfaces at all times at a temperature of $73 \pm 3^{\circ}\text{F}$ ($23 \pm 2^{\circ}\text{C}$) using water tanks or moist storing rooms.

Compressive strength testing is conducted in accordance with AASHTO T 22. In order to be tested, specimens must be within the specified tolerances for diameter and the ends must be plane. Specimens may need one or both ends trimmed or ground prior to testing if they do not meet planeness requirements. Immediately prior to testing, cylinders must be capped using bonded or unbonded material. Bonded caps consist of sulfur mortar, high strength gypsum plaster, neat cement paste or other materials. They must meet the requirements of AASHTO T 231. Unbonded caps consist of neoprene pads or other materials

that are used in conjunction with capping plates. They must meet the requirements of ASTM C1231.

AASHTO T 22 provides permissible time tolerances for various test ages (ranging from 12 hours to 90 days) in which test specimens must be broken. The permissible time tolerances for 7 and 28-day test ages are 6 and 20 hours, respectively.

Specimens are tested by compression loading at a constant rate to failure. The type of fracture, maximum load, cross-sectional area and calculated compressive strength are recorded. Length and diameter measurements are also made prior to testing. If the specimen length-to-diameter ratio is 1.75 or less, the length and diameter measurements must also be recorded and the compressive strength corrected by the appropriate correction factor.

The compressive strength of concrete cylinders is dependent upon the moisture condition, curing temperature and specimen size and shape. For these reasons compressive strength data obtained from field cured and standard cured specimens are used for different purposes.

Compressive strength data obtained from field cured specimens (cured with the structure) may be used for the purposes of:

- Determination of whether a structure is capable of being placed into service
- Comparison with test results of standard cured specimens or with test results from various in-place test methods (destructive and nondestructive)
- Adequacy of curing and protection of concrete in the structure
- For falsework or shoring removal time requirements

Compressive strength data obtained from standard cured specimens (initially cured in the field and final cured in a water storage tank or fog room) may be used for the purposes of:

- Acceptance testing for specified strength
- Checking the adequacy of mixture proportions for strength
- Quality control

For acceptance testing, the FP requires the compressive strength cylinders to be standard cured and tested at 28-days. At least four 6 by 12 inch (150 by 300 mm) or six 4 by 8 inch (100 by 200 mm) cylinders should be molded and cured for each sample taken from the same load. Two 6 by 12 inch (150 by 300 mm) or three 4 by 8 inch (100 by 200 mm) cylinders are typically tested for acceptance at 28-days age with the compressive strength result being the average of the tests. The other cylinders are retained or used for informational purposes such as obtaining 7-day strengths. They may also be used for acceptance testing if

specimen(s) that have been previously tested show evidence of improper sampling, molding or testing and have to be discarded.

The Project Engineer should closely monitor the compressive strength of the concrete during the construction process. If low strength test results occur, designers must perform calculations to assure that the load-carrying capacity of the structure is not impaired. If the likelihood of low strength concrete is confirmed and there is a need for additional investigation, tests of cores drilled from the area in question may be performed. If it is necessary to obtain cores, the specimens will be obtained in accordance with AASHTO T 24. Contact the Division Materials Engineer for specific guidance regarding the sampling and testing of concrete that does not meet the contract compressive strength requirement.

7.8 Field Verification of Concrete Quality

Fresh concrete testing (slump, air content, temperature, unit weight) occurs at the plant and at placement. These tests ensure the concrete being delivered matches the job mix formula.

Hardened concrete testing (strength cylinders) occurs after curing. Test results are compared to the required strength (f'_c). If results fall below specification, investigation is required. Possible causes include low cement content, high water content, poor curing, or contaminated materials.

Low strength results do not automatically require removal of concrete. Options include acceptance at reduced value, acceptance with demonstration that the structure still meets design requirements through core sampling and structural analysis, or removal and replacement. The contract and regulations guide these decisions.

Chapter 8

Sampling, Verification & Field Acceptance



8.1 Sampling Concrete: Quality Control and Verification

Concrete sampling during placement requires different techniques than sampling soil or aggregate. Concrete must remain fresh (above ~75°F) and be sampled from the interior of the truck, not from segregated material at the edges or bottom.

The contractor's quality control samples are obtained at regular intervals (e.g., one per 50 cubic yards or per 4 hours). Testing of these samples ensures the concrete being placed matches the job mix formula.

Government verification samples are obtained at random intervals. The Project Engineer witnesses sampling, obtains a split, and sends it to the laboratory for independent testing. Contractor and Government results are compared statistically to determine if the contractor's testing is valid.

Proper sampling technique and strict chain-of-custody procedures ensure reliable test results.

8.2 Sampling

The control of material is an important part of any construction project. It can only be accomplished when the material being incorporated into the work is acceptably inspected, properly sampled, and accurately tested. The importance of obtaining a good representative sample cannot be overstated.

Samples obtained or used on construction projects have different purposes. Samples can be obtained to verify proper testing is being performed, to control

production processes, or to verify product quality. Here are the general sample types and purposes that are typically used on FLH construction projects:

- **Quality Control (also called process control) Samples.** These samples are obtained by the contractor for the purpose of assessing and making adjustments to a production or construction process. Samples, taken during production, assist the contractor in making appropriate corrections for producing a quality product. Information obtained by testing these samples is used by the contractor to control the level of quality of the furnished end product. The contractor may take a quality control sample at any time. However, when the quality control sample test results are to be utilized in the material acceptance decision, the Government will randomly identify the material to be sampled and tested.

The Government will witness the sampling and splitting procedures and will immediately take possession of the Government's split portion of the sample. The Government must maintain control and custody of the sample at all times to ensure the integrity of the testing and verification process.

- **Acceptance Samples.** These samples are tested by the government to determine conformance to contract requirements.
- **Verification Samples.** These samples are obtained by the contractor; witnessed and tested by the government or its designated laboratory for the purpose of verifying the results of contractor tested quality control samples. The results are used in a statistical evaluation for the purpose of acceptance and payment. In the event that the contractor's test results are not verified, the Government's test results will be used for acceptance and payment for the material.
- **Independent Assurance Samples.** Any qualified person from a qualified laboratory, as defined in the contract, which are not associated with the contractor or the FLH project inspection staff, can take an Independent Assurance (IA) sample. This sample can be taken at any location and at any time within the project. The purpose of this sample is to provide an unbiased and independent evaluation of the sampling and testing procedures used in the acceptance decision. IA samples evaluate the sampling and testing personnel and their associated equipment. The sample cannot be used in the acceptance decision for the material since it is a biased non-random sample used to evaluate testing personnel and equipment. The Division Materials Engineer evaluates the results to determine if any discrepancies exist in the sampling and testing.
- **Proficiency Samples.** These samples are manufactured by the FLH central laboratory and used as a tool to evaluate the quality of the testing being performed for a project. The results are used in the same manner as the independent assurance samples. The Division Materials Engineer evaluates the results to determine if any discrepancies exist in the testing.

In all cases, it is critical to obtain a representative portion of the manufactured product that will be tested to verify that the material used or the work done conforms to the requirements of the contract. The use of proper sampling procedures and techniques is a vital piece of the verification process for quality highway construction.

8.2.1 Sampling Responsibilities

Generally speaking, the contractor is responsible for obtaining all of the samples on a construction project. The sampling process takes place under the supervision or witness of the Project Engineer or government representative. In addition to acquiring the sample, the contractor is also responsible for splitting the sample, if appropriate, and providing a split portion of the sample to the government. When results of the contractor testing are to be considered in the acceptance decision, the contractor needs to ensure that a government representative is present during the sampling and splitting process. Once this has been accomplished, the government will take immediate control of the sample. This sample may then be tested and the results used as part of the verification process. It is vitally important for the integrity of the acceptance process that the sampling is witnessed and that the chain of custody for the government portion of the sample has not been compromised.

The contractor is responsible for following proper sampling and testing methods in accordance with the submitted quality control plan and the contract specifications. This includes monitoring, certifying, or verifying the quality of products manufactured off-site and delivered to the project meet contract specifications. At a minimum, the contractor is required to perform all sampling and testing listed in the sampling and testing tables provided in the contract.

The Project Engineer is responsible for verifying that the required sampling is accomplished according to standard procedures and that the material used and work performed on the project, whether produced on the project or manufactured off-site and delivered to the project from an outside source, comply with contract specifications. In addition, the Project Engineer will ensure that all samples used to evaluate work for acceptance are retained until final acceptance.

8.2.2 Sampling Procedures

Established sampling methods provide specific guidance regarding the amount of material required for the sample. This amount should not be confused with the amount of material needed to perform the proper testing. The sample obtained needs to be taken in accordance with the appropriate referenced method. Subsequent testing is usually performed on a smaller representative portion of that sample. These smaller testing amounts will be specifically stated in the appropriate test method for the given material.

Project personnel should be knowledgeable in the following sampling criteria that are required by the contract.

- **Minimum required sample size.** The sampling methods, typically cited as AASHTO or ASTM methods, identify the size sample required for the particular material.
- **Sampling frequency.** Sufficient samples must be taken to represent the material that is delivered to the project for assurance that it complies with specification requirements. A non-uniform product can require more samples than the minimum specified in the contract for acceptance of its quality. For acceptance purposes, the contract will specify the minimum sampling frequency.
- **Sampling methods.** Different materials require different sampling methods. The appropriate test methods should be used to ensure a proper sample has been obtained. These methods will be referenced in the contract documents and also in this manual.
- **Sample location.** Where practicable, samples to be tested for acceptance shall be obtained from the finished product. The contract specifications identify where samples are to be taken for acceptance and at what minimum frequency.

8.2.3 Sampling Methodologies

Samples may be obtained at any time and at any location. Specific contract language in subsection 106.01 states that the government may inspect, sample, or test all work at any time before final acceptance of the project. In general, there are two sampling methodologies.

- **Selective sampling.** This is a biased non-random procedure in which a sample of material is obtained from a specific location determined by observation. The information obtained from the testing of this sample can be used to determine compliance with the contract but cannot be included in any statistical evaluation. This methodology may be used at any time.
- **Random sampling.** This is an unbiased sampling procedure in which a sample of material is chosen in such a manner that any incremental amount of material placed has an equal probability of being selected. For the statistical concepts and comparisons to function properly, the sample used for statistical acceptance must be selected on a random basis. Random sampling locations are selected in advance of the production and placement of the material to be sampled. These locations should be selected using random numbers generated by use of random number tables, the random number function on a calculator, or the random number function in computer software. QL-PAY has a random number

generator developed specifically for use with highway construction materials.

8.2.4 Sample Handling

Samples need to be stored and handled appropriately to ensure that the integrity of the material has not been compromised. The samples need to be properly labeled and identified so that all information regarding the sample location and test results can be correlated. If the samples are to be transported, use proper containers to maintain the integrity of the sample throughout the shipping process. Include a Request for Laboratory Tests form, FHWA 1600, for all samples shipped to the central laboratory.

8.2.4.1 Sample storage and retention

Once the government takes possession of the sample, it should be handled and stored in an appropriate manner. Care should be taken to avoid damage to the sample container, disturbance of the sample, or contamination. The Project Engineer will store, handle, label and date samples in a manner that will preserve the character of the material. Most samples should be stored in a dry environment and kept free from contamination until final acceptance of the project. It is important that all samples be cared for in this manner in the event that complete testing of verification or acceptance samples becomes necessary.

8.2.4.2 Sample labeling

When obtaining the sample, the contractor will need to label the sample container with the appropriate project information. As a minimum, the following information should be included on any sample. Additional information may be required depending on the specific location and/or purpose for the sample.

- Project name
- Project number
- Pay item number
- Pay item description
- Sample number
- Lot number
- Sublot number
- Date
- Location of sample

8.2.4.3 Sample transport and shipment.

Ship samples in a container of sufficient strength to prevent the loss, contamination or damage of the contents during shipment. Sufficiently identify all samples to facilitate reporting, logging, and tracking of sample information. Table 15 provides a brief summary list of containers to be used for common highway materials. If additional guidance is needed for a particular material, contact the Division Materials Engineer.

Table 15: Common Sample Containers.

Material	Appropriate Sample Container
Soil and Aggregate	Clean tight woven canvas sacks 5-gallon plastic buckets with tight lids
Cement, Lime, Fly ash	1-gallon watertight containers
Asphalt binder and cutback asphalts	1-quart cans
Emulsified asphalt	1-gallon large mouth plastic jugs with screw top lids
Asphalt mixture – uncompacted	6" x 12" cylinders 5-gallon plastic or metal buckets Cardboard box of sufficient size
Asphalt mixture – cores	Cushioned container 4" x 8" or 6" x 12" plastic concrete cylinder molds with appropriate packing
Concrete cylinders	Appropriate sized concrete cylinder molds shipped in a sturdy box with insulation and padding

8.2.5 Request for laboratory testing

All samples shipped to the FLH division laboratory must have a Request for Laboratory Tests form, form FHWA 1600, to provide instruction as to the testing to be performed. The form should be completed by the Project Engineer and attached to the outside of the sample container in a manner that will protect it during shipment. A duplicate copy should be placed inside the shipping container. The form can also be faxed or electronically sent in advance of shipment to alert the lab personnel that a sample will be arriving.

8.3 Verification Processes

8.3.1 Verification of Material Quality

Regardless of which acceptance method is used, it is always necessary to verify the quality of materials incorporated into the work. The responsibility for final acceptance of all materials rests with the Contracting Officer. Therefore, the

Project Engineer must be confident that the results obtained on which the acceptance decision is based are valid. Using qualified laboratories and qualified technicians facilitates achieving a quality project and having reliable test results on which to base acceptance decisions.

Whenever there are at least three samples tested by both the contractor and the Government, comparison of the results should be performed by entering them into QL-PAY. QL-PAY uses statistical procedures to analyze the data and determine if there are significant differences between the contractor's and Government's results or if the results are within what would be considered normal limits of variability. If the results are within normal variability limits, the contractor's results would be considered valid. If the results are not within normal variability limits, QL-PAY will issue an alert. It is essential that the Division Materials Engineer be contacted immediately and review the data before any action is taken. A final determination as to the validity of the contractor's results must be made by an individual having a background in both statistical analysis and materials in order to avoid making an incorrect decision.

When there are fewer than three samples tested by either party, the comparison cannot be done in QL-PAY. In those instances, the results of samples should be compared using the multi-laboratory precision limit specified in the applicable test method. This provides an acceptable range for two results obtained from different laboratories by different operators. If the results are within the multi-laboratory precision limit, the contractor's results would be considered valid.

8.3.2 Visual Inspection and Certification

Acceptance verification of material quality may be by visually inspecting the material and verifying the certification. If the Project Engineer has any doubts regarding material quality, he has the right to obtain a sample and have it tested and should do so. Normally, if a sample is desired, it should be obtained by the contractor in the presence of the Project Engineer with the Project Engineer determining the location of the sample. The Project Engineer should take immediate possession of the sample after it is obtained (and split if desired). The sample is usually obtained by using random numbers; however, the Project Engineer may elect to test in a specific location to verify the quality of the material.

8.3.3 Measured or Tested for Conformance

The Project Engineer should normally obtain and test a minimum of three random samples; however, for small quantities fewer samples may be appropriate. In the case where the Project Engineer has suspicions concerning the quality of the material, the Project Engineer may direct the contractor to obtain one or more samples from the suspect area rather than use random samples. The Project Engineer should take immediate possession of the sample after it is obtained (and split if desired) by the contractor.

8.3.4 Statistical Evaluation of Work and Determination of Pay Factor (Value of Work)

For this type of material acceptance, the contract specifies the sampling frequency and the Project Engineer determines the random location of all the samples. All samples intended for use in the acceptance decision must be obtained by the contractor in the presence of the Project Engineer. The sample location should not be revealed to the contractor until moments before the sample is to be obtained. The Project Engineer should take immediate possession of the sample after it is obtained and split. All comparisons of results should be made in QL-PAY.

8.4 Acceptance of Work and Value Determination

Acceptable work conforming to the contract should be paid for at the contract unit bid price. When material or work fails to meet the established specification, the material or work shall be removed and replaced unless in the public interest the Government consents to accept the work with an appropriate adjustment in price or corrective action. If the contractor requests to have the work accepted at a reduced price or requests permission to perform corrective measures, the request will be evaluated based on the public interest. It is the contractor's responsibility to submit a proposal outlining any action that will be taken in lieu of removal and replacement. The contractor may submit a written request to:

1. Have the work accepted at a reduced price; or
2. Be given permission to perform corrective measures to bring the work into conformity.

A written request must contain supporting rationale and documentation. This would include references or data justifying the proposal based on an evaluation of test results, effect on service life, value of material or work, quality, aesthetics, and other tangible engineering basis.

If the contractor submits a written request, the following process outline provides guidance for addressing the request to accept work at a reduced price:

- Meet to discuss the non-compliance material or workmanship. The meeting should include the Project Engineer, Construction Operations Engineer, and Technical Services Branch representative with expertise in or responsibility for the area of concern (i.e., bridge, hydraulics, materials).
- Review test data to determine the significance of non-compliance.
- Evaluate the degree of deviation from contract requirements. Such evaluation is a subjective process and must take into account the criticality of the material or work, the risk associated with any deviation from the contract requirements, and the degree of deviation from contract requirements.

- Reduce the contract unit price for the item in question depending on the significance of the noncompliance. The percent reduction in the unit price are based on the following guidelines:

0 to 5% Material substantially meets the contract requirements with minor deviations from the specifications.

6 to 15% Material fails to meet contract requirements and results in the use of an inferior product. Generally, this material will result in a reduction in the usable life of the item in question.

16 to 75% Material fails to meet contract requirements by a significant amount and is clearly an inferior product. Use of this material may meet the intended purpose; however, the quality is well below that specified. The criticality of this material may be low and does not warrant removal or other corrective action.

Likewise, corrective actions need to be evaluated to determine the level of effectiveness. The remedial/corrective work must provide results that are more desirable than reducing item pay amounts. In certain instances, corrective actions may be used in combination with a contract bid price reduction.

When it is determined that the material or work does not meet the intended purpose or results in substantial quality or safety deficiencies, it shall be removed and replaced.

Chapter 9

Roles, Responsibilities & Documentation



9.1 Personnel

Individuals performing sampling and testing of materials to be used in the construction of FLH projects must be knowledgeable in the sampling and testing procedures and requirements of the contract. In addition to sampling and testing requirements testing personnel must also be familiar with proper use and calibration of equipment required for the testing of materials.

In general, contractor personnel assigned to perform sampling, testing, or inspection functions should have 1 year or more of recent job experience in the type of sampling, testing or inspection required by the contract. Qualifications can also be demonstrated through other certifications or participation in proficiency testing. Examples of these types of qualifications include:

- NICET Level II certification in highway materials, or State Highway Agency (SHA) or industry certification-related sampling and testing equivalent to their contract responsibilities.
- Nationally accepted certification for intended sampling and testing responsibilities, i.e. WAQTC, ACI, NETTCP.
- Current or previous employment by an AASHTO accredited laboratory performing sampling and testing equivalent to their intended responsibilities.
- Demonstrated proficiency or successful testing of one or more proficiency samples (may be substituted for basic qualifications pending verification of test results).

9.1.1 Qualification Documentation

Before the start of the work, the Project Engineer should obtain documentation supporting personnel qualifications. Documentation requirements are listed in the contract.

9.1.2 Subcontracted Sampling and Testing

If sampling, testing or inspection is to be performed by a subcontractor, the Project Engineer should request from the prime contractor detailed information about how the sampling, testing and inspection by the subcontractor will interface with the prime contractor's work and other subcontractors performing work required by the contract.

The contractor is required to have a quality control system that includes the appropriate process control of material. The Project Engineer is responsible to ensure that material being incorporated into the work conforms to the contract requirements as supported by the appropriate inspections, sampling, and testing.

9.2 Equipment and Testing Laboratories

Testing of materials used in highway construction projects requires specialized materials testing equipment. Laboratories are essential to assure quality materials are incorporated in the project. Laboratories must be adequately staffed and properly equipped to conduct materials tests required by the contract quality control provisions.

The Project Engineer is responsible for inspecting, verifying, and documenting that field laboratories are properly equipped and staffed prior to the start of the work that requires sampling and testing.

9.2.1 Contractor-furnished Laboratories

The contractor may use a commercial laboratory or an on-site contractor furnished laboratory. The commercial or on-site contractor furnished laboratory must be equipped with all the testing equipment and accessories to meet contract sampling and testing requirements.

Laboratory facilities should be kept clean and equipment maintained in proper working condition. Subject to the terms of the contract, the Project Engineer has unrestricted access to the laboratory for inspection and review.

9.2.2 Government-furnished Laboratories

A government-furnished field laboratory trailer may be available for rent. If this is the case, the government will offer to the contractor a furnished field laboratory with testing equipment. Field laboratory availability and a listing of the testing equipment included in each field laboratory may be obtained by

contacting the CO. Due to the wide-range of construction complexity for FLH projects, the laboratory facility may not be equipped with all of the necessary testing equipment required for the project. It is the responsibility of the contractor to review the basic equipment list and provide any specialty or missing testing equipment needed for use on the project.

In general, the laboratory includes testing equipment to conduct process control and project acceptance testing for embankments, crushed aggregate base, asphalt paving materials, and plastic concrete. Other equipment, such as equipment for breaking and curing concrete cylinders, may be included on a specific contract basis. The Sampling and Testing tables located at the end of each Section in the contract will provide references to test methods and procedures that include the equipment requirements.

The laboratory facility should be kept clean and equipment maintained in proper working condition. Subject to the terms of the contract, the Project Engineer has unrestricted access to the laboratory for inspection and review.

9.2.2.1 Laboratory Cost

Field laboratory trailer and testing equipment are offered to the contractor at a cost specified in the contract. The contractor shall replace at their cost or be responsible for the replacement cost of all missing or damaged equipment (other than through reasonable wear and tear).

9.2.2.2 Laboratory Equipment

The contractor shall determine if the laboratory testing equipment is adequate to perform all testing required by the contract.

In addition, the following apply:

- The equipment has been checked and calibrated to applicable specifications. It is the contractor's responsibility to ensure the equipment is maintained in proper operating condition.
- No nuclear devices will be furnished.
- The contractor is responsible for providing the laboratory trailer with a water supply and adequate 240-volt, 60-cycle, 200 amp single-phase current for all laboratory electrical needs. A minimum of 60 kilowatts of power at the entrance box is required for effective use of electrical equipment. Equip the power supply with a regulator that will limit the voltage of the power furnished to not more than 240 volts and not less than 220 volts.
- The contractor shall accept responsibility for the trailer and equipment upon receipt.

- All equipment provided by the Government and replaced by the contractor shall become the property of the Government.
- The rental rate specified in the contract is in effect for the duration of the contract, excluding periods of seasonal or other work shut downs.
- The laboratory shall be used only for testing materials for a specific contract.

Upon completion of the work, the contractor should clean the equipment and trailer. All equipment should be properly stored and secured for the transport of the trailer to the FLH office. Any damage that occurs prior to the trailer being received at the FLH office will be handled according to the contract.

9.2.3 Equipment Calibration

Use only equipment that has been calibrated or verified for the specific test and meets the applicable testing requirements of the contract. Equipment will be calibrated or standardized in accordance with national, FLH Standards, State Highway Agency (SHA), industry standard, or Standard Accreditation Programs.

Prior to the beginning of sampling and testing on a project, the Project Engineer should inspect and document the acceptability of the sampling and testing equipment that will be used on the project.

All necessary equipment should be marked with a tag indicating the date of last inspection, inspector, and calibration number. Checking and monitoring of the equipment during the life of the project should be performed and documented by the contractor to ensure equipment is performing properly.

9.2.4 Equipment Calibration Documentation

The Project Engineer should obtain the following documentation supporting the calibration or verification of all necessary equipment prior to actual sampling and testing. The documentation should be on file.

1. Description of the equipment calibrated or verified, including model number, serial number, or other acceptable identification.
2. Identification of the individual performing the calibration or verification.
3. Identification of the calibration or verification procedure used.
4. Current calibration or verification date and the next due date.
5. Detailed report of calibration results of the work performed, i.e. dimension, mass, force, frequency, temperature, time etc.

The Project Engineer may check equipment to verify condition and calibration. If at any time, it is suspected that the test equipment is not functioning properly or is not calibrated within specification limits the Project Engineer should contact the FLH materials staff to determine what corrective action should be taken.

Under no circumstances should test results obtained using faulty equipment be accepted.

9.3 Contractor's Responsibilities

The contractor is responsible for constructing concrete pavements, structures, and various associated components to the requirements provided in the contract. As part of these requirements, the contractor is to control the quality of the materials provided and the construction process to ensure compliance. The contractor's submitted quality control plan should address sampling, testing, and inspection work that will be accomplished to check and validate the quality of workmanship and material components supplied.

There are various established procedures referenced in the specifications for concrete pavements and structures regarding furnishing products and materials. The contractor needs to follow these procedures to ensure that the material components produced or supplied meet the required specifications; and when combined, the resulting mixture meets the contract specifications. Therefore, the responsibilities for quality cover three general areas; individual supplied material (i.e. cement, aggregate, admixtures, steel, etc.), combined material requirements (i.e. concrete mix design, etc.), and finished product (i.e. placement, curing, strength, etc.). As a general list, the requirements of the contractor include:

- Provide an inspection system for processes and materials quality control.
- Submit and follow the written quality control plan detailing the inspection system.
- Monitor processes to ensure materials provided and work accomplished comply with contract requirements.
- Sample materials to be tested according to the proper sampling method.
- Testing and providing aggregate meeting quality requirements.
- Quality control of aggregate during production to ensure continued compliance with the specifications.
- Proper submittal for mix designs.
- Providing material components and split samples to the Government for verification testing, when requested.
- Monitor construction processes and verify on-site quality and consistency with proper testing.
- Provide appropriate documented test results.
- Provide appropriate certifications (either production or commercial) as established in the contract for supplied material.

- Provide consistent delivery methods for construction (i.e. shotcrete placement, pile driving, drilled shaft construction, etc.)

The contractor needs to provide information and test results according to the timeframes and formats stated in the contract. Distribution of the test reports or certifications should be according to the contract and quality control plan and contain the appropriate information to verify the quality of the material provided.

9.4 Government's Responsibilities

The Project Engineer or designated representative will review the test results and certifications for contract compliance. If clarification or additional expertise is required, the Division Materials Engineer should be contacted.

The Project Engineer or designated representative will also be present to witness all required split samples taken for the Government. In addition, samples that are taken and tested solely by the Government for acceptance, such as concrete strength specimens should be identified in some manner to verify the authenticity. Witnessing and proper sample identification are critical in maintain proper custody of the material samples. Any split samples or samples taken for testing and acceptance by the Government should be secured and immediately be placed in Government control. The Project Engineer needs to be aware of the contractor's operations and be available to witness the sampling, splitting, and testing activities.

As a general list, the responsibilities of the Government include:

- Review the quality control plan for completeness.
- Review aggregate quality test result and/or obtain Government samples for testing.
- Review all material data to ensure compliance with the contract requirements.
- Review and approve submitted mix designs.
- Review test methods, equipment, and protocols with contractor testing personnel.
- Ensure pre-work conferences occur and are attended by appropriate personnel.
- Obtain proper product certifications prior to incorporating material into the work.
- Ensure proper sampling and testing methods are used to evaluate materials and quality during construction.
- Verify proper sampling and testing techniques have been employed at the required frequencies.

- Witness on-site testing of concrete to ensure delivered material is in conformance with the contract.
- Monitor construction processes to ensure material and workmanship conform to contract requirements.
- Review batch tickets to ensure proper mix proportioning.
- Coordinate investigative process for any significant non-compliance issue, in particular low compressive strength concrete.

There are numerous resources available to project personnel to assist in the performance of these tasks. Trade organizations such as ACI, ACPA, and PCA provide excellent technical guidelines and documentation that can help project personnel in the execution of their duties. Additionally, the Division Materials Engineer will provide guidance and assistance to the project should the need arise.

9.5 Materials Certification Acceptance

Proper materials certifications pertaining to each applicable material type and source must be obtained by the Project Engineer and retained in project files. As part of the process for approving a Contractor's mix design, representative certifications should be submitted to the Division Materials Engineer for review and recommendation for approval along with the concrete mix design, form FHWA 1608. The FP requires hydraulic cement production certifications for structural concrete, prestressed concrete, shotcrete and minor concrete. Also, individual materials standards that have been specified in the contract should be referenced. They set forth additional detail pertaining to Contractor submittal of valid manufacturer certifications including required statements, test data and frequency. Certifications must be signed and dated as well as certify that the specified requirements of applicable standards and project specific special contracts requirements have been met. Table 16 summarizes individual concrete materials requiring manufacturer certifications as required in the FP in conjunction with the applicable materials standard to which they must be certified.

Table 16: Required Concrete Material Certifications.

Material	Test Method	Frequency
Hydraulic Cement: Portland Cement Blended Cement	AASHTO M 85 AASHTO M 240	1 per shipment 1 per shipment
Mineral Admixtures: Fly Ash Ground granulated blast furnace slag Silica Fume (microsilica)	AASHTO M 295 AASHTO M 302 AASHTO M 307	1 per shipment 1 per shipment 1 per shipment
Water	AASHTO M 157	1 for each source
Coloring Agents	ASTM C979	1 per type
Chemical Admixtures: Air-entraining Water-reducing, Set-controlling, Hydration stabilizing	AASHTO M 154 AASHTO M 194	1 per shipment 1 per shipment per admixture used

The FP further notes that material accepted by certification may be sampled and tested at any time to verify the properties stated as part of the certification. Sampling of concrete materials should be in accordance with the procedures and sample sizes noted in Table 17.

In general, it is good practice to obtain one sample with each shipment of material. These samples should be retained on the project until final project acceptance or provided to the Division Materials Engineer when required for the purpose of Government testing to verify conformance to the contract specifications.

Table 17: Material Sampling Specifications and Sample Sizes.

Material Component	Test Method	Sample Size
Hydraulic Cement:		
Portland Cement	AASHTO R 71	Representative of not more than 100 tons (90 Mg): Two grab samples at ≥ 10 lb (5 kg) each
Blended Hydraulic Cement	AASHTO R 71	Representative of not more than 100 tons (90 Mg): Two grab samples at ≥ 10 lb (5 kg) each
Mineral Admixtures:		
Fly Ash	ASTM C311	Representative of not more than 400 tons (360 Mg): One grab sample at ≥ 4 lb (2 kg) each
Ground granulated blast-furnace slag	AASHTO M 302	Representative of not more than 125 tons (115 Mg): Two grab samples at ≥ 5 lb (2 kg) each. Remove a 12-in. (300 mm) layer of slag in a hole before sampling.
Silica Fume (microsilica)	AASHTO M 307	Representative of not more than 110 tons (100 Mg): 2 grab samples at ≥ 2 lb (1 kg) each.
Water:		
Compressive strength	AASHTO M 157	As required for pertinent tests: liquid grab samples at ≥ 1 pt (0.5 L) each.
Time of set	AASHTO T 106	
Chloride as Cl	AASHTO T 131	
Sulfate as SO ₄	ASTM D512	
Alkalis	AASHTO T 290	
Total Solids	AASHTO T 105	
	ASTM C1603	
Aggregates	AASHTO R 90	Coarse Aggregate: 150 lb (75 kg)
(Coarse and Fine)		Fine Aggregate: 100 lb (50 kg)
Aggregate Sample Splitting	AASHTO R 76	Samples are properly split and reduced in size by use of sample splitters or quartering

Chemical Admixtures:		
Air-entraining	AASHTO M 154	Representative of not more than 2500 gal (9500 L): 3 liquid grab samples at $\geq$ qt (1 L) each
Water-reducing, Set-controlling	AASHTO M 194	Representative of not more than 2 tons (2 metric tons): 4 non-liquid tube samples at $\geq$ lb (1 kg) each Representative of a unit shipment or a single production lot: 3 liquid grab samples at $\geq$ 1 pt (0.5 L) each Representative of not more than 2 tons (2 Mg): 4 non-liquid tube samples at $\geq$ 2 lb (1 kg) each

As always, special contract requirements should be reviewed to ascertain if additional materials certifications and samples are required on a project-specific basis.

Appendix A: Form References

Form references for use in the testing of concrete and associated materials.

- Form FHWA 1600C – Request for Laboratory Tests (CFL)
- Form FHWA 1600E – Requests for Laboratory Tests (EFL)
- Form FHWA 1600W – Requests for Laboratory Tests (WFL)
- Form FHWA 1606 – Minor Portland cement concrete mix design trial batch summary
- Form FHWA 1608 – Concrete mix design submittal
- Form FHWA 1621 – Worksheet for sieve analysis of fine and coarse aggregate
- Form FHWA 1627 – Worksheet for sieve analysis of fine and coarse aggregate
- Form FHWA 1638 – Worksheet for determining concrete batch moisture/absorption corrections

FHWA Forms

The most current version of FHWA forms are found at the following website:

<https://flh.fhwa.dot.gov/resources/materials/>

Documentation and Record-Keeping

Maintain detailed records of all sampling, testing, certifications, and acceptance decisions. Keep contractor certifications, laboratory reports, test cylinder records, curing photographs, and strength test results organized by location and placement date. These records establish project compliance and provide evidence if strength results are questioned.

If low strength test results occur, follow the investigation and dispute resolution procedure. This may involve core sampling of the actual structure, structural analysis, or third-party testing to validate results. Documentation quality directly supports dispute resolution.

Appendix B: Sample Quantities Guide

Division 500					
	Material / Product	Characteristic	Sampling Method	Minimum Field Sample lbs (kg)	Minimum Split Size to FLH Lab lbs (kg)
Section 501	Aggregate source quality	Coarse aggregate: Alkali-silica Reaction (ASR) and AASHTO M 80 Gradation, AASHTO M 43	AASHTO R 90	—	200 (90)
		Fine aggregate: Alkali-silica Reaction (ASR) and AASHTO M 6 Gradation, AASHTO M 6	AASHTO R 90	—	25 (10)
	Structural concrete	Compressive Strength	AASHTO R 60 and AASHTO T 23	—	1 set of cylinders
Section 502	Aggregate source quality	Coarse aggregate: Alkali-silica Reaction (ASR) and AASHTO M 80 Gradation, AASHTO M 43	AASHTO R 90	—	200 (90)
		Fine aggregate: Alkali-silica Reaction (ASR) and AASHTO M 6 Gradation, AASHTO M 6	AASHTO R 90	—	25 (10)
	Structural concrete	Compressive Strength	AASHTO R 60 and AASHTO T 23	—	1 set of cylinders
Section 552	Aggregate source quality	Coarse aggregate: Alkali-silica Reaction (ASR) and AASHTO M 80 Gradation, AASHTO M 43	AASHTO R 90	—	200 (90)
		Fine aggregate: Alkali-silica Reaction (ASR) and AASHTO M 6 Gradation, AASHTO M 6	AASHTO R 90	—	25 (10)
	Structural concrete	Compressive Strength	AASHTO R 60 and AASHTO T 23	—	1 set of cylinders
Section 553	Prestressed concrete	Compressive Strength	AASHTO R 60 and AASHTO T 23	—	1 set of cylinders
Section 566	Aggregate source quality	Coarse aggregate: Alkali-silica Reaction (ASR) and AASHTO M 80 Gradation, AASHTO M 43	AASHTO R 90	—	200 (90)
		Fine aggregate: Alkali-silica Reaction (ASR) and AASHTO M 6 Gradation, AASHTO M 6	AASHTO R 90	—	25 (10)
	Shotcrete (Production)	Permeable void volume, Boiling absorption, Compressive Strength	AASHTO T 24	—	Cores from production panels

Appendix C: Pre-Concreting Meeting Agenda

PRE-CONCRETING MEETING AGENDA

PROJECT: _____

DATE: _____

1. Introduction and Titles (please sign sheet)
 - a. Contractor's Personnel
 - b. Federal Highway Administration Personnel
 - c. Suppliers/subcontractors
 - d. Other Agencies
 - e. Other
2. Purpose of the meeting
 - a. To discuss standard specification and special contract requirements as they pertain to structural concrete Item 552 and drilled shafts Item 565.
3. Schedule of work
 - a. Proposed schedule for concrete work
 - b. Work hours/days
4. Review approved concrete mix design/proportioning
 - a. Review/discuss all mix design classes of concrete for structural concrete
 - b. Methods of proportioning, cement, water, aggregates, additives (Subsection 552.06)
 - c. Allowable tolerances for proportioning (Subsection 552.05)
 - d. Calibrated batching equipment (Subsection 552.06)
 - e. Batch tickets (Subsection 552.09)
5. Quality Control
 - a. Designated QCS for concrete sampling and testing
 - b. Batch corrected weights, tickets
 - c. Gradations, moisture and FM-CA & FA, —minimum testing requirements
 - d. Truck mixing—revolutions 70 min and 100 max.
 - e. Delivery
 - i. Time restriction
 - ii. Use of set retarders
 - iii. Retempering
 - f. Slump, air content, unit weight and temperatures—sampling frequency and methods
 - g. Compressive strength:
 - i. acceptance—1 set per ____ cubic yards (meters)
 - ii. shipping cylinders
 - h. Discuss proper concrete cylinder curing
 - i. Discuss statistical evaluation (Subsection 106.05)

- j. Reporting strengths
 - k. Discuss acceptance for incidental items accepted by certification—rebar, cement, additives, steel, etc.,
6. Placing
- a. False work approval (Section 562)
 - b. Cold/hot weather plan—monitor temperatures for aggregates, water, placement, protecting, curing and temperature monitoring (Subsection 552.10)
 - c. Discuss pumping(loss of air and slump) if applicable (Subsection 552.11)
 - d. Vibrator/vibrating requirements (Subsection 552.11)
 - e. Delivery rate
 - f. Maximum drop
 - g. Rebar placement
7. Finishing (Subsections 552.14 and 552.16)
- a. Striking-off and floating
 - b. Straight edging
 - c. Texturing (Subsection 552.14)
 - d. Deck finishing machine (Subsection 552.14)
8. Curing (Subsection 552.15)
- a. Curing times
 - b. Water method
 - c. Form method
 - d. Membrane method
 - e. Deck curing
9. Loading
- a. Form Removal (Subsection 562.08)
 - b. Loads on deck and other members (552.18)

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