An *IPRF* Research Report

Innovative Pavement Research Foundation

Airport Concrete Pavement Technology Program

Report IPRF-01-G-002-06-2

<u>Handbook</u> *for* Proportioning Fly Ash as Cementitious Material in Airfield Pavement Concrete Mixtures

Programs Management Office
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Handbook *for* Proportioning Fly Ash as Cementitious Material in Airfield Pavement Concrete Mixtures

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Fly ash is a finely divided spherical residue resulting from the combustion of ground or pulverized coal in thermal power plans. It is used as a partial replacement to cement in concrete for the following reasons:

- Fly ash generally can make concrete more workable and can improve finishing.
- Fly ash can reduce the heat of hydration and delay set times, reducing thermal stresses in early age concrete.
- Fly ash can increase the ultimate strength of concrete.
- Fly ash can make concrete more durable, particularly to mitigate alkali-silica reactivity (ASR) and sulfate attack.
- Fly ash reduces the CO_2 footprint of concrete and reduces the embodied energy.
- Using fly ash in concrete reduces disposal in landfills and address the issue of high potential hazard to groundwater contamination.
- Fly ash can reduce the cost of concrete depending on the hauling distance from the source of production.

However, the mere inclusion of fly ash in a concrete mix does not guarantee enhanced performance. On the contrary, when careful attention is not paid in selecting the right type and dosage, fly ash may prove to be detrimental. Some challenges that might be encountered include problems with finishing, rapid set, poor strength gain, reduced air content, potential for ASR, and potential for scaling.

The benefits derived from using fly ash depend on its mineralogical and chemical properties and the quantity of fly ash replacement used in the concrete mix (Malhotra & Mehta, 2008; Thomas, 2007). The performance also depends on the other constituents of the mix and the environmental conditions that the pavement is subjected to. In other words, the same fly ash used in two different projects can produce distinctly different results depending on the project conditions, the fly ash replacement level used, and the properties of the other concrete mix design constituents. Effective specifications and proper guidelines for the use of fly ash are therefore very critical for achieving the desired performance level.

Current Specifications for Using Fly Ash in Airfield Paving Mixes

Specification Item P-501 for portland cement concrete (PCC) pavement in the current Federal Aviation Administration (FAA) Advisory Circular (AC) 150/5370-10E (USDOT FAA, 2009) allows the use of locally available materials for PCC mixes and specifies the expected performance requirements. Item P-501 sets limitations on aggregate reactivity and cement alkalinity to control the potential for ASR problems. Fly ash is expected to meet the requirements of ASTM C 618 Class C, F, or N, and the loss of ignition (LOI) is limited to 6 percent for Classes F and N. Additionally, the Class C fly ash materials are disallowed for projects with ASR potential.

The P-501 specification refers to the Portland Cement Association's (PCA) manual for mix design (PCA, 2008) procedures but provides general proportioning and strength requirements. A minimum 28-day flexural strength of 600 psi is required for most projects. However, for projects with critical opening time requirements, a strength requirement for the designated age is specified. A minimum cementitious material content of 564 lb/yd^3 and maximum water to cementitious materials content of 0.45 is specified. Fly ash is permitted for partial replacement of cement and can range between 15 and 30 percent by weight of the total cementitious content. If combined with ground granulated blast furnace slag, the replacement is limited to 10 percent.

The Unified Facilities Guide Specifications (UFGS) for concrete airfields and other heavy-duty pavements (USACE, 2008) uses the ASTM C 618 classification for fly ash. It also suggests the use of fly ash replacement for cementitious materials when sulfate bearing soils or water are encountered along with the use of Type II or V cements. It disallows the use of Class C fly ash as well as any fly ash with an LOI exceeding 3 percent. For ASR mitigation, the calcium oxide content of the fly ash and the total equivalent alkali content are limited to 13 and 3 percent, respectively. Fly ash replacement levels are limited to a maximum of 35 percent and to a minimum level of 15, 20, or 25 percent for sums of principal oxides exceeding 70, 80, and 90 percent. Strength and mix design requirements are comparable to the P-501 specifications.

Neither specification details the basis for the fly ash replacement requirements. Within the confines of the P-501 or UFGS specifications, fly ashes with a wide range of mineralogical, chemical, and granulometric properties can be used in a concrete mix design that can have little or no impact on the performance achieved on field. Each project and the materials selected for PCC mix design create a unique combination of parameters that needs to be fully accounted for in selecting fly ash source and replacement levels. From the standpoint of workability, strength, and durability performance, the effect of mineralogical, chemical, and particle size properties should be considered in mix optimization. Additionally, appropriate tests are needed to ensure constructability and long-term performance.

1.2 FLY ASH AND THE ENVIRONMENT

The concrete industry is believed to contribute to 7 percent of the CO_2 emissions, both from energy use and from the decomposition of the raw materials in the production of cement, estimated to be about 0.37 and 0.53 ton of CO_2/ton of clinker, respectively. Therefore, nearly a ton of CO_2 is produced for each ton of cement. The concrete industry views the potential for cement replacement with fly ash as a valuable tool to achieve greenhouse gas reduction goals. The benefits are twofold— it diverts coal power generation residue from landfills to beneficial use, and it reduces the use of cement. According to the annual survey results published by the American Coal Ash Association (ACAA, 2009), for the year 2009 the following statistics are offered:

- 63 million tons of fly ash was produced.
- 25 million tons were used in various applications.

- 10 million tons were used in concrete and concrete products, and about 2.5 million tons were used in blended cements and raw feed for clinker.

Environmental Protection Agency's Regulations on Fly Ash

Fly ash is one of several coal combustion residues (CCRs). CCRs also contain contaminants such as mercury, cadmium, and arsenic, which can pose a threat to the environment and public health in general, particularly through leaching into groundwater.

In 1980 the US Congress enacted the Beville Amendment, which exempts fly ash from being defined as a hazardous waste. Congress required the Environmental Protection Agency (EPA) to study fly ash and make a determination as to whether fly ash warrants regulation under Resource Conservation and Recovery Act (RCRA) Subtitle C, Hazardous Waste Regulation. Under the Beville Amendment, the EPA was required to consider eight factors in making its determination:

- Source and volumes of fly ash generated per year.
- Present disposal and utilization practices.
- Potential danger, if any, to human health and the environment from the disposal and reuse of fly ash.
- Documented cases in which danger to human health or the environment from surface runoff has been proved.
- Alternatives to current disposal methods.
- The cost of such alternatives.
- The impact of the alternatives on the use of coal and other natural resources.
- The current and potential use of fly ash.

In 1993 and 2000, the EPA determined that fly ash did not warrant regulation as a hazardous waste.

In December, 2008, an earthen dike of the fly ash pond at the Tennessee Valley Authority's Kingston Power Plant gave way and 5.4 million yd^3 of ash flowed out and engulfed 26 homes. There was no loss of human life, but clean up costs were estimated to exceed $1 billion. An earlier release at the Martin's Creek Power Plant in Pennsylvania in 2005 resulted in 0.5 million yd^3 flowing into the Delaware River. Clean up costs were $37 million.

In June 2010, the EPA published a proposal to regulate fly ash disposal under the RCRA. The proposal included a comment period until November 2010. This proposal contained two approaches to regulate disposal—listing fly ash as a special waste subject to RCRA Subtitle C, Hazardous Waste Regulation, or providing minimum national standards for State regulation under Subtitle D, Solid Waste Regulation. Under either approach the beneficial use of fly ash in concrete would be exempt from regulation.

After the proposed ruling and comment period, the EPA has not modified the existing Bevill exemption for beneficial use. Currently, there exist no changes to federal regulations that limit the use of fly ash in concrete.

1.3 PURPOSE AND SCOPE OF THE HANDBOOK

The handbook is one of three documents developed under the Innovative Pavement Research Foundation (IPRF) project IPRF-01-G-002-06-2. The research report (Rao, et al., 2011a) describes the technical effort, and the mix optimization catalog is the recommended protocol for proportioning fly ash in concrete mix designs. The catalog (Rao, et al., 2011b) provides the most likely range(s) of fly ash replacement levels, mix design components, admixtures, and curing practices for project-specific conditions. It also contains the standard tests that need to be performed for the recommended mix design within certain project-specific conditions:

- Deicer exposure – Yes/No.
- Aggregate reactivity – Reactive/Non-reactive Aggregates.
- Cement type – High Alkali/Low Alkali Cement.
- Opening time requirements – Critical/Non-critical.
- Paving weather – Cool/Moderate/Hot.

This handbook provides contractors, concrete producers, and engineers an understanding of fly ash as a material and the impacts of incorporating fly ash in concrete. It describes how the chemical and mineralogical properties of fly ash can affect concrete properties, thereby affecting the workability, strength, and durability of the concrete. It also introduces the protocol recommended in the mix optimization catalog and presents case studies validating the catalog.

Mix optimization, within the framework of this guide, offers the contractor and concrete producer the flexibility to select the best combination of materials, mix proportioning methods, and construction practices to satisfy the project performance criteria. It enables using local materials and/or evaluating the cost-effectiveness of hauling fly ash from distant sources that may be necessary to meet project specifications. These guidelines therefore can be used to develop performance specifications but might pose certain limitations with prescriptive specifications.

Mix optimization typically involves evaluating various percent replacements of a given fly ash and/or evaluating various fly ash sources. These guidelines do not limit the total cement content that may be adjusted during the iterative process to meet specification requirements. P-501 specifies only a *minimum* total cementitious content, not a maximum cementitious content. These guidelines provide a contractor/producer the utmost ability to be innovative with mix designs and still vary the total cementitious content as necessary to meet project performance requirements. However, increasing the total cement content of the mix might produce other undesirable effects, such as increased shrinkage and increased heat of hydration, which need to be considered by the user. As such, these guidelines do not encourage the use of higher cement contents.

From a sustainability standpoint, the use of fly ash generally reduces the CO_2 footprint of the concrete. The guidelines are indicative of the lower and upper bounds of fly ash replacement levels suitable for a project. However, the CO_2 footprint is controlled by the total cement content and not the total cementitious material content. For example, a concrete with a 50 percent fly ash replacement level using 400 lb/yd^3 of cement and a total cementitious content of 800 lb/yd^3 has a higher CO_2 footprint than a concrete with a 25 percent fly ash replacement level using 375 lb/yd^3 of cement and a total cementitious content of 500 lb/yd^3. The mix optimization catalog, therefore, does not necessarily lead to minimizing the CO_2 footprint of the selected concrete mix.

This document supplements FAA AC 150/5370-10E in selecting PCC mix constituents and mix proportions. It guides the user to the appropriate fly ash source and fly ash replacement levels necessary for the concrete mix to provide the expected level of performance. This guide does not purport to address the issues of rigid pavement design and construction in totality. Only those aspects of PCC mix design that interact with selection of type and quantity of fly ash are addressed.

Finally, the mixes considered in the development of the guidelines are limited to those that incorporate cement and only fly ash as a supplemental cementitious material (SCM). The recommendations do not apply to ternary mixes or mixes with other SCMs such as slag, silica fume, and blended cements.

1.4 ORGANIZATION AND USE

This handbook is divided into four chapters. The introductory chapter provides the necessary background for guidance when using fly ash in concrete mixes and details the scope of the document.

Chapter 2 discusses the properties of fly ash as an SCM. Specifically, it lists the chemical and mineralogical properties of fly ash, their effects on concrete mix designs, fresh concrete properties, and hardened concrete properties. This chapter also provides information about the myths and benefits of using fly ash, construction difficulties that using fly ash can create, and measures to prevent such problems. This chapter will help a user establish critical elements to optimizing a concrete mix that incorporates fly ash to meet workability, durability, finish, cost, and strength requirements.

Chapter 3 gives details about the guidelines for optimizing a concrete mix design using fly ash. The chapter refers to the mix optimization catalog that was developed to summarize the guidelines for specific project cases.

Chapter 4 presents case studies that demonstrate the effectiveness of the guidelines developed and illustrates the applications of the guidelines.

1.5 DEFINITION OF KEY TERMS

The handbook makes several references to fly ash *replacement*. The term *replacement* is not synonymous with *substitution*.

Fly ash *replacement* is the fly ash content in the mix, which represents a certain percentage of the total cementitious content in the mix design, not the total cement content in the mix. For example, for a baseline mix with 550 lb/yd^3 of cement, a 20 percent fly ash replacement results in using a cement content of 440 lb/yd^3 supplemented with 110 lb/yd^3 of fly ash. Fly ash replacement results in a reduction of cement content but does not change the total cementitious content of the mix.

Fly ash *substitution*, on the other hand, refers to the removal of a certain amount of cement combined with a rate of addition of fly ash. For example, the cement content may be reduced from 550 lb/yd^3 to 440 lb/yd^3 of cement and supplemented with of 138 lb/yd^3 of fly ash when a substitution rate of 1 to 1.25 is used. Fly ash substitution results in a reduction of cement content and may change the total cementitious content of the mix.

1.6 DISCLAIMER

This manual is neither a construction guidance specification nor a design tool. It does not provide detailed instructions on conducting specific design or construction-related activities. It does not constitute a standard, specification, or regulation. This handbook should not be used in lieu of a project specification. The requirements detailed in the project specifications will override this document.

CHAPTER 2. FLY ASH IN CONCRETE MIX DESIGN

2.1 FLY ASH PRODUCTION

Coal-fired power plants use pulverized coal, which typically is ground to fineness with 75 percent or more passing the No. 200 sieve (see Figure 1). Depending on the source and grade of coal, it consists of 10 to 40 percent non-combustible impurities. In the high temperature zone of a furnace, the volatile matter and carbon are burnt, leaving the non-combustible impurities to be carried by the flue gases in the form of ash. This travels through the combustion zone where the particles become fused. As the molten ash leaves the combustion zone, it is cooled rapidly (from about 1500 °C to 200 °C) and solidifies into spherical glassy particles. While a fraction of the fused matter agglomerates and settles to form the bottom ash, a majority of it "flies" out with the flue gas stream to be collected later as fly ash. Fly ash undergoes a sequence of processes to be separated from the flue gas. It passes through a series of mechanical separators followed by electrostatic precipitators. Fly ashes from modern thermal power plants do not require any further processing for use as a supplementary cementitious material.

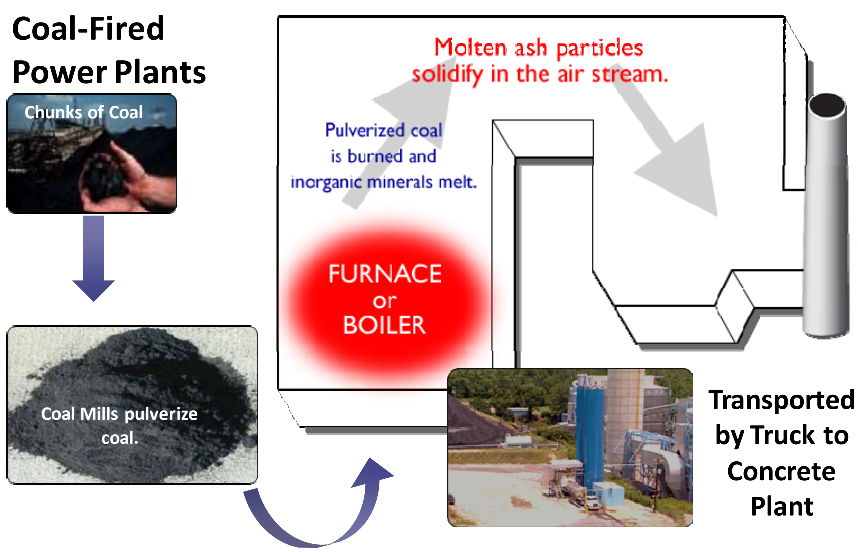

Figure 1. Fly ash is a by-product from coal fired power plants [Courtesy SEFA Group]

2.2 PROPERTIES OF FLY ASH

Fly ash is a complex, heterogeneous material consisting of glassy and crystalline phases. The glassy spheres and crystalline phases are not completely independent of one another and vary in their proportions, which makes fly ash a complex material to classify and characterize. Depending on the type and composition of the source coal used for combustion, the physical, chemical, and mineralogical characteristics of the fly ash may vary. Anthracite and bituminous coals are referred to as high rank coals, while lignite and sub-bituminous coals are referred to as low rank coals.

The basic chemical components of fly ash are similar to that in cement, but they vary in relative proportions. Irrespective of coal source, fly ash is composed of silica (SiO_2), alumina (Al_2O_3), ferrous oxide (Fe_2O_3), and calcium oxide (CaO). In addition to these oxides, MgO, SO_3, alkalis, and carbon are present in the fly ash.

The CaO content controls the reactivity of the fly ash. CaO often is referred to as the *lime* content or the *calcium* content by the industry in the context of chemical composition of fly ash. Fly ashes produced from the burning of sub-bituminous and lignite coals (low rank coals) contain more lime, often in excess of 10 percent and up to 35 percent. Fly ashes from bituminous or anthracite coal sources have a lower lime content, often below 10 percent. Figure 2 shows the distribution of calcium oxide content in fly ash sources from North America. Note that this information was compiled in 2007 and can vary in the future.

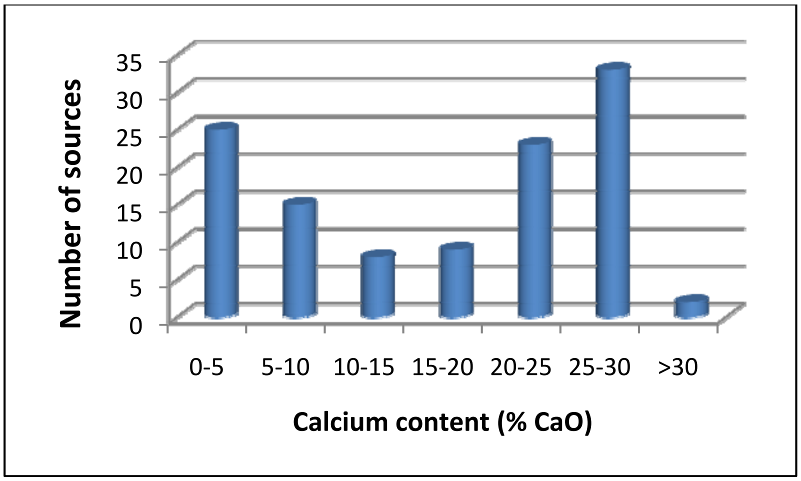

Figure 2. Distribution of calcium content in North American fly ash (Thomas, 2007)

In addition to the oxide level, the mineralogical composition of fly ash affects its reactivity. Fly ashes have a wide mineralogical composition, and the proportion of different minerals in fly ash depends on the source of coals. Crystalline minerals in low-calcium fly ashes usually consist of quartz, mullite, sillimanite, hematite, and magnetite. These minerals do not possess any pozzolanic properties. High-calcium fly ashes, on the other hand, contain quartz and cement minerals such as C_3A, calcium aluminosulfate, anhydrite, free lime, periclase, and alkali sulfates. All the crystalline minerals in high-calcium fly ash materials except quartz and periclase react with water, making these fly ashes more reactive. Some of them also tend to flash set. Additives such as gypsum have been used in concrete mixes to retard set.

The other important component of fly ash is its carbon content, which is a result of incomplete combustion of coal. The amount of unburnt carbon is expressed as the percentage LOI, and it depends on the system of combustion used in thermal plants. Fly ashes from modern thermal power plants tend to have very low LOI.

In summary, the source of coal and the coal burning process can vary the chemical composition of fly ash significantly. This fact is illustrated in Table 1, showing the chemical compositions of fly ashes from North America and listed by the source of coal. Table 2 shows the composition of various fly ashes for different classes of coals in the United States, as well as for typical cement. Note from Table 2 that chemical compositions vary to a much greater degree in fly ash than in PCC. So, the variability that can be expected by changing the cement source might have a smaller implication on concrete performance relative to a change in the fly ash source.

Table 1. Oxide analyses of some North American fly ashes (Malhotra & Mehta, 1996; 2008)

Source	Percent by mass								Classification	
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Alkalies	SO_3	LOI	ASTM Class	CSA Type
Bituminous	55.1	21.1	5.2	6.7	1.6	3.0	0.5	0.6	F	F
Bituminous	50.9	25.3	8.4	2.4	1.0	3.1	0.3	2.1	F	F
Bituminous	52.2	27.40	9.25	4.4	1.0	0.8	0.5	3.5	F	F
Bituminous*	48.0	21.5	10.6	6.7	1.0	1.4	0.5	6.9	F	F
Bituminous*	47.1	23.0	20.4	1.2	1.2	3.7	0.7	2.9	F	F
Subbituminous	38.4	13.0	20.6	14.6	1.4	2.4	3.3	1.6	F	CI
Subbituminous	36.0	19.8	5.0	27.2	4.9	2.1	3.2	0.4	C	CH
Subbituminous*	55.7	20.4	4.6	10.7	1.5	5.7	0.4	0.4	C	CI
Lignite	36.9	9.1	3.6	19.2	5.8	8.6	16.6	-	C	CI
Lignite*	44.5	21.1	3.4	12.9	3.1	7.1	7.8	0.8	C	CI
Max	55.7	27.4	20.6	27.2	5.8	8.6	16.6	6.9		
Min	36.0	9.1	3.4	1.2	1.0	0.8	0.3	0.4		
Average	46.5	20.2	9.1	10.6	2.3	3.8	3.4	2.1		

Note: Sources with "*" are Canadian sources and the rest are from the US

Table 2. Chemical composition of fly ash from various coal sources in the U.S. and for portland cement (Frohnsdorff & Clifton, 1981; Aïtcin, 2008)

Chemical Composition	Anthracite	Bituminous	Sub-bituminous	Lignite	Portland cement
SiO_2	47–68	7–68	17–58	6–45	18-24 (21)
Al_2O_3	25–43	4–39	4–35	6–23	4-8 (6)
Fe_2O_3	2–10	2–44	3–19	1–18	1-8 (3)
CaO	0–4	1–36	2–45	15–44	60-69 (65)
MgO	0–1	0–4	0.5–8	3–12	0-5 (2)
Na_2O	–	0–3	–	0–11	0-2 (1)
K_2O	–	0–4	–	0–2	0-2 (1)
SO_3	0–1	0–32	3–16	6–30	0-3 (1)

Finally, the granulometric properties of fly ash, such as the particle shape, fineness and particle size distribution including particle packing, affect the properties of fly ash concrete. Fly ash is a fine-grained material consisting mostly of spherical, glassy particles. Some ashes also contain irregular or angular particles. The particle shape depends on the nature and granulometry of the coal burned and on the combustion conditions in the power plant. The spherical shape of the fly ash particles produces a ball-bearing effect at the point of aggregate contact, thereby reducing the friction at the aggregate paste interface. This effect improves the fluidity of the cement paste.

Fly ash particles less than 10μm in size are pozzolanic, and those larger than 45μm show no pozzolanic activity. Fly ash from North American sources typically contains 40 to 50 percent particles smaller than 10μm and less than 20 percent particles larger than 45μm. The average size is generally in the 15 to 20μm range.

The proportion of finer particles (<45μm) in fly ash is the major factor in reducing the water demand, whereas the inclusion of larger fly ash particles (>45μm) has no effect on the water requirement. The use of coarser fly ash leads to a reduction in compressive strength for equal water to cementitious material (w/cm) ratios. This effect increases with decreasing w/cm ratio (Figure 3).

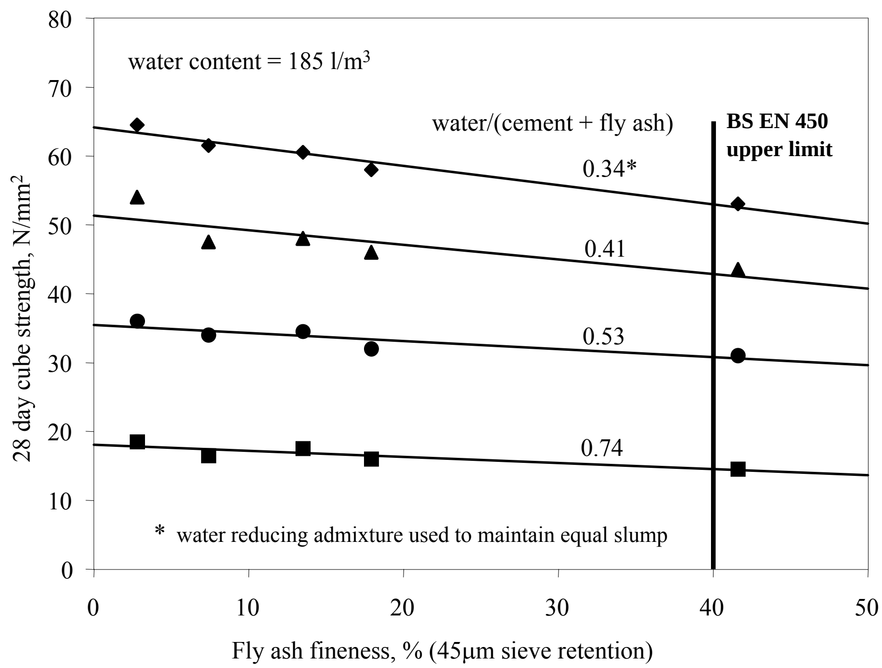

Figure 3. Relationship between fly ash fineness and 28 day strength (Dhir et al., 1998)

2.3 STANDARD PROCEDURES AND FLY ASH CLASSIFICATION

The two standard classifications adopted in North America are the ASTM and the Canadian Standards Association (CSA).

The ASTM Standard C 618 classifies fly ash based on its chemical composition, primarily the sum of the three principal oxides—SiO_2, Al_2O_3, and Fe_2O_3. The two primary types and requirements are as follows:

- Class F – $SiO_2 + AL_2O_3 + Fe_2O_3 \geq 70\%$.
- Class C – $SiO_2 + AL_2O_3 + Fe_2O_3 \geq 50\%$.

An additional class, Class N, includes raw or calcined pozzolans. The other requirements for the fly ash classes are shown in Table 3. The ASTM C 311 standard procedure is followed to test a fly ash material and generate results to compare against the ASTM C 618 requirements. A sample of ASTM C 311 test data is shown in Table 4 for a fly ash material that has been classified as Class C fly ash per ASTM C 618 requirements. (Note that the sum of principal oxides is above 50 percent but less than 70 percent.) This information typically is furnished by the fly ash vendor for each fly ash shipment and is provided by the contractor for mix design approval. This test also may be performed by the contractor for verification.

Table 3. ASTM C 618 chemical and physical specifications for fly ash classification

	Mineral Admixture Class		
Chemical Requirements	N	F	C
Silicon Dioxide, Aluminum Oxide, Iron Oxide ($SiO_2 + Al_2O_3 + Fe_2O_3$), min., %	70	70	50
Sulfur Trioxide (SO_3), max., %	4	5	5
Moisture Content, max., %	3	3	3
LOI, max., %	10	6[A]	6
Physical Requirements	N	F	C
Fineness: Amount retained when wet-sieved on 45 µm (No. 325) sieve, max., %[B]	34	34	34
Strength Activity Index[C] with Portland Cement at			
7-day, min. % control	75[D]	75[D]	75[D]
28-day min. % control	75[D]	75[D]	75[D]
Water Requirement, max., % control	115	105	105
Soundness Autoclave Expansion or Contraction, max., %[E]	0.8	0.8	0.8

[A] The use of Class F pozzolan containing up to 12% LOI may be approved by the user if either acceptable performance records or laboratory test results are made available.
[B] Care should be taken to avoid the retaining of agglomeration of extremely fine material.
[C] The strength activity index with portland cement is not to be considered a measure of the compressive strength of concrete containing the fly ash or natural pozzolan. The mass of fly ash or natural pozzolan specified for the test to determine the strength activity index with portland cement is not considered to be the proportion recommended for the concrete to be used in the work. Strength activity index with portland cement is a measure of reactivity with a given cement and may vary as to the source of both the fly ash or natural pozzolan and the cement.
[D] Meeting the 7-day or 28-day strength activity index will indicate specification compliance.
[E] If the fly ash or natural pozzolan will constitute more than 20% by weight of the cementitious material in the project mix design, the test specimens for autoclave expansion shall contain that anticipated percentage.

Note: Class N fly ashes are raw or calcined natural pozzolans.

Table 4. Sample report of fly ash testing which is a reference to use mix optimization catalog

SOURCE:	XYZ		
CONFORMANCE:	The sample meets the chemical and physical requirements listed below, as per ASTM C 618 for a **Class C fly ash**		
TEST METHOD ASTM : C 311		**ASTM C 618 REQUIREMENTS**	
		CLASS F	**CLASS C**
CHEMICAL COMPOSITION			
Silicon Dioxide (SiO_2), %	39.8		
Aluminum Dioxide (Al_2O_3), %	19.3		
Iron Oxide (Fe_2O_3), %	7.1		
Total	66.2	70 min	50 min
Calcium oxide (CaO), %	20.4		
Magnesium oxide (MgO), %	4.6		
Sulfate (SO_3), %	1.4	5.0 max	5.0 max
Moisture content, %	0.11		
Loss on ignition, %	0.25	6.0 max	6.0 max
PHYSICAL REQUIREMENTS			
Fineness: Retained on #325 sieve, %	6.0	34 max	34 max
Density, g/cm	2.67		
Strength Activity Index	-		
7 days, % of control	100	75 min at 7 or 28 days	75 min at 7 or 28 days
28 days, % of control	106		
Water Requirement, % of control	96		
Soundness, %	±0.05	±0.8 max	±0.8 max

The CaO content is determined in the ASTM C 311 procedure. Class C fly ash generally contains more than 20 percent CaO, whereas CaO in Class F fly ash typically ranges from 1 to 12 percent. Class F fly ash is normally produced from burning anthracite or bituminous coal and Class C fly ash is normally produced from lignite or sub-bituminous coal. Also, Class F ashes are pozzolanic while Class C ashes are both hydraulic and pozzolanic.

Other points regarding ASTM C 618 include the following:

- Routine quality control (QC) of fly ash performed based on ASTM C 618 determines the oxides of the ash. The mineralogical composition is not determined in routine QC tests.
- While the calcium oxide content is determined in a fly ash characterization test under ASTM C 311, the C 618 standard does not consider the quantity of calcium oxide in the classification.
- Routine QC of fly ash only determines the retention of 45 μm sieve based on ASTM C 618. The actual distribution of fly ash particle size rarely is known.

CSA classifies fly ash into three categories based on the CaO content and LOI, as shown in Table 5. As of April 2010 CSA 3001 revisions, the CaO of Type F fly ash has been limited to 15 percent. The advantage over the ASTM standards is that the CaO content may be considered in developing specifications.

Table 5. Classification of fly ash based on Canadian standards (prior to 2010)

Type	CaO, %	LOI, %
F	<8	8 max.
CI	8 to 20	6 max.
CH	> 20	6 max.

The ASTM and CSA specifications have an overlap across the categories, but for most part, there exists a correlation between the CaO content and the $SiO_2 + Al_2O_3 + Fe_2O_3$, as shown in Figure 4 for classifications prior to April 2010. CSA Type CI fly ashes overlap into both ASTM Class C and F ashes. This also is observed in the sample of North American fly ash sources shown previously in Table 1.

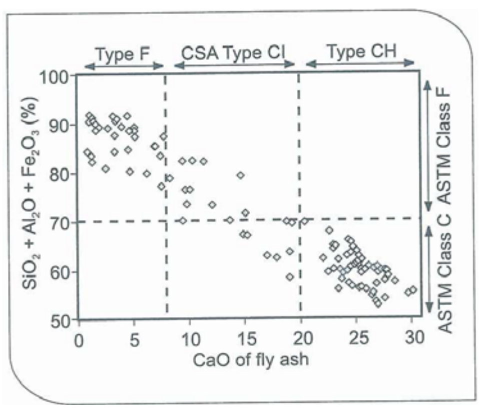

Figure 4. Comparison of ASTM and CSA specifications for North American fly ash sources (Thomas, 2007)

2.4 EFFECTS OF FLY ASH IN CONCRETE

Fly ash can affect various concrete properties, ranging from its rheological characteristics during the mixing stage to the long-term strength and durability during the life of the pavement structure. When fly ash is incorporated in a concrete mix, adequate testing is necessary to verify that the performance requirements are satisfied. This typically will involve several trial batches to select the fly ash source and/or to determine the optimum fly ash replacement level.

The effects of fly ash on concrete properties are summarized here. Details of the physical and chemical processes involved are provided in the research report (Rao et al., 2011a). This section identifies the interaction effects of various fly ash properties and mix design parameters and their impact on concrete properties.

2.4.1 Fresh Concrete Properties

Workability and Water Demand

The spherical shape of fly ash particles and their fineness affect the rheological properties of concrete, primarily by improving workability and reducing water demand. The spherical shape of the particles reduces the inter-particle friction. Additionally, they improve the particle packing in the system and act as excellent void fillers. Thus, concrete mixtures containing fly ash generally require less water content than mixes without fly ash for equal workability. The water demand can be reduced by as much as 20 percent (see Figure 5). This also reduces bleeding in fresh concrete. However, the carbon content absorbs a larger quantity of water. Therefore, the use of fly ash with low LOI, typically Class C fly ash, improves workability and reduces bleeding.

- *Use a low w/cm ratio to take advantage of improved workability in fly ash mixes.*
- *Use fly ash with low LOI if workability is important.*
- *Reduced water content also reduces bleeding.*

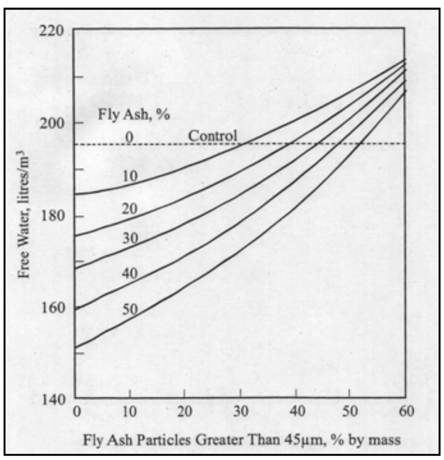

Figure 5. Effect of the proportion and particle size of fly ash on water demand for equal workability of concrete (Owen, 1979)

Test Methods to Verify Performance

- Test for slump - ASTM C 143
- Test for bleeding of concrete - ASTM C 232

Set Time

The cement hydration reaction produces calcium silicate hydrate (C-S-H) and calcium hydroxide (CH). C-S-H is primarily the glue that holds the cement paste together while CH is still soluble. C-S-H contributes to strength and impermeability and is therefore desirable. CH, on the other hand, is associated with lower strength and durability problems and is therefore less desirable. A pozzolanic material reacts with the CH (produced from cement hydration) and converts it to C-S-H which improves the strength and impermeability of the concrete paste and concrete. Hence, the set time and strength gain is prolonged to accommodate the pozzolanic reaction.

- *Use set accelerating admixture to reduce set time.*
- *Use elevated curing temperatures to accelerate set.*
- *Use gypsum in mix design to address flash set.*
- *Use higher than normal dosage of calcium sulfate in cement blends to increase rate of reaction.*

Generally, Class F fly ash replacement slows the setting time of concrete for comparable cementitious material content. However, the apparent delay in set time is not due to the addition of fly ash; instead, it is because of the secondary influence of dilution of cement (reduced cement content) for the same total cementitious content.

Class C fly ashes have shown mixed behavior in setting characteristics of concrete depending on its composition. They might prolong set times, but they may show a tendency for rapid set. They also may delay set times up to a threshold fly ash replacement level but reverse to a flash set if the replacement level is increased any further.

Test Methods to Verify Performance

- Test for time of setting of concrete – ASTM C 403

Air Content

Air content is influenced by the LOI of the fly ash. Concrete with fly ash requires more air-entraining admixture than concrete without fly ash. Also, concretes containing Class C fly ash (low LOI) generally require less air-entraining admixture than those with Class F fly ash (high LOI).

- *Increase air entraining agent dosage as needed.*
- *Important for free-thaw climates.*

Test Methods to Verify Performance

- Test for air content in fresh concrete – ASTM C 138 or C 173
- Test for air content in hardened concrete – ASTM C 457

Plastic and Autogeneous Shrinkage

Shrinkage is related to the water content in the mix as well as the pore structure. Since concrete with fly ash uses less water in the mix, plastic shrinkage potential is reduced; this is achieved if the mix uses less water and if adequate curing is provided. However, denser pastes having discontinuous pore structures undergo higher autogeneous shrinkage.

- *Reduce water content to take advantage of improved workability.*
- *Provide extended curing to control shrinkage.*

Poor curing conditions could be more detrimental to the compressive strength development of fly ash concrete as compared to ordinary PCC. In large part, this can be attributed to the curing required during the delayed pozzolanic reaction of fly ash, much beyond the peak activity in cement particles.

Test Methods to Verify Performance

- Test for concrete length change using ASTM C 157. Shrinkage on field is controlled by curing and ambient conditions.

2.4.2 Mechanical Properties of Concrete

Strength Gain Rate and Ultimate Strength

Generally, concrete with fly ash can result in a slower rate of strength gain and lower compressive strengths than ordinary PCC. However, as the rate of strength gain of the portland cement decreases, the continued pozzolanic activity in the fly ash concrete contributes to faster strength gain and higher compressive strengths at later stages. The slower rate of strength gain in early stages of fly ash concrete is controlled by the reactivity of fly ash. Generally, concrete containing Class C fly ash exhibits higher early strength than concrete containing Class F fly ashes. Use of Class F fly ash and higher dosages of fly ash in a mix require additional curing to support the prolonged hydration process.

- *Use lower rates of Class F fly ash replacement if strength gain is critical and if paving in cooler temperature conditions.*
- *Higher replacement rates may be needed if ASR is a concern. Use other ASR mitigating measures.*
- *Consider the use of curing blankets for paving in cool weather.*

Several approaches may be adopted to enhance early age concrete strength. Elevated curing temperatures can trigger increased hydration. The use of fine ground fly ash and/or the addition of chemical activators and set accelerators are other alternatives to accelerate strength gain. Also, adding a small quantity of silica fume can offset loss in early strength. Note that grinding fly ash results in angular particles that can affect the workability of fresh concrete. Moreover, grinding is an energy-intensive process and might have other implications associated with processing costs.

The long-term strength of fly ash concrete mixes is not an issue. Often, higher long-term strengths can be achieved. Adequate curing is critical for strength gain.

Test Methods to Verify Performance

- Test for compressive strength – ASTM C 39
- Test for flexural strength – ASTM C 78
- Test for elastic modulus – ASTM C 469

2.4.3 Durability of Concrete

Freeze-Thaw Resistance

The freeze-thaw resistance of concrete made with or without fly ash depends on the adequacy of the air void system, the soundness of aggregates, and strength of the concrete. Fly ash concrete can achieve good free-thaw resistance if a proper air void system is present. The carbon content of fly ash affects the freeze-thaw resistance of concrete due to high adsorption of air-entraining mixtures by carbonaceous particles. Increasing the dosage of air entraining admixture is necessary for concrete with fly ash, particularly with use of Class F high carbon ash.

- *Use aggregates that are resistant to freeze-thaw damage.*
- *Provide necessary air void characteristics.*
- *Use adequate air entrainment admixture dosage: higher dosage for higher LOI.*

The application of deicers causes higher loss of surface mortar or surface scaling in concretes containing fly ash, primarily due to their finer pore structures. More scaling damage is likely to occur with increasing proportions of fly ash.

Test Methods to Verify Performance

- Test for resistance of concrete to rapid freezing and thawing – ASTM C 666

Permeability

Permeability has a profound effect on concrete durability, as most durability-related problems are initiated with the free movement of water or other harmful elements such as CO_2, chloride, and sulfate ions through the concrete pore structure. Controlling permeability is an effective means of achieving good durability. Generally, fly ash reduces permeability because of the reduced water demand and tighter pore structure. However, an adequate curing regime supporting the prolonged pozzolanic reaction is necessary to achieve these benefits.

Most effective methods to reduce permeability are by:

- *Reducing water content.*
- *Providing adequate curing. Consider extended curing when using fly ash.*

Test Methods to Verify Performance

- Test for concrete's ability to resist chloride ion penetration – ASTM C 1202

Carbonation

Maintain low permeability to prevent carbonation. This is not a common problem in pavements.

Carbonation occurs by the diffusion of CO_2 into the concrete, where it dissolves in the pore solution. The diffused CO_2 then reacts with dissolved CH, resulting in the formation of $CaCO_3$. Permeability and fly ash reactivity are the key factors that influence the carbonation process. Lower permeability slows the diffusion process, resulting in a lower carbonation rate. Therefore, well-compacted and properly cured concrete at a low w/cm ratio will be sufficiently impermeable to resist carbonation.

Sulfate Resistance

- *Use fly ashes with calcium oxide levels below 10 percent, most typical in Class F fly ash.*
- *Consider replacing cement with Type II cement.*
- *Use Type II cement in combination with low calcium fly ash for extreme sulfate exposure levels.*

Fly ash improves sulfate resistance of concrete because of the reduction in the free lime content from the pozzolanic reaction as well as the reduction in permeability. The replacement of cement with fly ash also has a "dilution effect" by decreasing the total amount of C_3A, the main compound responsible for sulfate attack in the concrete mixture. Fly ash with higher CaO can increase the concrete's susceptibility to sulfate attack; fly ash with lower CaO content decreases the potential for sulfate attack. Class F ashes are preferred. In extreme sulfate exposure conditions, the use of Type II cement in combination with Class F ash is most effective. However, it is critical to provide adequate curing and achieve low permeability in these cases.

Test Methods to Verify Performance

- Test for sulfate expansion – ASTM C 1012

Alkali-Silica Reaction

ASR is the reaction between the alkali hydroxide in portland cement and certain forms of reactive silica from the aggregate source. The product of this reaction is an alkali-silicate gel, which has a tendency to swell in the presence of water. This swelling can be detrimental and manifest as cracking and, ultimately, failure of concrete. The two necessary conditions for ASR are the presence of reactive aggregates and a high alkali content contributed by cement and fly ash. An industry accepted threshold level for the total alkali content is 5 lb/yd^3.

ASR is the most common of concrete durability problems that is mitigated with the use of fly ash. The CaO is considered the most deleterious constituent in expanding ASR; therefore, fly ashes with a low CaO content are effective in mitigating ASR. Hence, Class F fly ashes are considered more beneficial than Class C fly ashes for controlling ASR problems. Additionally, a fairly large fly ash replacement rate is required, typically above 25 percent.

Interestingly, there is a pessimum limit for fly ashes with regard to alkali aggregate reaction; this is when small amounts of fly ash, typically in the range of 5 to 10 percent, actually tend to increase the expansion. This effect is very pronounced for Class C fly ash (with typical CaO contents between 10 and 30 percent) and also is present with Class F fly ash (with typical CaO contents between 0 and 10 percent). For Class F fly ash with 10 percent CaO, the effect often occurs for replacements around 10 to 15 percent, and the minimum replacement to reduce the expansion to an acceptable level is at least 30 percent.

- *Use fly ash with low oxide content.*
- *Use fly ash replacement levels of 25 percent or higher. Do not use low replacement levels.*
- *Use cement with low alkali content and reduce overall alkali content to less than 5 lb/yd^3.*
- *Use non-reactive aggregates.*

In optimizing mixes with fly ash, if strength gain is a concern or if the project requires paving in cold weather, the challenge lies in selecting a fly ash replacement level that provides adequate strength while also mitigating ASR. Options might include decreasing the alkali content of the cement or selecting aggregates that are not reactive.

Test Methods to Verify Performance

- Test for aggregate reactivity – ASTM C 1260 or ASTM C 1293;
- Test for ASR potential in cementitious blend – ASTM C 1567 in non-deicer environment
    - This test uses1N NaOH as the soak solution to determine 14-day expansions.
- Test for ASR potential in cementitious blend – Modified ASTM C 1567 in deicer environment.
    - This test uses 3M Ka + 1N NaOH as the soak solution to determine 14-day expansions.
    - Refer to the most current FAA practice used to screen aggregates for ASR potential and deicer sensitivity. (See additional note below)

Additional Note about Testing for ASR Potential

EB-70 test was developed to screen aggregates for ASR potential in deicer environments (FAA, 2005) and used a 6.4M potassium acetate (KAc) solution to replace the 1N sodium hydroxide (NaOH) soak solution in the standard ASTM test procedure. EB-70, as an interim test protocol, was evaluated by FAA, and has now been rescinded by the FAA. The Modified ASTM C 1567, which uses 3M Ka + 1N NaOH as the soak solution, is considered more effective to screen aggregates for ASR potential and deicer sensitivity simultaneously. A revised procedure has been developed for the modified test (ACPA, 2011). However, for mix optimization, refer to the most current FAA practice to test for ASR potential in deicer environments.

2.5 SUMMARY

Current specifications for fly ash use in PCC are not adequate from a performance standpoint. There are many variables that factor into optimal fly ash use for a particular situation. At the same time, it is recognized that standard specifications are necessarily simple, direct, and prescriptive; hence, they are limited to the class of fly ash and the replacement rate to be used. The recommendations tend to stay conservative in fly ash use, and they are likely to be effective in most cases. However, this conservative approach may result in the underutilization of fly ash, or in using it in quantities detrimental to the performance of the pavement.

While the mineralogical and chemical compositions of a fly ash affect the early age properties, long-term strength, and durability of the concrete mix, there is a significant level of interaction with properties of other materials in the mix design. Table 6 provides a summary of the effects of fly ash on concrete properties, interaction of fly ash properties and mix design parameters, methods to control mix design performance, and standard tests to verify performance.

Table 6. Effects of fly ash on concrete properties, interaction of fly ash properties and mix design parameters, methods to control intended results, and standard test methods to verify performance

Concrete property	Effect of fly ash	Interaction with other material or mix parameters	Methods to achieve desired results and control unintended results	Test Methods to verify performance
Workability and water demand	Fly ash improves workability, increases slump, and hence reduces water demand.	• Finer the fly ash, the lower the water demand. • Lower the LOI lower the water demand.	• Use low water to cementitious materials ratio to achieve required slump.	Test for slump - ASTM C 143
Bleeding	Fly ash reduces bleeding because of lesser water demand.	• Class C fly ashes reduce bleeding much more than Class F ashes.	• Need to reduce water content to get lower bleeding.	Test for bleeding of concrete - ASTM C 232
Set time (affects finishing and saw time)	Fly ash delays set time generally.	• Set time increase is because of reduced cement content or dilution of cement. • Class C fly ash may cause flash set depending on its composition. • Class C fly ash with high CaO content may also show unexpected signs of long setting times.	• Use set accelerating admixture to reduce set time. • Use gypsum in mix design to address flash set. • Use higher than normal dosage of calcium sulfate in cement blends to increase rate of reaction.	Test for time of setting of concrete – ASTM C 403
Air content	Fly ash reduces air content.	• Higher carbon content reduces air content in plastic concrete. • Class C fly ash requires lower air entrainment dosage.	• Use adequate air entraining agent in the mix design. • Not a concern for climates without freeze-thaw.	Test for air content: Fresh concrete - ASTM C 138 or C 173. Hardened concrete - ASTM C 457.

Table 6, Continued

Concrete property	Effect of fly ash	Interaction with other material or mix parameters	Methods to achieve desired results and control unintended results	Test Methods to verify performance
Plastic and autogeneous shrinkage	Fly ash reduces bleeding and shrinkage because of lesser water demand.	• Need to reduce water content to get lower shrinkage and bleeding. • Curing is more important in hotter and dryer climates.	• Take advantage of improved workability by reducing water content. • Increase curing time and/or use wet extended curing.	May test for shrinkage using ASTM C 157, but shrinkage on field is dependent on ambient conditions and curing.
Strength gain and long term strength	Fly ash reduces rate of strength gain, produces equal or higher long term strength gain, and occasionally lowers long term strength gain.	• Affected by calcium content in the fly ash. • Reduced w/cm ratio can enhance strength at 14 days or 28-days. • Depends on whether a pozzolanic reaction controls the strength gain. • Depends on curing temperature and temperature at placement.	• Use lower rates of class F fly ash if strength gain is critical and if paving in cooler temperature conditions. • Might need higher replacement if ASR is a concern. • Consider the use of curing blankets for paving in cool weather.	Test for compressive strength - ASTM C 39; Test for flexural strength - ASTM C 78; Test for elastic modulus - ASTM C 469.
ASR	Fly ash reduces ASR potential	• Effectiveness depends on calcium content and total alkali content. • Class F (reduced calcium and alkali hydroxide) is more effective than Class C; Class C in very high dosage is sometime effective. • Also depends on aggregate reactivity and alkali availability for ASR (sources can be cement, fly ash and environment).	• Use fly ash with low oxide content. • Use fly ash replacement levels of 25 percent or higher. Do not use low replacement levels. • Use cement with low alkali content and reduce overall alkali content to less than 5 lb/yd^3. • Use non-reactive aggregates.	Aggregate reactivity using ASTM C 1260 or ASTM C 1293; ASR potential for cementitious blend using ASTM C 1567 in non-deicer environment or Modified ASTM C 1567 in deicer exposure.*

Table 6, Continued

Concrete property	Effect of fly ash	Interaction with other material or mix parameters	Methods to achieve desired results and control unintended results	Test Methods to verify performance
Freeze-thaw resistance	Reduces F-T damage by reducing permeability	• Depends on aggregate soundness, w/cm ratio, air entrainment used in mix design and number of freeze-thaw cycles in project location.	• Use aggregates that are resistant to freeze-thaw. Use adequate air entrainment admixture dosage. Higher dosage for higher LOI.	Test for resistance of concrete to rapid freezing and thawing - ASTM C 666.
Deicer salt scaling	Fly ash may increase scaling potential	• Depends on replacement rate. Lower replacement rates are preferable for scaling resistance.	• Avoid using very high replacement rates (> 50%) in deicer environments.	Test for scaling resistance - ASTM C 672 if pavement is exposed to deicers.
Permeability and chloride penetrability	Reduces permeability with increasing fly ash content	• Lower permeability for low calcium (Class F) than for high calcium (Class C) ashes. Non-issue for high volume fly ash mixes.	• The most effective way to reduce permeability is by providing adequate curing to support full hydration.	Test for concrete's ability to resist chloride ion penetration - ASTM C 1202.
Sulfate resistance	Reduces sulfate attack	• Low calcium fly ash is more effective than high calcium fly ash. High C3A and calcium content in fly ash decreases sulfate resistance. In some conditions addition of fly ash does not reduce sulfate attack caused due to sodium sulfate sources.	• Use Class F fly ash with calcium oxide levels below 10 percent. Use Type II cement in combination with low calcium fly ash to improve sulfate resistance.	Test for sulfate expansion - ASTM C 1012.

* Refer to the most current practice for testing combined potential for ASR and deicer sensitivity

Mix optimization to achieve the desired levels of workability, strength, and durability requires specifying appropriate:

- Levels of fly ash replacement.
- Admixtures and dosages of admixtures.
- Curing and temperature management regimes.

Material selection and mix optimization also should include verification using standard tests to ensure that the desired results are achieved.

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CHAPTER 3. MIX OPTIMIZATION GUIDELINES

3.1 INTRODUCTION

The guidelines that follow are essentially a concrete mix optimization protocol that addresses the practical needs identified in the previous chapters. The recommendations are based largely on empirical mix design and performance data collected from various sources, including literature, laboratory tests, and real-world projects. The approach guides the user with careful selection of materials, mix proportioning and mix design routines, curing regimes, and verification testing required to ensure the desired levels of workability, constructability, strength, and durability are achieved.

The mix optimization protocol is condensed into a catalog format, which is available as a standalone document: *Recommendations for Proportioning Fly Ash as Cementitious Materials in Airfield Pavement Concrete Mixtures* (Rao et al., 2011b). The catalog recommendations also have been incorporated into a software tool that provides a quick and easy way to evaluate the effect of changing project parameters.

Scope of the Mix Optimization Catalog

The catalog is intended to:

- Guide the user to a range of fly ash replacements for a project.
- Alert the user to additional requirements needed to use fly ash successfully in a project.
- Outline the tests that need to be run to select the optimum fly ash content.

Based on the recommendation, the user is expected to select at least three fly ash replacement rates within the range and perform the recommended tests to verify its performance (note that the tests recommended are project-). Next, the user is required to review and analyze results so that an optimum fly ash content may be determined. Finally, the user needs to re-batch and test at optimum and submit the required results for approval.

3.2 MIX OPTIMIZATION CATALOG

The mix optimization catalog contains five distinct sections:

1. Project Conditions*:* This section lists the project conditions that are known to affect the selection of fly ash type and quantities.
2. Recommendations for Fly ash Properties*:* This section lists the fly ash properties that are recommended for the project conditions selected by the user.
3. Recommendations for Admixtures and Curing: This section lists the factors that need to be considered in the mix design and during construction.
4. Recommended Tests*:* This section lists the standard tests that need to be performed while evaluating the mix.

5. Sulfate Check: Based on the final recommendations, this section provides a check on the fly ash properties to resist sulfate attack for different levels of sulfate exposure.

Item 1 is the only section where the user's selection is displayed. Items 2, 3, and 4 form the recommendations for optimizing the mix. Item 5 is applicable only to projects subject to sulfate exposure.

Under items 2, 3, and 4, the catalog provides two levels of recommendations—primary and secondary. Primary recommendations imply the specified value for a given parameter is the optimum case, but the secondary recommendation also has significant potential to meet performance requirements. For example, the catalog might present a primary recommendation of 30 to 50 percent replacement and a secondary recommendation of 15 to 30 percent replacement of a fly ash with a specified limit on the calcium oxide level for a project in a deicer environment using reactive aggregates and high alkali cements. If hauling the required fly ash to a project location is not economically feasible, the secondary recommendation may be evaluated in the trial batches instead of a range from the primary recommendation. For the given example, it might be possible to meet project specifications at a replacement level closer to 30 percent, in which case a 25 percent replacement may be the optimum.

3.2.1 Project Conditions

The recommendations were developed for five broad categories of project conditions:

- Deicer exposure – deicer or non-deicer.
- Aggregate reactivity – reactive or non-reactive aggregates.
- Cement type – high alkali or low alkali cement.
- Opening time requirements – quick opening time or non-critical opening time.
- Paving weather – cool, moderate, or hot.

This results in 48 possible combinations of project-specific variables, each of which is provided with a unique set of recommendations for fly ash properties, mix design methods, and construction practices for good performance. For each combination of variables, the catalog also recommends tests that are necessary to evaluate the mix design and verify its strength and durability characteristics. These tests also are appropriate for the project environment and for preventing potential problems that can arise with the recommended materials and mix design.

Deicer Exposure

The catalog does not define a criterion to classify a project location as one with deicer exposure or not. The user is expected to select this category based on past experience for the airport or other airports in the general area.

Aggregate Reactivity

The catalog uses FHWA's standards to classify aggregate reactivity (Thomas et al., 2008). This classification is based on accelerated mortar bar tests in accordance with ASTM C 1260 (also required by P-501) to be performed individually for coarse and fine aggregates. The criteria used are as follows:

- Aggregates that result in 14-day expansion less than 0.1 percent are considered non-reactive.
- Aggregates that result in 14-day expansion greater than 0.2 percent are considered reactive.
- Aggregates that result in expansions between 0.1 and 0.2 percent are potentially reactive. The user can classify such aggregates based on two options:
    - Further testing is required to confirm it reactivity using the ASTM C 1293 concrete prism test, which is considered a more reliable test to determine aggregate reactivity. Aggregates that result in 1-year expansions below 0.04 percent can be classified as non-reactive, and those with 1-year expansions above 0.04 percent can be classified as reactive.
    - A conservative approach—classifying the aggregate as reactive—may be adopted without further testing.

Note that this screening process does not examine the aggregate's sensitivity to deicer environment and therefore uses the same protocols for projects with and without deicer exposure. Additionally, the reactivity of coarse and fine aggregates is to be considered individually under this screening protocol. Coarse and fine aggregates may be tested separately using ASTM C 1260; this test should not be used to evaluate the job combination of coarse and fine aggregate blends.

Cement Type

The catalog classifies cements as low alkali and high alkali cements—those with alkali content of less than 0.6 percent are classified as low alkali cements, and those with 0.6 percent or greater are classified as high alkali cements. These reports typically are provided by the cement vendor.

Opening Time Requirements

Opening time requirements are classified as quick or non-critical. Quick opening time refers to projects that need to be opened to traffic at 14 days and, therefore, have early age strength requirements. Projects that need conventional opening to traffic times and those that specify only 28-day strength requirements are classified as non-critical under this category.

Paving Weather

In the catalog, paving weather is classified as cool (below 60 °F), moderate (between 60 and 80 °F), or hot (above 80 °F).

3.2.2 Recommendations for Fly Ash Properties

The information provided in this section is not a user-defined parameter for the project. The recommendations for fly ash include the chemical and physical properties as well as the substitution level.

Calcium Oxide

Recommendations provided for the calcium oxide content for fly ash are provided in three categories:

- Low – defined as calcium oxide levels below 10 percent.
- Moderate – defined as calcium oxide levels between 10 and 20 percent.
- High – defined as calcium oxide levels above 20 percent.

This information is provided by the fly ash supplier or from the ASTM C 311 test report to classify the fly ash per ASTM C 618 requirements. See the sample test report in chapter 2 (Table 4).

Fineness

Fly ash fineness is classified into three groups:

- Coarse.
- Fine.
- Fine ground.

The ASTM C 618 requirements limit the fines passing the 45µm sieve (#325 sieve) to 34 percent, which is met consistently by commercial current fly ash producers. In most cases, this parameter is not above 20 percent in current fly ash supplies in North America. Standard ASTM reports do not provide the particle size distribution or the percent retained on smaller sieve sizes. The fineness obtained from a fly ash vendor or can be based on experience using the material.

Loss on Ignition

LOI is classified as follows:

- Low – LOI less than 2 percent.
- Moderate – LOI between 2 and 6 percent.
- High – LOI greater than 6 percent.

The standard ASTM C 618 conformance report lists the LOI.

Recommended Substitution Level

This is the key recommendations in optimizing the concrete mix design using the catalog. Fly ash replacement levels are classified as:

- Low – replacement below 15 percent.
- Moderate – replacement between 15 and 30 percent.
- High – replacement between 30 and 50 percent.
- Very high – replacement greater than 50 percent.

3.2.3 Recommendations for Admixtures and Curing

Recommendations for appropriate use of admixtures and curing practices are provided in the catalog.

Admixtures

The recommendations consider the need for the following admixtures:

- Air entraining agent.
- Water reducer.
- Set accelerating admixture.

These recommendations do not specify the admixture brands and dosages required to meet air content, workability, or strength requirements. Trial batching and laboratory testing are used to further verify the effectiveness and compatibility of the admixtures selected for specific projects. The catalog leads the user to consider critical the mix design issues.

Curing Practices

The recommendations consider the need for the following curing regimes:

- Wet normal curing.
- Wet extended curing.
- Curing blankets/autogeneous curing.

The intent of these recommendations is to remind the user that extra attention to curing may be required, depending on the combination of fly ash replacement recommendation, paving weather, and opening time requirements for the project.

3.2.4 Recommendations for Standard Tests

The catalog directs the user to the most appropriate set of tests depending on the project conditions and the other fly ash recommendations provided for the trial batches. The standard tests are grouped into four broad categories:

- Fresh concrete tests.
- Hardened concrete tests.
- Mortar bar tests.
- Materials review.

Fresh Concrete Tests

The following fresh concrete tests are recommended:

- ASTM C 143 for measuring the slump of concrete to meet the P-501 specification requirements of 1 to 2 inches for side-form paving concrete and 0.5 to 1.5 inches for slip-form paving concrete.
- ASTM C 138, ASTM C 173, or ASTM C 231 to determine the air content by gravimetric, volumetric, or pressure methods, respectively, to meet the air content requirements of the P-501 specification. Note that the air content requirements are presented in the P-501 specification as a function of exposure level and maximum aggregate size ranging from 2 percent for mild exposure and 2-inch aggregate size to 7 percent for severe exposure level and ½-inch aggregate size.
- ASTM C 138 for determining the unit weight of concrete.
- ASTM C 403 to determine the initial and final set times of the paste. This test is not a requirement in the P-501 specification, but it is recommended for fresh concrete because the effect on set time with varying fly ash replacements can be evaluated while selecting optimum replacement rate. Some fly ashes have a less significant impact on set time than others do and can be an important consideration in determining the exact saw time.
- ASTM C 232 to determine the bleeding in concrete. This test is not a requirement under the current P-501 specification, but it has been recommended to evaluate the effect of fly ash replacement rate on bleeding of concrete. This is critical to plan the curing regime and the time of curing after placement.

Hardened Concrete Tests

The following tests and performance criteria are recommended for hardened concrete:

- ASTM C 78 for measuring the flexural strength of concrete if the flexural strength criterion is used for the project consistent with the P-501 specifications. The samples for the flexural strength will be cast in accordance with ASTM C 192. The age at testing is as per project requirements. However, a 28-day strength requirement is determined for most projects.
- ASTM C 39 for compressive strength of concrete when the design strength in Item 501-3.1 is based on compressive strength. The compressive strength tests shall be performed at the same ages as the flexural strength tests, typically the 28-day strength.
- ASTM C 78 and C 39 tests are recommended to measure the strength gain rate of a concrete mix. Strength gain rates are specific to projects with early opening requirements and are recommended at 3, 7, 14, 28, and 56 days.

- ASTM C 457 to determine the air void parameters in hardened concrete. This test is not specified in the current P-501 specification, but it is recommended to ensure that the air content and air void distribution required for freeze-thaw resistance are achieved. The total air content specified in Item 501-3.3 should be verified. Additionally, the entrained air content should be no less than 3 percent, and the spacing factor determined from ASTM C 457 tests should be less than 0.01 inches.
- ASTM C 666 to determine the resistance of concrete to rapid freeze-thaw. The current P-501 specification requirements of minimum durability factor of 95 percent will apply to the trial batch samples.
- ASTM C 672 to determine the scaling resistance of concrete surfaces exposed to deicing chemicals. This test is not a requirement in the current P-501 specification but is recommended to ensure that mixes recommended with higher levels of fly ash replacement do not increase the scaling potential of the concrete.

The test for elastic modulus, ASTM C 469, may also be included in the hardened concrete tests.

Mortar Bar Tests

The following mortar tests and performance criteria are recommended for the trial batches:

- Standard ASTM C 1567 using 1N NaOH as the soak solution to determine the ASR potential for the combined cementitious materials and aggregate. Mortar bars, one with coarse aggregate and one with fine aggregate, are to be tested independently. This is not a required test in the current specifications but is recommended in the mix optimization catalog to assess the collective impact of the cement, fly ash at the recommended replacement rate, and the aggregate in mitigating ASR when the project is not exposed to deicer chemicals.
- Refer to FAA's most current policy on mitigation testing. At the time of the publication of this report, the Modified ASTM C 1567 test was considered an interim test to screen aggregates for ASR potential and mitigating deicer distress potential simultaneously (ACPA, 2011). This involves performing the ASTM C 1567 test using 3M KAc + 1N NaOH as the soak solution and measuring mortar bar expansions at the end of 14 days. It is assumed that each aggregate either has been screened already or will be screened concurrently for freeze-thaw durability.

NOTE: As of April 2011, the Modified ASTM C 1567 test (ACPA, 2011) is preferred over the discontinued EB-70 test. Note that EB-70 was the current document at the time the testing was accomplished under the IPRF 06-2 study. Therefore, the validations from the laboratory test plan and the case studies used results from the EB-70 test protocol.

Materials Review

The following tests are used to review the materials being used:

- ASTM C 150 for cement.
- ASTM C 311 and C 618 for fly ash.

- ASTM C 1260, C 1293, C 295, C 227, and C 289 for aggregates.

3.2.5 Sulfate Check

This section provides a check to the final recommendations from the mix optimization catalog to ensure they can provide the necessary resistance to sulfate attack if the project is exposed to a sulfate environment. Table 7 provides a summary of the specific recommendations for three different sulfate exposure levels.

Table 7. Fly ash recommendations for sulfate exposure

SULFATE EXPOSURE	RECOMMENDATIONS			
	Cement type and fly ash	Fly ash calcium oxide	Fineness	Additional test required
No	Follow recommendations from catalog for project conditions			None
Moderate	Type I cement with Class F ash or Type II cement	Low oxide only	Fine or fine ground	ASTM C 1012
Severe	Type II cement with Class F fly ash	Low oxide only	Fine or fine ground	ASTM C 1012

3.3 USING THE MIX DESIGN OPTIMIZATION CATALOG

3.3.1 Mix Optimization Using the Catalog

The mix optimization catalog includes 48 different sheets, each representing a unique combination of the 5 categories of project conditions.

A sample catalog sheet is shown in Figure 6 for project in a deicer exposure environment with reactive aggregates, high alkali cement, non-critical opening time, and paved in moderate temperature conditions. These conditions generally would represent fairly tight control from the standpoint of both ASR mitigation and strength gain. The primary recommendations in the catalog are highlighted in green, and the secondary recommendations are highlighted in yellow.

PROJECT CONDITIONS SELECTED				
Deicer exposure	**Aggregate reactivity**	**Cement type**	**Opening time**	**Paving weather**
Yes	Reactive (> 0.2%)	High alkali (>= 0.6%)	Non-critical (> 14 days)	Moderate (60 to 80°F)

RECOMMENDATION FOR MIX DESIGN, CONSTRUCTION PRACTICES, AND TESTS

RECOMMENDATIONS FOR FLY ASH PROPERTIES

Calcium oxide	*Fineness*	*LOI*	*Replacement level*
Low (<10%)	~~Coarse~~	Low (<2%)	~~Low (< 15%)~~
~~Moderate (10 to 20%)~~	Fine	Moderate (2 to 6%)	Moderate (15-30%)
~~High (>20%)~~	Fine ground	~~High (>6%)~~	High (30%-50%)
			~~Very high (>50%)~~

RECOMMENDEDATIONS FOR ADMIXTURES AND CURING

Admixtures	*Curing*
Air entraining agent	Wet - normal
Water reducer	Wet - extended
Set accelerating	~~Curing blanket /autogeneous curing~~

RECOMMENDATIONS FOR STANDARD TESTS (ASTM)

Fresh concrete	*Hardened concrete*	*Mortar bar*	*Materials review*
Slump (C 143)	Strength (C 39, C 78, C 469)*	~~ASR potential (C 1567)~~	Fly ash (C 618, C 311)
Air (C 138 or C 173)	~~Strength gain rate (C 39, C 78, C 469)*~~	ASR and deicer reactivity (Modified ASTM C 1567)	Aggregates (C 1260, C 1293, C 227, C 295, C 289)
Unit weight (C 138)	Hardened air voids (C 457)		Cement (C 150)
Set time (C 403)	Rapid freeze thaw (C 666)		
Bleed test (C 232)	Scaling resistance (C 672)		

COMMENTS AND OTHER CONSIDERATIONS

* Strength tests include ASTM C 39 for compressive strength, C 78 for flexural strength, and C 469 for elastic modulus.

1. The key is to maintain a replacement level high enough to mitigate ASR, but if necessary, it might be possible to optimize the mix to lower replacement levels if scaling potential increases. Therefore, lower values in the moderate range can be an option.
2. The low LOI level is recommended, but the moderate level may be adequate to meet air void requirements.
3. Wet extended curing is recommended for the high replacement level. Wet normal curing may be adequate for the moderate replacement level.

Figure 6. Mix optimization catalog recommendations for project with deicer exposure, reactive aggregates, high alkali cement, non-critical opening time, and moderate paving weather

For these conditions, the mix optimization catalog suggests:

- The fly ash should:
    - Have a calcium oxide in the low range.
    - Be fine or fine ground.
    - Have an LOI in the low range.

    - Be incorporated at a replacement level most likely in the high range and possibly in the moderate range.
- The admixtures for the mix include air entraining agent, water reducer, and set accelerator.
- Wet extended curing should be provided for the high replacement rate and a wet-normal curing may be adequate for the moderate replacement rate.
- Fresh concrete tests should be performed for slump, air content, unit weight, set time, and bleeding.
- Hardened concrete tests should be performed for routine strength determination, air void content, rapid freeze-thaw resistance and scaling resistance.
- Mortar bar testing should be performed to examine the concrete's resistance to ASR in a deicer environment.

The catalog provides multiple combinations of materials and fly ash properties feasible for a given project location. The mix optimization process is iterative, requiring the user to make judicious choices in selecting the optimum combination of materials, most likely based on cost-effectiveness or the contractor's familiarity in working with a certain set of materials. The optimization process cannot be generalized, as it depends on the outcome of the materials used and the test results obtained.

Steps Involved in Mix Optimizations

The process broadly involves the following steps as illustrated in Figure 7:

Step 1 – Assess Project Conditions: Understand the project conditions that can impact the selection of materials and the fly ash replacement level. This includes, within the scope of the catalog:

- Whether the pavement will be exposed to deicer chemicals and freeze-thaw cycles.
- Whether the project has early opening requirements.
- Paving weather.

Step 2 – Select Materials: Select the most preferred cement, fly ash, and coarse and fine aggregate materials. This selection may be based on either cost-effectiveness or local availability of the materials. Familiarity and experience with the material to provide good constructability and performance also might influence the selection of materials.

Step 3 – Review Materials: Review the materials test data that are available or are provided by the supplier for the materials. If needed, additional testing may be performed to evaluate the materials. This review will help classify the materials within the context of the catalog:

- Determine coarse and fine aggregate reactivity individually.
- Determine alkalinity of cement.
- Determine fly ash class, oxide level, fineness category, and LOI.

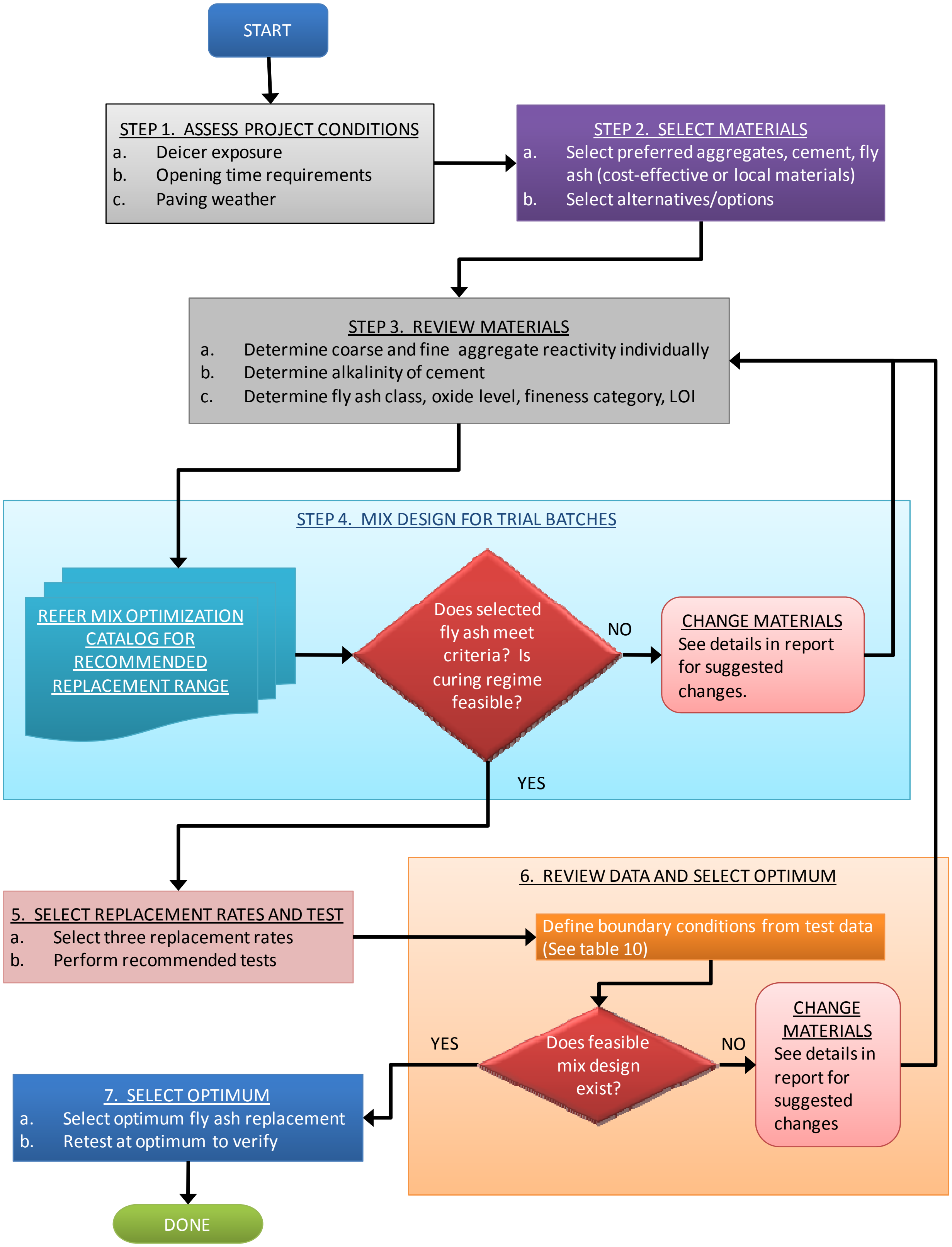


Figure 7. Steps involved in the mix optimization procedure

Step 4 – Mix Design for Trial Batches: For the given project conditions in step 1 and the cement and aggregate type determined in step 2, refer to the catalog for the recommended fly ash properties and the replacement levels. Also understand the implications of the recommended construction practices and curing regimes. At this step, evaluate if the project specifications can be met.

- Do the properties of the selected fly ash source from step 2 satisfy the criteria specified in the catalog?
  - If yes, further testing is required to verify that project specifications can be met. Got to step 5.
  - If not, the materials need to be changed and the properties re-evaluated. There are several options to revise material selections. This depends on the project conditions as well as the properties of the materials selected in step 2. The following is a partial list of suggestions, one or more of which may be applicable and needed to satisfy the catalog recommendations:
    - i. If the project is in a deicer exposure environment and the LOI is higher than the recommended range, use a fly ash with a lower LOI.
    - ii. If the aggregate selected is reactive:
      1. Change to a non-reactive aggregate and/or
      2. Change to a low alkali cement if a high alkali cement was selected in step 2 and/or
      3. Change to a fly ash source with a lower oxide level than that of the fly ash selected in step 2.
    - iii. If the project has a quick opening time requirement, and the selected combination of materials requires the use of curing blankets, consider paving in warmer temperatures to eliminate the need for curing blankets.

Step 5 – Select Replacement Rates and Test: Within the recommended fly ash replacement range, select three or more replacement rates for trial batches. Perform all tests listed in the catalog for the recommended replacement levels.

Step 6 – Review Data and Select Optimum: Analyze the data generated from the laboratory tests conducted in step 5 and select an optimum replacement level depending on the performance criteria applicable for each project. Use the format provided in Table 8 to determine the boundaries or the minimum and maximum replacement rates that are feasible for a given set of materials:

- The maximum fly ash content that exceeds the flexural strength at the specified age(s).
- The maximum fly ash content that has acceptable set time characteristics for constructability.
- The minimum fly ash content that limits 14-day mortar bar expansion below 0.1 percent when tested as appropriate for deicer and non-deicer environments.
- The maximum fly ash content that still provides adequate freeze-thaw and scaling durability.
- The minimum/maximum fly ash content that yields an acceptable mix cost depending on the unit cost of the selected fly ash and the hauling costs.

Table 8. Criteria to determine feasible range of fly ash replacement for a given set of materials

Percentage fly ash replacement	**Selection criteria for mix design optimization**						
	Flexural strength (and other strength parameters)[1]	**Set time**[2]	**ASR mitigation**[3]	**Freeze-thaw resistance for deicer environment**[4]	**Scaling resistance**[5]	**Cost**[6]	**Setting feasible range**
Minimum			*			*	Minimum for feasible range[7]
Maximum	*	*		*	*	*	Maximum for feasible range[7]

NOTES
1. Based on ASTM C 78 strength tests and strength gain tests as recommended.
2. Based on ASTM C 403.
3. Based on ASTM C 1567 for non-deicer environment and Modified ASTM C 1567 for deicer environment. Applicable only for reactive aggregates.
4. Based on ASTM C 457 and ASTM C 666 as recommended. Applicable only for deicer exposure environments.
5. Based on ASTM C 672 and applicable only for deicer exposure environments.
6. Cost-effectiveness is project-specific
7. If MIN is greater than MAX, change materials and iterate. Go back to step 2.

Next, evaluate if the feasible replacement range determined in Table 8 is practical for the mix design:

- For the feasible range determined here, if the minimum is below the maximum, an optimum value within the feasible range may be selected. Go to step 7.
- If the materials selected do not satisfy the test criteria, or if the minimum is higher than the maximum in the feasible range, this set of materials cannot be combined in the proportions used in the trial batches. Change the materials selected for the project to meet test criteria and return to step 2. Again, there exist multiple options for changing mix design materials, and this depends on the project conditions and the specific tests that did not meet requirements. The following is a partial list of suggestions, one or more of which may be applicable:
    - If set time is not acceptable, try incorporating a set accelerator.
    - If strength at 28 days or strength gain is not satisfactory, try using a combination of materials or a paving weather which allows a lower fly ash replacement rate or increase the total cementitious content. If reactive aggregates are used, necessitating higher replacement rates of low oxide fly ash for ASR mitigation, consider using non-reactive aggregates. Or, if high alkali cement is used in combination with reactive aggregates, then use low alkali cement that might allow lower fly ash replacement rates to meet strength criteria.
    - If ASR mitigation is not achieved with the maximum fly ash replacement rate (often controlled by strength requirements), consider changing to a non-reactive

aggregate source and/or reducing the alkalinity of the cement. Similar considerations apply if the material does not meet scaling resistance requirements.

- If freeze-thaw resistance is not achieved, then consider increasing the air entraining agent dosage and/or use a fly ash with lower LOI. Additionally, if freeze-thaw resistance is not achieved due to the use of a high replacement rate of low oxide fly ash for ASR mitigation, then consider using non-reactive aggregates or reduce the alkalinity of the cement as explained above.
- If resistance to rapid freeze-thaw is not achieved, consider changing to better quality aggregates.

Step 7 – Select Optimum: Select an optimum level of fly ash replacement for the given set of materials based on the results from Table 8. Rebatch at the optimum level and verify results from all laboratory tests recommended in the catalog.

3.4 RAPID TESTING ALTERNATIVES DURING MIX OPTIMIZATION

3.4.1 Need for Rapid Tests

The catalog provides a range of fly ash replacement levels for use in trial batching. In the best case scenario, the user batches three mix designs at three contents and performs the tests recommended to determine the optimum fly ash replacement level for the given project conditions. In other cases, depending on the results of the tests performed, it may be necessary to re-batch and retest additional fly ash replacement rates before the optimum level can be determined. If extensive testing is expected, rapid test procedures may be used to minimize the number of laboratory tests during trial batches and to expedite the mix optimization process. Semi-adiabatic calorimetry is being suggested as a rapid tool to "estimate" key properties such as strength and set times without elaborate testing for each trial batch.

This does not imply that the catalog-recommended tests need not be verified for the final selected mix design. It is imperative that the final mix design be fully evaluated under all recommended laboratory tests.

3.4.2 Calorimetry and Applications

Calorimetry involves the measurement of heat evolved from a chemical reaction or change of physical state of a material. Calorimetry can be performed under three conditions:

- Adiabatic conditions when measurements are made without loss or gain of heat (<0.02 k/h temperature loss) utilizing some form of insulation. Adiabatic calorimetry does not account for the effect of ambient temperature on the thermal measurements.
- Isothermal conditions when measurements are made under a constant temperature. This is more suitable for cement pastes, but it does not take into account the cement reactivity change due to the change of temperature.
- Semi-adiabatic conditions when heat evolution from a hydrating cementitious material is measured in an environment with marginal insulation (maximum heat loss < 100 J/h.K),

and it is suitable for pastes, mortars, and concrete samples. It simply measures a concrete mixture's temperature history over time, typically over the first 24 to 48 hours.

Semi-adiabatic test data generally are repeatable, and the test process is amenable for use in the field or the laboratory. No national standard methods currently exist for semi-adiabatic calorimetry for cementitious materials, although commercial devices provide manufacturer-specified standard test methods applicable for each device. Standard sample sizes and testing procedures are followed. However, there are ongoing efforts to standardize test equipment and test procedures, which may be used as they become available.

Further, semi-adiabatic calorimetry may be used as a QC tool to alert engineers about unexpected changes to the mix design for concrete delivered to the site, such as changes in admixture type or dosage, cement source, and so on. During paving, calorimetry may be a rapid and effective method to provide confidence about a mix.

Semi-adiabatic Test Data Interpretation

Figure 8 shows a sample of semi-adiabatic calorimetric temperature monitoring, henceforth referred to as calorimetry or temperature monitoring. The figure represents the data for a mix at 30 percent fly ash replacement, identified as mix 1. The initial peak in temperature occurs due to the hydration of C_3A, followed by a short dormant period in the hydration reactions. The significant peak seen subsequent to the dormant period represents the heat generated from the C_3S hydration. As the rate of hydration decreases (even while hydration progresses), the temperature falls gradually until the mixture attains a stable temperature corresponding to the ambient conditions or the curing temperature conditions. The amount of heat and the temperature history are influenced by cement and fly ash chemistry, mix temperature, fly ash replacement level, admixture dosages, admixture incompatibility, and reactivity. An evaluation of these data can help troubleshoot concrete on field or identify other set time or early hydration issues, including flash set (Cost & Gardiner, 2009).

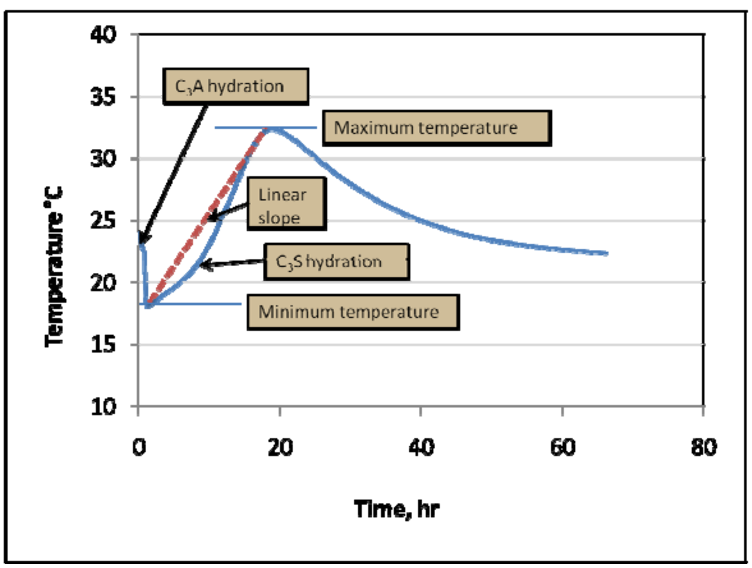


Figure 8. Sample semi-adiabatic temperature monitoring data plot

In Figure 9, the calorimetry output is shown together with the occurrence of the initial set and final set for the sample mix, as measured by the ASTM C 403 test. The time temperature history recorded in the calorimetry test also can be used to calculate the maturity (area under the curve), as shown in Figure 10.

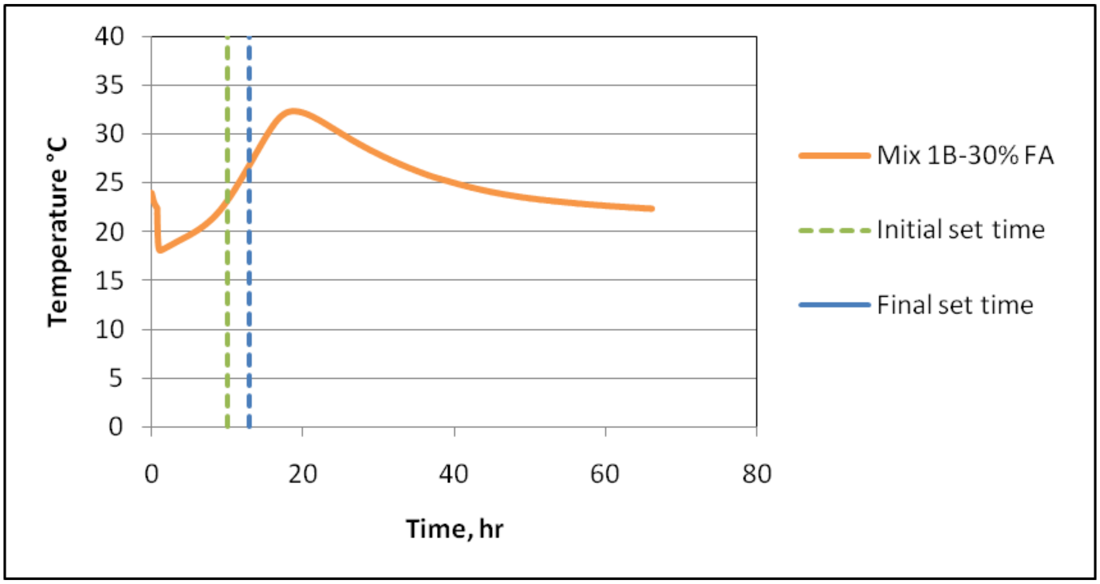


Figure 9. Temperature history and set time for mix 1 at 30 percent fly ash replacement

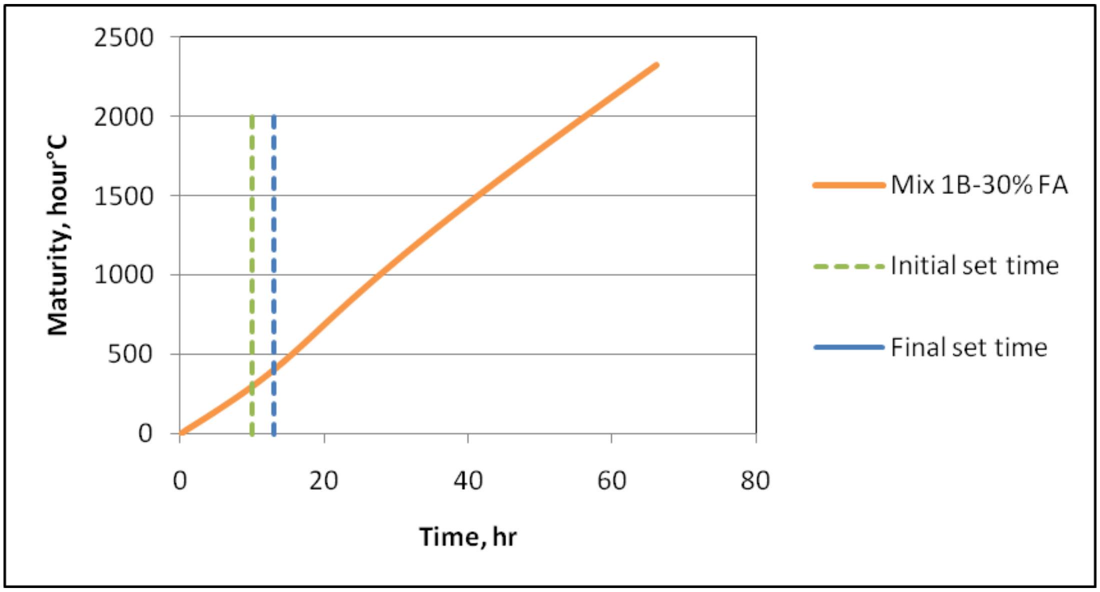


Figure 10. Maturity in mix 1 with 30 percent fly ash replacement

The effect of changing a mix parameter can be identified through changes in these temperature profiles. In the example in Figure 11, the fly ash replacement level is the mix parameter being changed. Figure 11 shows the temperature profiles and the maturity developments for mix 1 with fly ash replacement levels of 15, 30, and 50 percent. The increase in fly ash content reduces the peak temperature and delays the time at maximum temperature peak (associated with delayed hydration of the fly ash). The shift in set times is more significant with the increase in fly ash replacement from 15 to 30 than from 30 to 50 percent. Therefore, calorimetry data can be used to track trends in the mix and to identify concerns when changes to the mix produce unintended results.

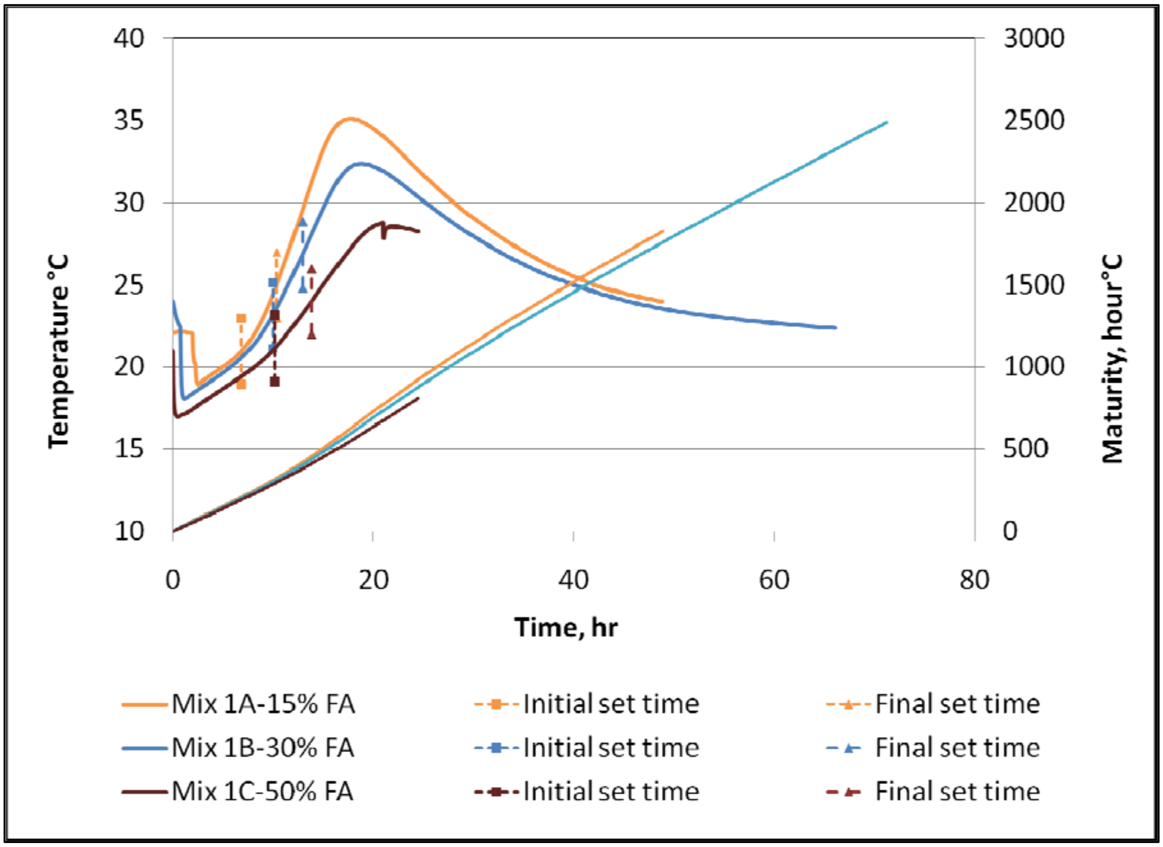


Figure 11. Effect of fly ash replacement for mix 1

3.4.3 Using Calorimetry to Predict Material Properties

Mathematical parameters defining the shape of the curve can be derived using the calorimetry data. These parameters can serve as indicators of the degree of hydration, and therefore can be used to estimate set times and strength. A few simple parameters, for example, would be the approximate linear slope of the curve that tracks primarily the C_3S hydration, the time of occurrence of the maximum temperature, and the maximum temperature itself. Other parameters that may be more mathematically complex are parameters obtained by generating the first and/or second derivatives to the functional form of the heat of hydration curve, which essentially would track the rate of heat evolution and the rate of change in heat evolution. Regardless of the approach and the parameters selected, the objective is to characterize trends in each mix and use calorimetry as a tool to predict set times or strengths. In other words, the shape of the three curves in Figure 11 representing the three replacement levels can be combined into a mathematical form, which can be used to predict set times of strength at other intermediate replacement levels.

The following are two examples of methods used to predict concrete set time using semi-adiabatic calorimetry data:

1. Concrete set times have been correlated to the change in slope of the heat evolution curve (Cost & Gardiner, 2009; Wang et al., 2007; Schindler, 2004). The time at which the first derivative of the curve peaks has been correlated to the final set time, and the time at which the second derivative of the curve is at a maximum, have been correlated to the initial set time. ASTM is considering this correlation as a basis for procedures to determine set times.
2. A second method of estimating set times has been a fixed percentage of the time taken to reach the maximum temperature. Initial set times have been in the range of 19 to 30 percent, and final set times have been in the range of 40 to 60 percent of the time taken to reach maximum temperature.

Under IPRF laboratory evaluations, these procedures were explored using limited test data for five mixes and using three or four fly ash replacement levels for each mix. The testing did not demonstrate good predictive abilities for estimating set times within the scope of the laboratory study performed and are not necessarily recommended for use during mix optimization. Additionally, they cannot be used for flexural strength predictions. However, a user may explore these options if set times are the only parameters of interest and if the user concludes an acceptable level of accuracy with these methods. <u>Note again that the use of calorimetry is recommended only during trial batches, and laboratory tests are required for the fly ash replacement level selected for the final mix</u>.

<u>Recommended Method for the Prediction of Strength and Set Times Using Temperature Monitoring Data</u>

Based on the IPRF laboratory evaluations, it was determined that the predictions of two material properties are valuable when using semi-adiabatic calorimetry procedures during mix optimization:

- Initial set time and final set time which are important for saw cutting operations.
- Flexural strength, which is important for opening the pavement to traffic and as a construction quality.
    - Flexural strengths at 7-days and 28-days were verified but the use of this tool for prediction of 14-day strengths is also encouraged.

The set time and flexural strength can be estimated based on two parameters defining the shape of the curve, namely:

- The temperature rise monitored in the calorimetry measurements.
- The linear slope of the heat of hydration curve.

The prediction model may be expressed as:

$$y = A + B*x_1 + C*x_2$$

where

y =	Prediction parameter—initial set time, final set time, 7-day flexural strength or 28-day flexural strength
A, B, C =	Constants (regressed)
x_1 =	Temperature rise monitored in the calorimetry measurements, °C
x_2 =	linear slope of the heat of hydration curve, °C/hour

The values of the constants *A, B,* and *C* are to be determined through regression.

This model can be derived after identifying that each of these parameters individually is significant for the prediction of strength and set times.

The model should be developed using at least three fly ash replacement levels selected for the initial trial batches in the mix optimization process. For subsequent trial batches when the fly ash replacement is within the initial range selected, the set times and flexural strengths may be estimated using the model and data generated from 24 hours of temperature monitoring.

3.4.4 Step-by Step Approach for Predicting Set Times and Flexural Strength Using Semi-Adiabatic Calorimetry

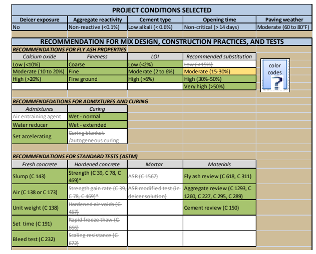
This is not a necessary procedure to be followed during the mix optimization process, but rather an option to minimize laboratory testing and to make quick estimates of 14- and 28-day strengths within 24 to 48 hours of batching. After the selection of the optimal fly ash replacement level, it is necessary to re-batch and retest the mix using the conventional tests recommended in the catalog.

The following approach is suggested for the use of semi-adiabatic calorimetry to estimate set times and flexural strength. Examples for prediction of set time and strength are shown using four mix designs. The approach is illustrated graphically in Figure 12.

Step 1: Select Fly Ash Replacement Levels

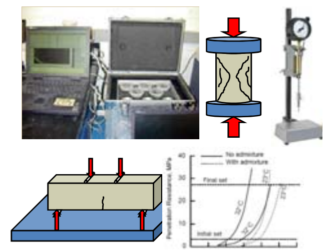
- Determine recommended range of fly ash replacement from the mix optimization catalog.
- Select three replacement levels - FA1, FA2, FA3.

FA1% < FA2% < FA3%
FA1% and FA3% refer to the limits of the recommended replacement levels approximately



Step 2: Laboratory Tests – Strength, Set Times and Calorimetry for 3 Mixes

- ✓ Determine flexural and/or compressive strengths at required ages, ex. 7-, 14-, and 28-days based on ASTM C 78 and C 39.
- ✓ Determine initial and final set times based on ASTM C 403
- ✓ Evaluate heat evolution and temperature g
  - o Determine temperature rise, *Δtemp = max– min temperature*
  - o linear slope of the curve = *Δtemp /Δtime for dominant peak*



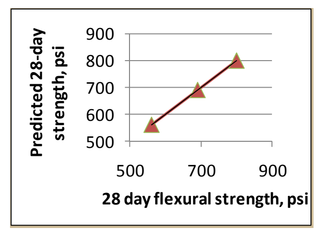
Step 3: Develop Models for Mix Design

- ✓ Develop models to predict initial set time, final set time, strength at a given age by correlating lab measured values to heat of hydration curve parameters:
  - o Temperature rise, Δtemp
  - o linear slope of the curve, Δtime

Examples

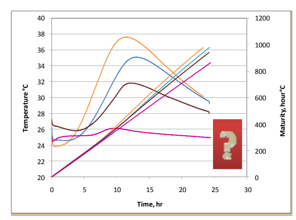
*Final set time = 7.88 + 1.51*Δtemp - 20.58*(Δtemp/ Δtime)*

$M_{r\,(28\text{-}day)}$ *= 73.95 + 31.05*Δtemp – 211.39*(Δtemp/ Δtime)*



Step 4A: Predict Feasibility of Using Other Fly Ash Replacement Levels

- ✓ For fly ash replacements evaluated between FA1% and FA3%
  - o Monitor semi-adiabatic temperature rise for a period of 24 hours
  - o Determine temperature rise and linear slope, Δtemp and Δtemp / Δtime
  - o Predict Strength and Set times from models in step 3
  - o Evaluate heat evolution curve for indications of anomalies



Step 4B: Field Use

- ✓ For fly ash replacements between FA1% and FA3% used on field
  - o Repeat process outlined in step 4A to evaluate consistency in mix used for paving
    - o Identify change in materials (cement, admixture)
    - o Identify incompatibility between materials

Figure 12. Using semi-adiabatic calorimetry for the estimation of set times and strength

<u>Step 1 – Select Fly Ash Replacement Level</u>: Use the mix optimization catalog and select at least three fly ash replacement rates, say, FA1, FA2, and FA3, where FA1 < FA2 < FA3.

<u>Step 2 – Perform Laboratory Tests</u>: Use the selected fly ash replacement rates in trial batches and perform laboratory tests. The tests should include:

- Flexural strength tests (ASTM C 78) at the applicable ages (for example, 7, 14, and 28 days).
- Concrete set time to measure initial setting and final setting time (ASTM C 403).
- Semi-adiabatic calorimetry using the equipment manufacturer's standard test procedure to record temperature data in the hydrating mix for a period of at least 24-48 hours after mix.
    - Determine *temperature rise*, Δ*temp* = *max– min temperature*
    - Determine *linear slope* of the curve = Δ*temp* /Δ*time for dominant peak*

Next, assemble the data in a systematic manner for the prediction of 7- and 28-day flexural strengths and initial and final set times. The sample data in Table 9 represent the curves shown in Figure 11.

Table 9. Data assembly for developing prediction models

Column 1	*Column 2*	*Column 3*	*Column 4*	*Column 5*	*Column 6*	*Column 7*	*Column 8*
MIX ID	**Fly ash replacement level**	**Temperature rise, °C**	**Linear slope, °C/hour**	**7-day flexural strength, psi**	**28-day flexural strength, psi**	**Initial set time, hr**	**Final set time, hr**
Mix 1	FA1 – 15%	16.13	1.07	690	800	6.83	10.37
	FA2 – 30%	14.34	0.81	585	690	10.00	12.95
	FA3 – 50%	11.74	0.57	450	560	10.17	13.83

<u>Step 3 – Develop Prediction Models for Mix</u>: Examine the calorimetry data for the mix with each replacement level. Ensure that the data are reasonable and that the trends represent the expected mix behavior.

Next, ensure that each individual material property of interest—set time and/or flexural strength—shows a good correlation with each calorimetry curve parameters to be used for the model development. As an example, Figure 13 and Figure 14 show a good correlation between the temperature rise parameter vs. 7-day and 28-day strengths for four different mixes including mix 1 (Note: Data for mix 1 is tabulated in Table 9). Likewise, Figure 15 and Figure 16 show a good correlation between the linear slope parameter and the 7-day and 28-day flexural strengths. Evaluate the correlation for the set time parameters in a similar manner.

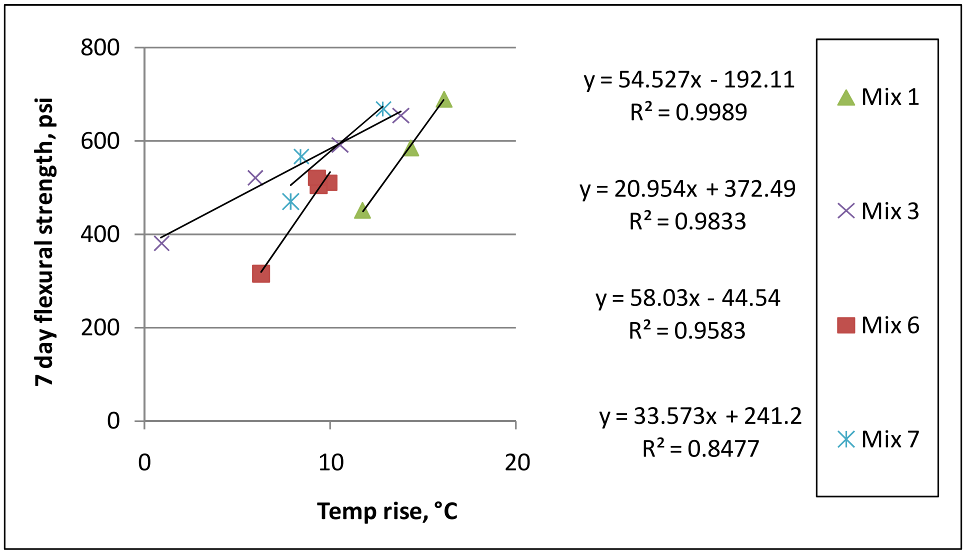


Figure 13. Good correlation between temperature rise and 7-day flexural strength

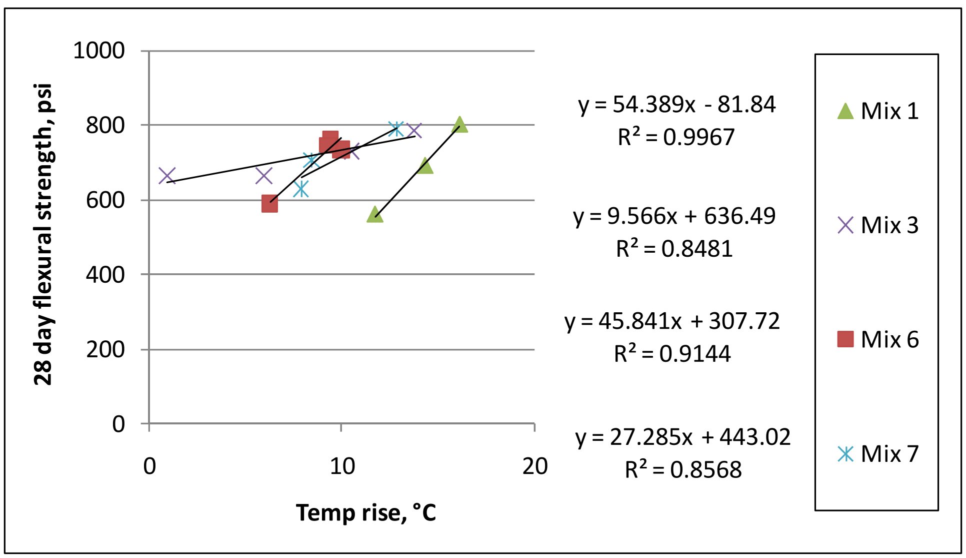


Figure 14. Good correlation between temperature rise and 28-day flexural strength

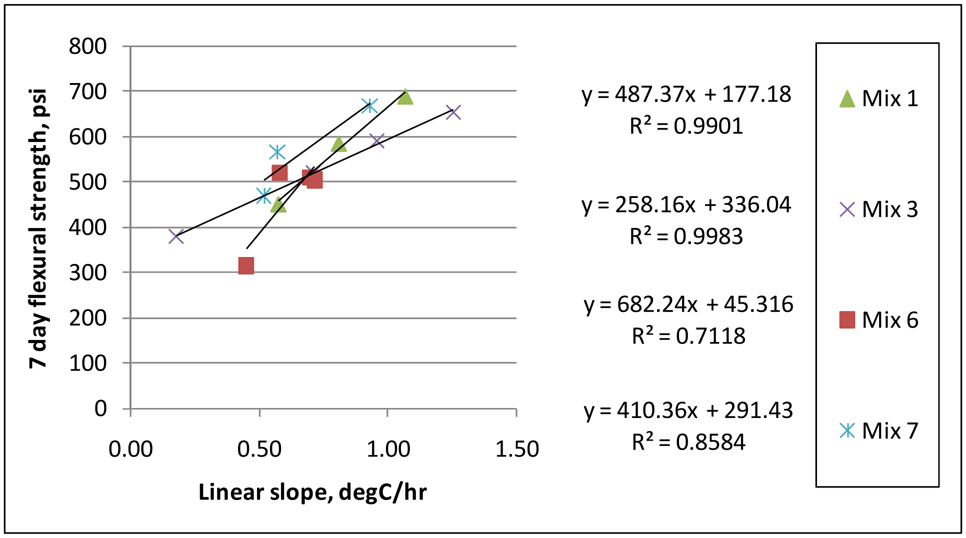


Figure 15. Good correlation between linear slope and 7-day flexural strength

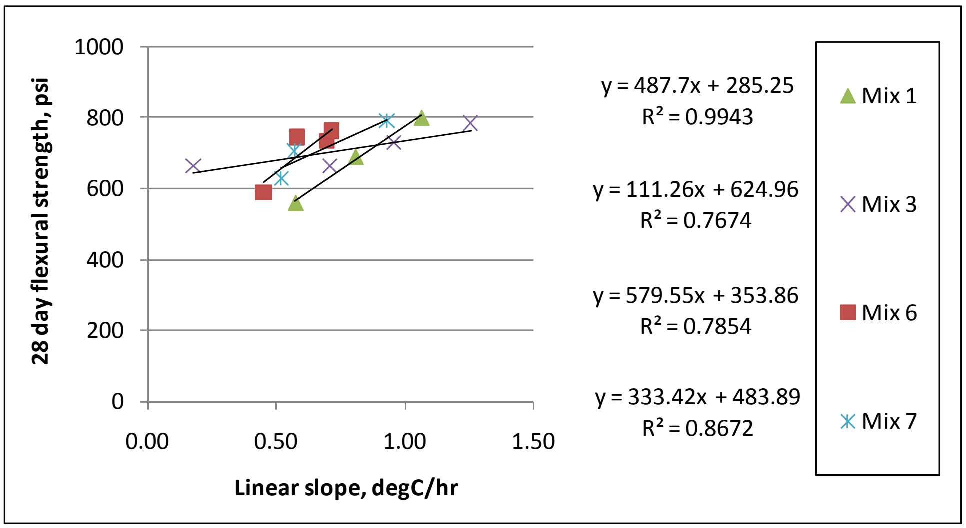


Figure 16. Good correlation between linear slope and 28-day flexural strength

Next, correlate the parameters of interest—initial set time, final set time, 7-day and 28-day flexural strengths—to the calorimetry curve parameters *temperature rise* and *linear slope*. Develop prediction models using a linear function of the form:

$$y = A + B*x_1 + C*x_2$$

where

y =	Dependent variable—initial set time, final set time, 7-day flexural strength or 28-day flexural strength
A, B, C =	Constants (regressed)
x_1 =	Temperature rise monitored in the calorimetry measurements, °C
x_2 =	Linear slope of the heat of hydration curve, °C/hour

For example,

$$\textit{Final set time} = 7.88 + 1.51*\Delta temp - 20.58*(\Delta temp/\Delta time)$$
$$M_{r\,(28\text{-}day)} = 73.95 + 31.05*\Delta temp - 211.39*(\Delta temp/\Delta time)$$

For the example mix design used in Table 9 and Figure 11, the regression coefficients for set times and flexural strength at 7 and 28 days are summarized in Table 10. An example is used here for the purpose of demonstrating the procedure. A different set of coefficients will be obtained for each mix design.

Table 10. Model coefficients for the prediction of flexural strength and set time

Model & Coefficient	Calorimetry curve parameter	Prediction Parameter			
		7-day flexural strength	*28-day flexural strength*	*Initial set time*	*Final set time*
A	Constant	-101.18	73.95	-4.45	7.88
B	Temp rise	40.91	31.05	2.80	1.51
C	Slope	123.37	211.39	-31.82	-20.58

Plot the data and examine the predictive ability of the model. The 7-day and 28-day flexural strength predictions for four different mixes are shown in Figure 17 and Figure 18. These figures also show the data for mix 1 that correspond to the laboratory data tabulated in Table 9. Therefore, using the laboratory test data, it is shown here that the predicted flexural strengths are very close to that measured in the laboratory testing. Figure 19 and Figure 20 show the prediction of set times for four different mixes, including mix 1. The predicted flexural strengths and set times are tabulated in Table 11 for the chosen example with mix 1.

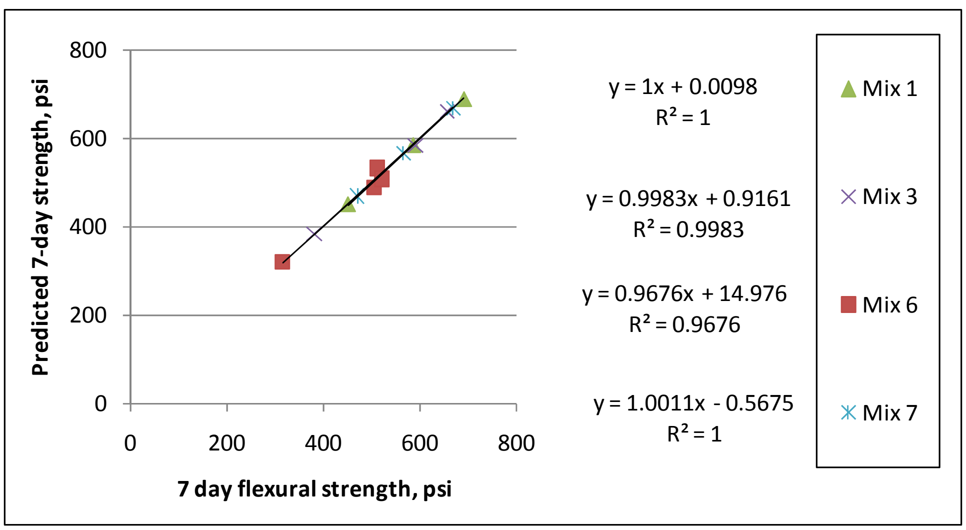


Figure 17. Predicted vs. measured 7-day flexural strength for four different mixes

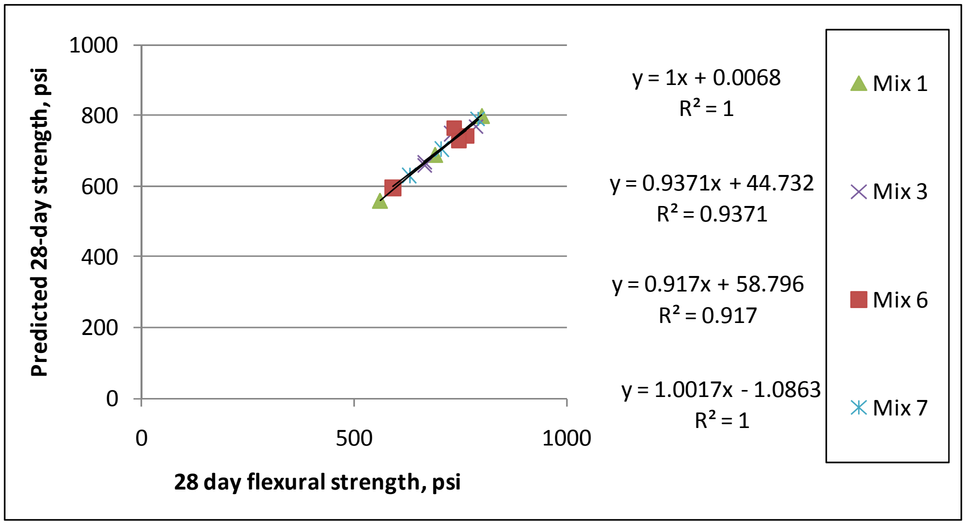


Figure 18. Predicted vs. measured 28-day flexural strength for four different mixes

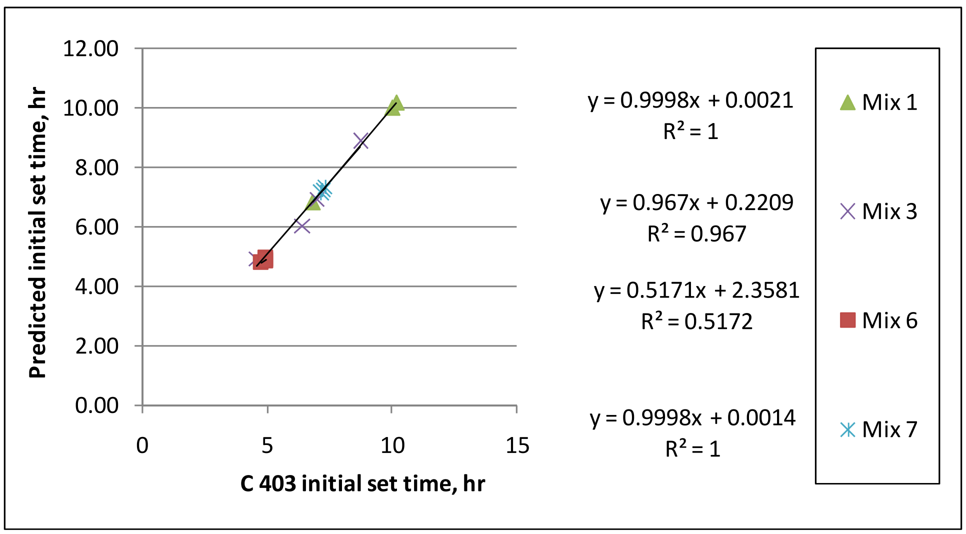


Figure 19. Predicted vs. measured initial set time for four different mixes

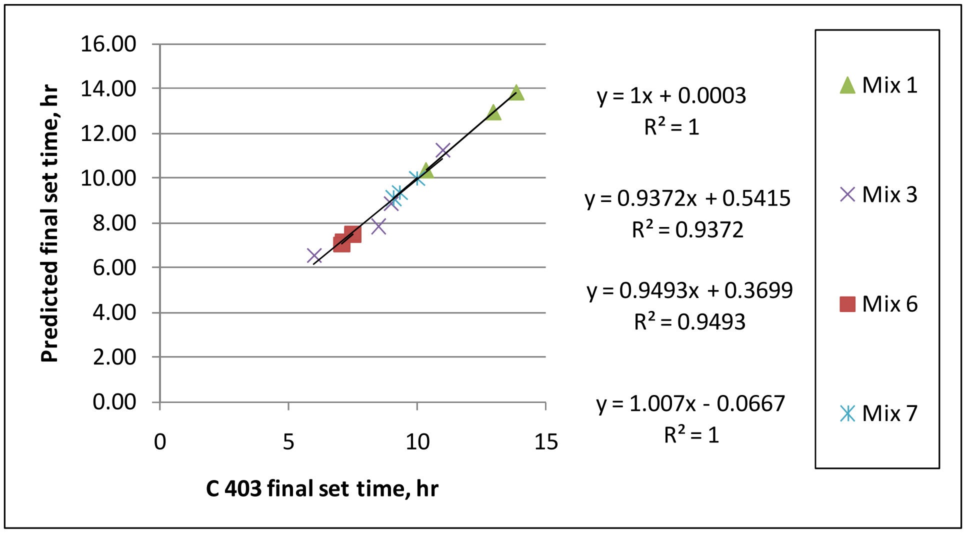


Figure 20. Predicted vs. measured final set time for four different mixes

Table 11. Summary of predicted and measured flexural strengths and set times for mix 1

Flexural strength predictions										
Mix	*Fly ash, %*	*Measured flexural strength, psi*		*Predicted flexural strength, psi*		*Error in prediction*		*Sum of squared error*	
		7-day	*28-day*	*7-day*	*28-day*	*7-day*	*28-day*	*7-day*	*28-day*
1	15	690	800	690	800	0.0	0.0	0.0	0.0
1	30	585	690	585	690	0.0	0.0		
1	50	450	560	450	560	0.0	0.0		
Set time predictions									
Mix	*Fly ash, %*	*Measured set time, hours*		*Predicted set times, hours*		*Error in prediction*		*Sum of squared error*	
		Initial	*Final*	*Initial*	*Final*	*Initial*	*Final*	*Initial*	*Final*
1	15	6.83	10.37	6.83	10.37	0.00	0.00	1E-06	2E-07
1	30	10.00	12.95	10.00	12.95	0.00	0.00		
1	50	10.17	13.83	10.17	13.83	0.00	0.00		

Step 4 – Use Prediction Models to Estimate Strength and Set Times: Use the models developed to predict flexural strength and set times to estimate flexural strength and set times with other fly ash replacement rates between FA1% and FA3%. These may be used in the laboratory during mix optimization to predict feasibility of other fly ash replacement levels or on field during paving. Details are discussed below.

It is recommended that the same calorimeter device type (i.e., same manufacturer and model) used for developing the models in step 3 should be used for the prediction of material properties. In general, in the absence of ASTM procedures or other standard practices, the user should ensure that the test conditions are consistent. This also eliminates the risk of variability in test data when the equipment and test methods are switched out.

Step 4A: Predict Feasibility of Using Other Fly Ash Replacement Levels: During the mix optimization process, if trial batches with fly ash replacement levels between FA1% and FA3% are evaluated in the laboratory, calorimetry may be used to replace conventional set time and strength tests in the interest of cost and time savings. For estimating strength and set times:

- Monitor semi-adiabatic temperature rise for a period of 24 hours.
- Evaluate heat evolution curve for indications of anomalies.
- Determine temperature rise and linear slope, Δtemp and Δtemp/Δtime.
- Predict strength and set times from the models in step 3.

Step 4B: Field Use: For fly ash replacements between FA1% and FA3% used in paving mixtures on field, consider using semi-adiabatic calorimetry as a QC tool. Collect sample and monitor semi-adiabatic temperature rise:

- Repeat process outlined in step 4A to evaluate consistency in mix used for paving.
- Identify change in materials (cement, admixture) by tracking the heat evolution curve and comparing with laboratory measurements from step 3.
- Identify incompatibility between materials by tracking the heat evolution curve and comparing with laboratory measurements from step 3.

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CHAPTER 4. AIRPORT PROJECT CASE STUDIES

4.1 INTRODUCTION

Six airfield project case studies are presented to validate the catalog and to demonstrate the value of the recommendations therein. The case studies cover a fairly wide range of parameters considered in the catalog—fly ash mineralogy, chemical composition and physical properties, cement alkalinity, aggregate reactivity, paving weather conditions, deicer exposure, opening time, and fly ash replacement levels. The locations of the projects are shown in Figure 21. It can be observed that these projects are located in both freeze-thaw and non freeze-thaw environments. They also utilized both Class C and Class F fly ashes. None of these projects had sulfate exposure issues.

All projects selected were completed several years ago, and performance data from these projects were used to corroborate the catalog recommendations.

Extensive laboratory testing was performed to validate the catalog recommendations during the IPRF research study. Details are discussed in the research report (Rao et al., 2011).

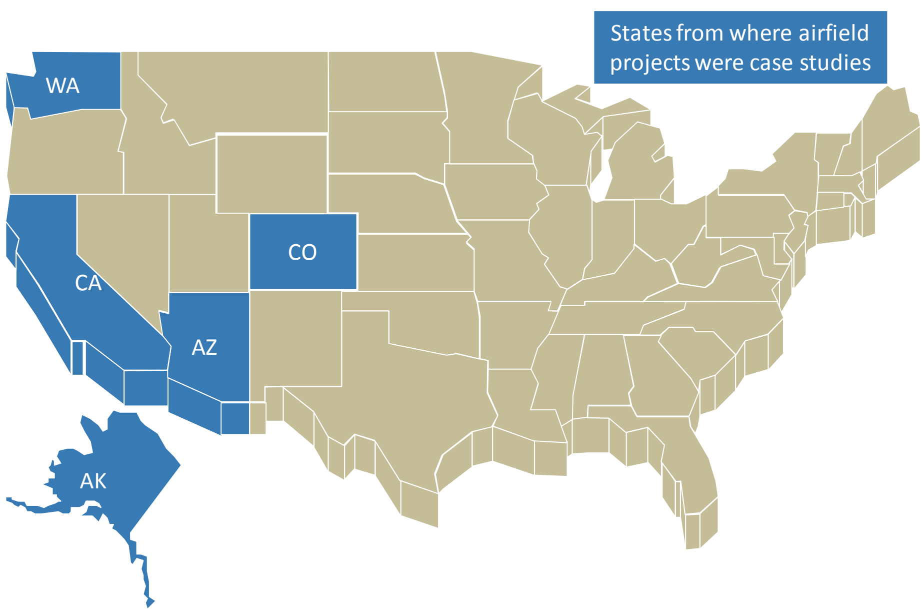

Figure 21. States with airport projects selected for case studies

4.2 CASE STUDIES

The following projects are included as case studies:

- Project A: Airport in Colorado that used fly ash successfully and pavement shows good performance.
- Project B: Airport in Colorado that used fly ash and extensive early failures were observed.
- Project C: Airport in Washington that used high fly ash replacement level but had constructability problems.
- Project D: Airport project in California that used laboratory testing to determine fly ash replacements to achieve good durability.
- Project E: Airport project in Alaska that used laboratory testing to determine optimum fly ash content to meet specifications.
- Project F: Airport in Arizona that eliminated fly ash from the mix design and is experiencing durability problems.

4.2.1 Airport A – Airport in Colorado with Good Performance

This project was paved in 2006 and replaced a badly deteriorated pavement. The mix design information provided by the contractor is presented Table 12. Petrographic analysis on the cores extracted from this pavement showed no signs of distress.

The mix design was Type I-II cement and 30 percent Class F ash. The aggregates used were reactive aggregates. The cement used in the mix design had an alkali content of 0.55 percent and can be categorized as a low-alkali cement (below 0.6 percent) per ASTM C 150.

Tests on the fly ash showed that it had moderate oxide levels (10 to 20 percent) with a low LOI. Chemical analysis was performed by the fly ash vendor as well as an independent laboratory, and they respectively determined oxide levels of 11.3 and 10.62 percent and LOIs of 0.46 and 0.23 percent.

The coarse aggregate used in this project was categorized as reactive with ASR potential based on the conventional ASTM C 1260 mortar bar tests. The results from the ASTM C 1260 tests were not available for review.

For the combined aggregate and cementitious materials blend (including the 30 percent fly ash), the expansion was found to be 0.07 percent at 30 days and 0.03 percent at 16 days when tested under the ASTM C 1567 test procedure. The modified ASTM C 1567 test procedure, also referred to as the interim EB-70 procedure, was performed for mortar bars using 6M potassium acetate solution for soaking the samples. (Note that the EB-70 test procedure was current at the time of this project construction.) Under this test, the expansions were measured to be 0.02 and 0.01 percent at 30 and 16 days, respectively. These expansions are below the 0.1 percent critical level.

Table 12. Mix design for Airport A and properties of the materials used

Mix design component	**Per yd^3**	**Other information**
Cement, Holcim Type I/II	411.2 lb	
Fly ash, Boral Class F	176.3 lb	
Fine aggregate	1264.8 lb	
Coarse aggregate #57	1897.4 lb	
Water	211.5 lb	
Entrained air	5.5%	
Admixture: Air entraining admixture (AEA) Low range water reducer	 0.5 oz/100 lb of cement 4 oz/100 lb of cement	
Approximate physical properties		
Unit weight	146.7 pcf	
Slump, inch	1.75 inches	
Air content	4 – 8%	
w/cm ratio	0.36	
7-day flexural strength	635 psi	
28-day flexural strength	765 psi	

This airfield is exposed to deicer environment, and paving was performed in cooler temperatures. The catalog recommendation for this project is shown in Figure 22.

CATALOG RECOMMENDATION: Fly ash replacement level of 15 to 30 percent. Since there is a secondary recommendation of 30 to 50 percent replacement, it may be inferred that a replacement close to 30 percent would be most favorable. The catalog is in agreement with the selected replacement level for this project. However, the catalog recommends the Modified ASTM C 1567 test.

This mix design has controlled ASR problems on this project successfully. Under the current study, two 18-inch cores were extracted from this project and underwent petrographic examination in the laboratory. The test results indicate that there is no active ASR in the concrete.

PROJECT CONDITIONS SELECTED				
Deicer exposure	**Aggregate reactivity**	**Cement type**	**Opening time**	**Paving weather**
Yes	Reactive (> 0.2%)	Low alkali (< 0.6%)	Non-critical (> 14 days)	Cool (< 60°F)

RECOMMENDATION FOR MIX DESIGN, CONSTRUCTION PRACTICES, AND TESTS

RECOMMENDATIONS FOR FLY ASH PROPERTIES

Calcium oxide	*Fineness*	*LOI*	*Replacement level*
Low (<10%)	Coarse	Low (<2%)	~~Low (< 15%)~~
Moderate (10 to 20%)	Fine	Moderate (2 to 6%)	Moderate (15-30%)
~~High (>20%)~~	Fine ground	~~High (>6%)~~	High (30%-50%)
			~~Very high (>50%)~~

RECOMMENDEDATIONS FOR ADMIXTURES AND CURING

Admixtures	*Curing*
Air entraining agent	Wet - normal
Water reducer	Wet - extended
Set accelerating	~~Curing blanket /autogeneous curing~~

RECOMMENDATIONS FOR STANDARD TESTS (ASTM)

Fresh concrete	*Hardened concrete*	*Mortar bar*	*Materials review*
Slump (C 143)	Strength (C 39, C 78, C 469)*	~~ASR potential (C 1567)~~	Fly ash (C 618, C 311)
Air (C 138 or C 173)	~~Strength gain rate (C 39, C 78, C 469)*~~	ASR and deicer reactivity (Modified ASTM C 1567)	Aggregates (C 1260, C 1293, C 227, C 295, C 289)
Unit weight (C 138)	Hardened air voids (C 457)		Cement (C 150)
Set time (C 403)	Rapid freeze thaw (C 666)		
Bleed test (C 232)	Scaling resistance (C 672)		

COMMENTS AND OTHER CONSIDERATIONS

* Strength tests include ASTM C 39 for compressive strength, C 78 for flexural strength, and C 469 for elastic modulus.

1. The high replacement level might increase scaling potential. ASTM C 672 and C 666 are recommended.
2. The low LOI level is recommended, but the moderate level may be adequate to meet air void requirements critical for cold climates.
3. Wet extended curing is recommended for the high replacement level.

Figure 22. Mix optimization catalog recommendations for Airport A

4.2.2 Airport B – Airport in Colorado with Poor Performance

This project was paved in 1991. The mix design used Type I LA cement manufactured by Holcim with 8 percent Class C high oxide fly ash replacement. The cement conformed to ASTM C 150 and had an alkali content of 0.31 percent, which falls under the low alkali content category in the catalog. The aggregates were considered reactive and were tested to meet specification requirements for gradation, specific gravity/absorption, abrasion resistance, lightweight pieces, sodium sulfate soundness, and clay lumps and friable particles.

This airfield pavement has performed very poorly and has been the subject of investigation for many years. The pavement showed early signs of distress that was attributed to ASR damage and D-cracking.

The surface condition of this pavement as observed during a visual survey in fall 2009 is shown in Figure 23. The presence of ASR and D-cracking was evident on this runway. Cores from this pavement were extracted for petrographic analysis. Results of the petrographic analysis indicated no evidence of ASR. The coarse and fine aggregates appeared to be non-reactive.

Figure 23. Surface condition of pavement in Airport B

In 2010, materials comparable to those used in this project were used to evaluate the mix design in laboratory tests with fly ash replacement levels of 0, 15, 35, and 60 percent. In addition to conventional strength tests, rapid freeze-thaw resistance (ASTM C 666) and scaling resistance tests were conducted. The results are summarized in Table 13 and Table 14. The mix with fly ash replacement level of 60 percent does not indicate good durability. Also, the length change is higher than the threshold for all the fly ash replacement levels.

Table 13. Freeze-thaw results for mix from Airport B

Fly ash replacement level	Weight loss, %	Length change, %[1]	Durability factor[2]
0	0.35	0.04	85.5
15	0.525	0.045	70.5
35	0.99	0.065	70.5
60	3.3	0.13	60

[1] Length change below 0.0375 percent ensures that the aggregate is not susceptible to D-cracking.
[2] The recommended threshold for the durability factor is a value of 60.

Table 14. Scaling test results for mix from Airport B

Fly ash replacement, %	Rating, 0=good & 5=poor[3]	Weight loss@ 50 cycles, gm	Area	Scaling rate, gm/sec
0	1	2.4	60	0.04
15	***3***	9.85	60	0.165
35	***4***	25.35	60	0.42
60	***5***	81.6	60	1.36

[1] Ratings above 2 are susceptible for scaling problems

A visual examination of the freeze-thaw samples corroborated findings from the freeze-thaw tests. The aggregates in this project were not of good quality. The aggregates did not hold up well, as shown in Figure 24. The pictures show a variety of problems with the aggregates used in this mix. The two pictures on the top show aggregate sockets indicating the aggregates disintegrated through the freeze-thaw cycles. The two pictures on the bottom are magnified 10 times and show a crack passing through the aggregate particles. The problems with Airport B appear to be associated with poor-quality aggregates.

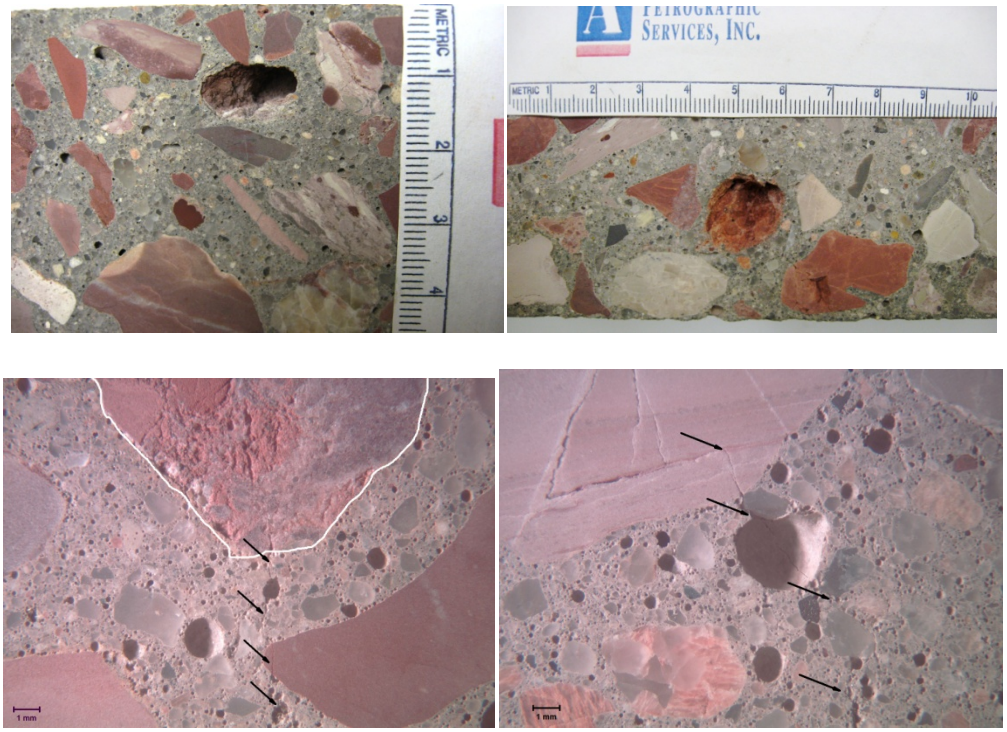

Figure 24. Visual examination of the freeze thaw samples used from Airport B

This case study was used to verify if the catalog recommends a different fly ash type or replacement level that could have prevented some of the observed distresses in the pavement. Additionally, the catalog recommends tests that might have allowed identification of the problems observed on field. The catalog recommendation for this project is shown in Figure 25.

CATALOG RECOMMENDATION: Low or moderate oxide fly ash at replacement level of 15 to 30 percent, and possibly higher replacement rates to mitigate durability problems. Therefore, the mix design used in the project is not in agreement with the catalog. Additionally, freeze-thaw tests and scaling tests are recommended, which would have identified the problems associated on the field.

Indirectly, this confirms the validity of the catalog recommendations for low oxide levels and higher replacement rates for the fly ash to curb ASR damage.

PROJECT CONDITIONS SELECTED				
Deicer exposure	**Aggregate reactivity**	**Cement type**	**Opening time**	**Paving weather**
Yes	Reactive (> 0.2%)	Low alkali (< 0.6%)	Non-critical (> 14 days)	Hot (> 80°F)

RECOMMENDATION FOR MIX DESIGN, CONSTRUCTION PRACTICES, AND TESTS

RECOMMENDATIONS FOR FLY ASH PROPERTIES

Calcium oxide	*Fineness*	*LOI*	*Replacement level*
Low (<10%)	Coarse	Low (<2%)	~~Low (< 15%)~~
Moderate (10 to 20%)	Fine	Moderate (2 to 6%)	Moderate (15-30%)
~~High (>20%)~~	Fine ground	~~High (>6%)~~	High (30%-50%)
			~~Very high (>50%)~~

RECOMMENDEDATIONS FOR ADMIXTURES AND CURING

Admixtures	*Curing*
Air entraining agent	Wet - normal
Water reducer	Wet - extended
~~Set accelerating~~	~~Curing blanket /autogeneous curing~~

RECOMMENDATIONS FOR STANDARD TESTS (ASTM)

Fresh concrete	*Hardened concrete*	*Mortar bar*	*Materials review*
Slump (C 143)	Strength (C 39, C 78, C 469)*	~~ASR potential (C 1567)~~	Fly ash (C 618, C 311)
Air (C 138 or C 173)	~~Strength gain rate (C 39, C 78, C 469)*~~	ASR and deicer reactivity (Modified ASTM C 1567)	Aggregates (C 1260, C 1293, C 227, C 295, C 289)
Unit weight (C 138)	Hardened air voids (C 457)		Cement (C 150)
Set time (C 403)	Rapid freeze thaw (C 666)		
Bleed test (C 232)	Scaling resistance (C 672)		

COMMENTS AND OTHER CONSIDERATIONS

* Strength tests include ASTM C 39 for compressive strength, C 78 for flexural strength, and C 469 for elastic modulus.

1. The high replacement level might increase scaling potential. ASTM C 672 and C 666 are recommended.
2. The low LOI level is recommended, but the moderate level may be adequate to meet air void requirements critical for cold climates.
3. Wet extended curing is recommended for the high replacement level.

Figure 25. Mix optimization catalog recommendations for Airport B

4.2.3 Airport C – Airport in Washington

The mix design used in this case study was used for apron construction in 2004. The aggregates at this site are from a volcanic source and were considered reactive when tested under ASTM C 1260. The cement was Type I-II cement with a low alkali content and produced by Lafarge in Richmond, Washington. The alkali content for the cement was determined as 0.50 percent in laboratory tests. The mill certification from Lafarge reported it as 0.46 percent.

The fly ash was Class F from Edmonton, Alberta, with 9 percent calcium oxide and LOI of 0.5 percent. This qualifies as a low oxide ash with a low LOI.

For the mix design using no fly ash, the mortar bar test expansion was at 0.4 percent. Using a 70/30 blend of cement and fly ash, the expansion was reduced to below 0.10 percent when tested using the ASTM C 1567 test procedure.

For the purpose of validating the catalog, other project details selected included deicer exposure environment and cool paving weather. Project reports indicate that the paving was performed at 50 °F. A non-critical opening time was assumed.

The catalog recommendation for this project is presented in Figure 26.

CATALOG RECOMMENDATION: 15 to 30 percent replacement for non-critical opening time when a low oxide fly ash with a low LOI is used. The catalog is in agreement with this mix design.

During the construction of this project, a few construction issues had to be addressed with the high fly ash replacement rate. There were issues with edge slump and strength gain. The use of admixtures in the original paving mix is not clear. Therefore, it is recommended that the samples be cured at a temperature representative of the paving conditions so that strength gain determinations can represent in-situ conditions.

PROJECT CONDITIONS SELECTED				
Deicer exposure	**Aggregate reactivity**	**Cement type**	**Opening time**	**Paving weather**
Yes	Reactive (> 0.2%)	Low alkali (< 0.6%)	Non-critical (> 14 days)	Cool (< 60°F)

RECOMMENDATION FOR MIX DESIGN, CONSTRUCTION PRACTICES, AND TESTS

RECOMMENDATIONS FOR FLY ASH PROPERTIES

Calcium oxide	*Fineness*	*LOI*	*Replacement level*
Low (<10%)	Coarse	Low (<2%)	~~Low (< 15%)~~
Moderate (10 to 20%)	Fine	Moderate (2 to 6%)	Moderate (15-30%)
~~High (>20%)~~	Fine ground	~~High (>6%)~~	High (30%-50%)
			~~Very high (>50%)~~

RECOMMENDEDATIONS FOR ADMIXTURES AND CURING

Admixtures	*Curing*
Air entraining agent	Wet - normal
Water reducer	Wet - extended
Set accelerating	~~Curing blanket /autogeneous curing~~

RECOMMENDATIONS FOR STANDARD TESTS (ASTM)

Fresh concrete	*Hardened concrete*	*Mortar bar*	*Materials review*
Slump (C 143)	Strength (C 39, C 78, C 469)*	~~ASR potential (C 1567)~~	Fly ash (C 618, C 311)
Air (C 138 or C 173)	~~Strength gain rate (C 39, C 78, C 469)*~~	ASR and deicer reactivity (Modified ASTM C 1567)	Aggregates (C 1260, C 1293, C 227, C 295, C 289)
Unit weight (C 138)	Hardened air voids (C 457)		Cement (C 150)
Set time (C 403)	Rapid freeze thaw (C 666)		
Bleed test (C 232)	Scaling resistance (C 672)		

COMMENTS AND OTHER CONSIDERATIONS

* Strength tests include ASTM C 39 for compressive strength, C 78 for flexural strength, and C 469 for elastic modulus.

1. The high replacement level might increase scaling potential. ASTM C 672 and C 666 are recommended.
2. The low LOI level is recommended, but the moderate level may be adequate to meet air void requirements critical for cold climates.
3. Wet extended curing is recommended for the high replacement level.

Figure 26. Mix optimization catalog recommendations for Airport C

4.2.4 Airport D – Airport in California

This project used a Type II-V LA cement manufactured by California Portland Cement Company and a Class F fly ash from Gallup Fly Ash. The cement was certified to have an alkali content of 0.57 percent. There was also the option of using a high alkali cement with an alkali content of 1 percent. The fly ash had a low oxide level with a calcium oxide content of 4.78 percent. The fly ash can be considered coarse grained, and it had a low LOI of 0.28. The aggregates were considered reactive.

The selection of cement type and fly ash replacement level was determined through a series of ASTM C 1567 mortar bar tests to verify expansion at 14 days. Both the low and high alkali cements, as well as replacement levels of 0 and 25 percent, were used in the tests. Expansion levels were brought down from 0.4 percent (high alkali cement without fly ash) to 0.024 percent (low alkali cement with 25 percent replacement). Also, the high alkali cement with 25 percent fly ash replacement reduced the expansion to 0.12 percent, and the low alkali cement with no fly ash had an expansion of 0.28 percent.

The final mix design selected used a 15 percent replacement without the use of a water reducer.

The catalog recommendation for this project is shown in Figure 27.

CATALOG RECOMMENDATION: 15 to 50 percent fly ash replacement. The catalog offers other construction considerations depending on the time of paving. The recommendation of 15 to 30 percent replacement applies regardless of the opening time requirements. Higher replacements recommend a water reducer. The catalog is in agreement with this mix design.

4.2.5 Airport E – Airport in Alaska

This project used Type I-II cement and 25 percent Class F ash. The project is in a deicer exposure environment. The aggregates were tested for reactivity under expansion tests at different fly ash replacement levels based on the ASTM C 1567 test. It was determined that the aggregates were reactive at 0 percent replacement and non-reactive at 25 percent replacement. The fly ash used was a Class F ash with a moderate oxide level of 11 percent, low LOI of 0.22, and can be considered fine.

This project involved very detailed material tests and mix design evaluations, including strength gain tests to track the compressive strength and flexural strength at 7, 14, and 28 days. Strength gain at w/cm ratios of 0.27, 0.33, and 0.37 were evaluated. The w/cm ratio required to produce a 720 psi flexural strength was selected from the analyses of strength data. However, ASR durability test results were the primary consideration in selecting the fly ash replacement level. The mix design used for paving did not use a set retarder or accelerator. An air entraining agent and a water reducer were used.

The catalog recommendation for this project is shown in Figure 28.

CATALOG RECOMMENDATION: 15 to 30 percent fly ash replacement regardless of opening time requirements. The catalog is in agreement with this mix design. However, note that the catalog recommends the Modified ASTM C 1567 test.

PROJECT CONDITIONS SELECTED

Deicer exposure	Aggregate reactivity	Cement type	Opening time	Paving weather
No	Reactive (> 0.2%)	Low alkali (< 0.6%)	Non-critical (> 14 days)	Moderate (60 to 80°F)

RECOMMENDATION FOR MIX DESIGN, CONSTRUCTION PRACTICES, AND TESTS

RECOMMENDATIONS FOR FLY ASH PROPERTIES

Calcium oxide	Fineness	LOI	Replacement level
Low (<10%)	Coarse	Low (<2%)	~~Low (< 15%)~~
Moderate (10 to 20%)	Fine	Moderate (2 to 6%)	Moderate (15-30%)
~~High (>20%)~~	Fine ground	High (>6%)	High (30%-50%)
			Very high (>50%)

RECOMMENDEDATIONS FOR ADMIXTURES AND CURING

Admixtures	Curing
~~Air entraining agent~~	Wet - normal
Water reducer	Wet - extended
Set accelerating	~~Curing blanket /autogeneous curing~~

RECOMMENDATIONS FOR STANDARD TESTS (ASTM)

Fresh concrete	Hardened concrete	Mortar bar	Materials review
Slump (C 143)	Strength (C 39, C 78, C 469)*	ASR potential (C 1567)	Fly ash (C 618, C 311)
Air (C 138 or C 173)	~~Strength gain rate (C 39, C 78, C 469)*~~	~~ASR and deicer reactivity (Modified ASTM C 1567)~~	Aggregates (C 1260, C 1293, C 227, C 295, C 289)
Unit weight (C 138)	~~Hardened air voids (C 457)~~		Cement (C 150)
Set time (C 403)	~~Rapid freeze thaw (C 666)~~		
Bleed test (C 232)	~~Scaling resistance (C 672)~~		

COMMENTS AND OTHER CONSIDERATIONS

* Strength tests include ASTM C 39 for compressive strength, C 78 for flexural strength, and C 469 for elastic modulus.

1. Strength requirements will need to be evaluated for replacements in the very high range.
2. Wet normal curing may be adequate for the moderate replacement level. However, wet extended curing is recommended for the high and very high replacement levels.

Figure 27. Mix optimization catalog recommendations for Airport D

PROJECT CONDITIONS SELECTED				
Deicer exposure	**Aggregate reactivity**	**Cement type**	**Opening time**	**Paving weather**
Yes	Reactive (> 0.2%)	Low alkali (< 0.6%)	Non-critical (> 14 days)	Cool (< 60°F)

RECOMMENDATION FOR MIX DESIGN, CONSTRUCTION PRACTICES, AND TESTS

RECOMMENDATIONS FOR FLY ASH PROPERTIES

Calcium oxide	*Fineness*	*LOI*	*Replacement level*
Low (<10%)	Coarse	Low (<2%)	~~Low (< 15%)~~
Moderate (10 to 20%)	Fine	Moderate (2 to 6%)	Moderate (15-30%)
~~High (>20%)~~	Fine ground	~~High (>6%)~~	High (30%-50%)
			~~Very high (>50%)~~

RECOMMENDEDATIONS FOR ADMIXTURES AND CURING

Admixtures	*Curing*
Air entraining agent	Wet - normal
Water reducer	Wet - extended
Set accelerating	~~Curing blanket /autogeneous curing~~

RECOMMENDATIONS FOR STANDARD TESTS (ASTM)

Fresh concrete	*Hardened concrete*	*Mortar bar*	*Materials review*
Slump (C 143)	Strength (C 39, C 78, C 469)*	~~ASR potential (C 1567)~~	Fly ash (C 618, C 311)
Air (C 138 or C 173)	~~Strength gain rate (C 39, C 78, C 469)*~~	ASR and deicer reactivity (Modified ASTM C 1567)	Aggregates (C 1260, C 1293, C 227, C 295, C 289)
Unit weight (C 138)	Hardened air voids (C 457)		Cement (C 150)
Set time (C 403)	Rapid freeze thaw (C 666)		
Bleed test (C 232)	Scaling resistance (C 672)		

COMMENTS AND OTHER CONSIDERATIONS

* Strength tests include ASTM C 39 for compressive strength, C 78 for flexural strength, and C 469 for elastic modulus.
1. The high replacement level might increase scaling potential. ASTM C 672 and C 666 are recommended.
2. The low LOI level is recommended, but the moderate level may be adequate to meet air void requirements critical for cold climates.
3. Wet extended curing is recommended for the high replacement level.

Figure 28. Mix optimization catalog recommendations for Airport E

4.2.6 Airport F – Airport in Arizona

Concrete produced in the desert southwest uses river gravels often as sources of sand and gravel. These sources frequently contain siliceous particles vulnerable to ASR. A paving project at a major metropolitan airport built over 15 years ago is experiencing advanced ASR distress in a pavement. These distresses were observed when the pavement was a little over 14 years old. A value engineering proposal accepted during the project construction eliminated fly ash from the mix design, increasing the likelihood of ASR. The primary reason for eliminating fly ash and boosting the cement factor was a concern for strength development, as the project had a critical opening time requirement.

The observed distresses are considered extensive, and some sections have been scheduled for replacement. For the new mix design, extensive concrete tests have been performed, including verification for mortar bar expansions based on ASTM C 1260 and 1-year beam expansions from ASTM C 1293.

The standard mix design incorporating fly ash that was planned originally but was not used on the project paving job is presented in Table 15. The mix design used for paving used no fly ash replacement.

The catalog recommendation for this project is shown in Figure 29.

CATALOG RECOMMENDATION: 15 to 30 percent fly ash replacement, and possibly a higher replacement along with the use of a water reducer in the mix design. Also note the requirement to verify strength gain rate and the recommendation for extended curing. The catalog is in agreement with this mix design and indirectly explains the material-related distresses observed on the field.

Table 15. Original mix design intended for Airport F

<table>
<tr><th>Mix design component</th><th>Batch weights per yd^3</th><th>Other Mix Details</th></tr>
<tr><td>Cement, Type II Clarkdale</td><td>411 lb</td><td rowspan="9">w/c ratio = 0.34
Slump = 1.25 inch
Air content = 2.8%
Unit weight = 147 pcf
Initial set time = 3:41 hours
Final set time = 5:53 hours

Air temperature = 94 °F
Mix temperature = 90 °F

7-day flexural strength = 615 psi
14- day flexural strength = 660 psi
21-day flexural strength = 690 psi
28-day flexural strength = 735 psi</td></tr>
<tr><td>Fly ash, Cholla Class F</td><td>176 lb
(30% replacement)</td></tr>
<tr><td>Water</td><td>235</td></tr>
<tr><td>Fine aggregates</td><td>1213</td></tr>
<tr><td>Coarse aggregate #67</td><td>1092</td></tr>
<tr><td>Coarse aggregate #4</td><td>842</td></tr>
<tr><td>BASF PaveAir (AEA)</td><td>4.4 oz</td></tr>
<tr><td>BASF MasterPave (water reducer)</td><td>41.8 oz</td></tr>
<tr><td>Air content %</td><td>2.8 %</td></tr>
</table>

NOTE: Mix design used for paving eliminated the fly ash and used 587 lb of cement

PROJECT CONDITIONS SELECTED				
Deicer exposure	**Aggregate reactivity**	**Cement type**	**Opening time**	**Paving weather**
No	Reactive (> 0.2%)	Low alkali (< 0.6%)	Quick (< 14 days)	Hot (> 80°F)

RECOMMENDATION FOR MIX DESIGN, CONSTRUCTION PRACTICES, AND TESTS

RECOMMENDATIONS FOR FLY ASH PROPERTIES

Calcium oxide	*Fineness*	*LOI*	*Replacement level*
Low (<10%)	Coarse	Low (<2%)	~~Low (< 15%)~~
Moderate (10 to 20%)	Fine	Moderate (2 to 6%)	Moderate (15-30%)
~~High (>20%)~~	Fine ground	High (>6%)	High (30%-50%)
			~~Very high (>50%)~~

RECOMMENDEDATIONS FOR ADMIXTURES AND CURING

Admixtures	*Curing*
~~Air entraining agent~~	Wet - normal
Water reducer	Wet - extended
~~Set accelerating~~	Curing blanket /autogeneous curing

RECOMMENDATIONS FOR STANDARD TESTS (ASTM)

Fresh concrete	*Hardened concrete*	*Mortar bar*	*Materials review*
Slump (C 143)	Strength (C 39, C 78, C 469)*	ASR potential (C 1567)	Fly ash (C 618, C 311)
Air (C 138 or C 173)	Strength gain rate (C 39, C 78, C 469)*	~~ASR and deicer reactivity (Modified ASTM C 1567)~~	Aggregates (C 1260, C 1293, C 227, C 295, C 289)
Unit weight (C 138)	~~Hardened air voids (C 457)~~		Cement (C 150)
Set time (C 403)	~~Rapid freeze thaw (C 666)~~		
Bleed test (C 232)	~~Scaling resistance (C 672)~~		

COMMENTS AND OTHER CONSIDERATIONS

* Strength tests include ASTM C 39 for compressive strength, C 78 for flexural strength, and C 469 for elastic modulus.

1. The high replacement level can be evaluated in trial batching, but strength gain may be a concern to meet opening strength requirements at this level. If early strength gain is a concern, increasing the total cementitious content may also be considered.
2. Curing blankets may be necessary for opening strength requirements.
3. Wet extended curing is recommended for the high replacement level. Wet normal curing may be adequate for the moderate replacement level.

Figure 29. Mix optimization catalog recommendations for Airport F

4.3 CONCLUSIONS FROM PROJECT CASE STUDIES VALIDATION

Based on the outcome of this validation effort, it is reasonable to say that the catalog recommendations are in agreement with the practices that resulted in good performance of pavements. Additionally, the catalog was validated indirectly with projects that did not provide the expected performance, largely due to the inappropriate use of fly ash or inappropriate material selection.

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Fly Ash Tests

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