Concrete Aggregate Durability Study

Final Report 575

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16. Abstract

There are many factors that affect the durability of Portland cement concrete (PCC), including the mix design and the materials used, the quality of construction, and the environment. Durability is not an intrinsic property of the concrete, but instead is related to how the material interacts with the environment. Durability-related deterioration is referred to as materials-related distress (MRD). Common MRDs include those caused by physical processes, such as freezing and thawing, or chemical processes, such as alkali-silica reactivity (ASR) and sulfate attack. This research project was undertaken to determine whether concrete used in the ADOT system is experiencing, or is potentially susceptible to, ASR or sulfate attack, and if so, to what degree.

Based on this study, ADOT's current practices are consistent with those of its neighboring states, but by no means are they the most rigorous, particularly related to controlling ASR. The following recommendations are made to improve ADOT's approach to ASR and sulfate attack mitigation to ensure success in the future:

- ADOT should review its supplementary cementitious material (SCM) specifications to ensure that those materials being used in its concrete have the desired effect of mitigating ASR and sulfate attack.
- A number of neighboring states permit the use of ASTM C1157 performance-specified cements and ADOT should investigate allowing the use of these cements as well.
- ADOT is following the current state-of-the-practice regarding aggregate screening for ASR susceptibility. New FHWA guidelines (Thomas et al. 2008A) recommend that long-term concrete prism testing be conducted in accordance with ASTM C1293, *Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction,* to establish an empirical relationship with the ASTM C1260 test results to ensure mitigation. This would require ADOT to embark on a long-term study to test their most common ASR-susceptible aggregates, but it is the only currently acceptable approach to developing confidence that the ASTM C1260/C1567 results accurately predict field performance.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	Square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.093	square meters	m^2	m^2	Square meters	10.764	square feet	ft^2
yd^2	square yards	0.836	square meters	m^2	m^2	Square meters	1.195	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	square kilometers	km^2	km^2	Square kilometers	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	m^3	Cubic meters	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	m^3	Cubic meters	1.308	cubic yards	yd^3
	NOTE: Volumes greater than 1000L shall be shown in m^3.								
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000lb)	0.907	megagrams (or “metric ton”)	mg (or “t”)	mg	megagrams (or “metric ton”)	1.102	short tons (2000lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C	°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION					**ILLUMINATION**		
fc	foot candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2	cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE AND PRESSURE OR STRESS					**FORCE AND PRESSURE OR STRESS**		
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380

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EXECUTIVE SUMMARY

There are many factors that affect the durability of Portland cement concrete (PCC), including the mix design and the materials used, the quality of construction, and the environment. Durability is not an intrinsic property of the concrete, but instead is related to how the material interacts with the environment. Durability-related deterioration is referred to as materials-related distress (MRD). Common MRDs include those caused by physical processes, such as freezing and thawing (F-T), or chemical processes, such as alkali-silica reactivity (ASR) and sulfate attack.

Although considered an issue in surrounding states, MRD in general, and ASR and sulfate attack in particular, have not been formally identified in structures or bridges managed by the Arizona Department of Transportation (ADOT). Yet there is ample reason to be concerned that durability could pose a problem for ADOT's PCC. A recent study of a 14-year old PCC pavement on a major airfield in Arizona determined that significant ASR had occurred. Further, ASR has been identified in many hydraulic structures in Arizona, including the Coolidge Dam, Parker Dam, and Steward Dam. Since ASR is a reaction between susceptible aggregates and the alkalis (sodium and potassium) present in the concrete pore solution, this suggests that MRD may be more of a concern to ADOT than previously believed. It is also well-documented that many of the soils in Arizona have sufficient sulfate levels to pose a possible sulfate attack problem. Thus it seems prudent that the possibility of ASR and sulfate attack in Arizona be researched further.

This research project was undertaken to determine whether concrete used in the ADOT system is experiencing, or is potentially susceptible to, ASR or sulfate attack, and if so, to what degree. This objective was addressed through the completion of the following four tasks:

- Task 1. Contact Arizona industries and local and federal agencies in Arizona for published and unpublished experience with ASR/sulfate problems or suspected problems.

- Task 2. Review the history of cement production for cement used in Arizona and the development of specifications used by ADOT for both pavements and structures. Review the historical development of ADOT's aggregate specifications used in concrete.

- Task 3. Review specifications used in surrounding states and national guidelines and compare them to ADOT's specifications for mitigating the impact of ASR and sulfate attack.

- Task 4. Prepare a report documenting the findings of the previous tasks and identifying any needed specification changes to ADOT's current concrete specifications.

The findings of this study can be summarized as follows:

- Both ASR and sulfate attack can potentially impact concrete transportation structures in Arizona, although little evidence exists that links either mechanism to degradation in newly constructed pavements or bridges.

- In particular, there is little immediate concern over ASR, although it is known that reactive aggregates can be found over a broad geographic area including in the vicinity of the Salt (and possibly the Gila) River and along the Santa Cruz River. ADOT has likely avoided obvious ASR problems through the routine use of relatively low alkali cement (0.60 percent Na2Oeq) and the use of low CaO content Class F fly ash (at 25 to 32 percent replacement for cement). ADOT makes allowance for the use of blended Portland-pozzolan cement (ASTM C 595 Type IP (MS)), which would also likely be effective at mitigating ASR.

- The relatively recent addition of aggregate screening testing to the ADOT specification in accordance with ASTM C1260, *Standard Test Method for Potential Alkali Reactivity of Aggregates* (14-day expansion limit of 0.10 percent), is a good step in identifying susceptible aggregates. Mitigation of potentially reactive aggregates follows the current state of the practice, requiring testing using ASTM C1567, *Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate,* in which the cementitious system is a blend of the Portland cement and supplementary cementitious materials (SCMs) to be used in the job mix.

- Although ADOT now requires aggregate screening, many of the surrounding states have more detailed guidance in their specifications related to the use of SCMs, either as a replacement for or as an addition to Portland cement. New Mexico has the most rigorous approach to mitigate ASR using SCMs, whereas Texas provides numerous options for blending various SCMs. Guidance associated with the use of SCMs includes limiting available alkalis in the mix, specifying the addition of pozzolans (20 to 25 percent minimum), and limiting the CaO content of the fly ash (8 to 15 percent maximum). Although not a supplementary material, it is noted that some states also allow the use of lithium-based admixtures to mitigate ASR.

- The potential for sulfate attack exists over a wide geographical area, with 6.9 and 5.9 percent of the surface area of Arizona considered as having moderate to high potential for concrete corrosion (including sulfate attack), respectively. ADOT specifies either Type II or V cements, which have moderate or high resistance to sulfate attack, respectively. Further, there is allowance for the use of blended Portland-pozzolan cement (ASTM C 595 Type IP (MS)) which would likely be effective at mitigating sulfate attack.

- The significantly expanded section in the ADOT specifications on SCMs allows a much broader category of materials to be considered, but few limits are placed. Sulfate attack is addressed by testing cement/SCM blends through use of ASTM C1012, applying expansion limits of 0.10 percent at 6 months for moderate sulfate resistance and 0.05 percent at 6 months and 0.10 percent at 1 year for high sulfate resistance. Since the maximum allowable replacement of Portland cement with an SCM is 25 percent, resistance to sulfate attack is not ensured, but there is provision for the use of additional SCMs if mitigation is sought.

- ADOT's approach to mitigating sulfate attack is consistent with that of most surrounding states, which also specify the use of Type II and V cements. Further, guidance associated with the use of supplementary cementitious materials for addressing sulfate attack includes specifying the addition of pozzolans (20 to 25 percent minimum), limiting the CaO content of the fly ash (8 to 15 percent maximum), and the use of ASTM C1012, *Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution* expansion testing.

Based on this study, ADOT's current practices are consistent with that of its neighboring states, but by no means are they the most rigorous, particularly related to controlling ASR. The following recommendations are made to improve ADOT's approach to ASR and sulfate attack mitigation to ensure success in the future:

- Although ADOT has benefited from abundant sources of low CaO Class F fly ash, it is important to recognize that fly ash characteristics are changing as the coal source, combustor technology, collection methodology, and increasing environmental demands change. Thus there is no assurance that the effectiveness of the fly ash ADOT is currently using will be maintained in perpetuity. ADOT should review its SCM specifications to ensure that those materials being used in its concrete have the desired effect of mitigating ASR and sulfate attack. Of the specifications reviewed, those currently employed by New Mexico's highway department are the most thorough.

- For the most part, ADOT's specifications for cement are similar to those of the surrounding states with one exception: a number of neighboring states also permit the use of ASTM C1157 performance-specified cements. ADOT should investigate allowing the use of these cements as well.

- With regards to aggregate screening for ASR, ADOT is following the current state-of-the-practice utilizing accelerated mortar bar testing in compliance with ASTM C1260/C1567. This testing protocol has some limitations, but its short duration (16 days from casting to completion) makes it extremely attractive for project use. The new FHWA guidelines (Thomas et al. 2008A) recommend that long-term concrete prism testing be conducted in accordance with ASTM C1293, *Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction,* to establish an empirical relationship with the ASTM C1260 test results to ensure mitigation. This would require ADOT to embark on a long-term study to test its most common ASR-susceptible aggregates, but it is the only currently acceptable approach to developing confidence that the ASTM C1260/C1567 results accurately predict field performance.

CHAPTER 1.
OVERVIEW

Introduction

The durability of Portland cement concrete (PCC) has long been identified as a problem by the transportation community. There are many factors that affect the durability of PCC, including the mix design and the materials used, the quality of construction, and the environment. Durability is not an intrinsic property of the concrete, but instead is related to how the material interacts with the environment. As a result, deterioration that results from durability is now referred to as materials-related distress (MRD). Common MRDs include those caused by physical processes such as freezing and thawing (F-T) in a saturated state (paste F-T damage and aggregate F-T damage) or as a result of salt crystallization (physical salt attack) or chemical processes including alkali-aggregate reactivity (including alkali-silica reactivity (ASR) and alkali-carbonate reactivity), sulfate attack, and chemical deicer attack. It is known that MRD affects a large percentage of PCC pavements in certain geographical regions of the United States.

Although considered an issue in surrounding states, MRD in general, and ASR and sulfate attack in particular, have not been formally identified in structures or bridges managed by the Arizona Department of Transportation (ADOT). Yet there is ample reason to be concerned that durability could pose a problem for ADOT's PCC. A recent study of a 14-year old PCC pavement on a major airfield in Arizona determined that significant ASR had occurred. Further, ASR has been identified in many hydraulic structures in Arizona, including the Coolidge Dam, Parker Dam, and Steward Dam. Since ASR is a reaction between susceptible aggregates and the alkalis (sodium and potassium) present in the concrete pore solution, MRD may be more of a concern to ADOT than previously believed. It is also well-documented that many of the soils in Arizona have sufficient sulfate levels to pose a possible sulfate attack problem. Unfortunately, these problems typically take many years to manifest themselves and once detected, corrective action is often times difficult to undertake; because of this, prevention is the best solution. Thus it seems prudent that the possibility of ASR and sulfate attack in Arizona be researched further.

Project Objective

Under ADOT Project 575, research was undertaken to address the objective of determining whether concrete used in the ADOT system is experiencing, or is potentially susceptible to, ASR or sulfate attack, and if so, to what degree. The approach that was followed to make this determination is described below.

Research Approach

The project objectives were met by carrying out the following four tasks:

- Task 1. Contact Arizona industries and local and Federal agencies in Arizona for published and unpublished experience with ASR/sulfate problems or suspected problems.
- Task 2. Review the history of cement production for cement used in Arizona and the development of specifications used by ADOT for both pavements and structures. Review the historical development of ADOT's aggregate specifications used in concrete.
- Task 3. Review specifications used in surrounding states and national guidelines and compare them to ADOT's specifications for mitigating the impact of ASR and sulfate attack.
- Task 4. Prepare a report documenting the findings of the previous tasks and identifying any needed specification changes to ADOT's current concrete specifications.

CHAPTER 2.
ALKALI-SILICA REACTIVITY

Overview of ASR

ASR is a deterioration mechanism in concrete which can cause serious expansion and cracking resulting in major structural damage. ASR progresses in a number of stages, and is not considered deleterious until the concrete is damaged by the reaction (Thomas et al. 2008A). The reaction initiates when available hydroxyl ions (OH^- present in the alkaline pore solution to balance the charge contributed by the positively charged alkali ions of sodium (Na^+) and potassium (K^+)) decompose certain siliceous components of reactive aggregates. This frees the silica to react with the alkali to form the alkali-silica reaction product, or gel. As this gel imbibes water, it swells. It is believed that the swelling of this gel alone does not cause damage, as it has relatively low viscosity and therefore moves readily through the concrete pore network into available space. But as this gel reacts with calcium present in the cement paste, it becomes more viscous and stresses develop, exerting an expansive pressure inside concrete. At a certain point, this pressure exceeds the tensile strength of the aggregate and/or concrete and cracking initiates. ASR causes a characteristic pattern cracking in concrete as shown in Figure 1. At times, it has also been observed to more severely affect joints, as shown if Figure 2, due to the localized increased availability of water. Figure 3 clearly shows the gel product exuding onto the pavement surface through cracks.

Figure 1: Pattern cracking observed in a concrete pavement due to ASR.

Figure 2: Cracking concentrated at joints in a concrete pavement due to ASR.

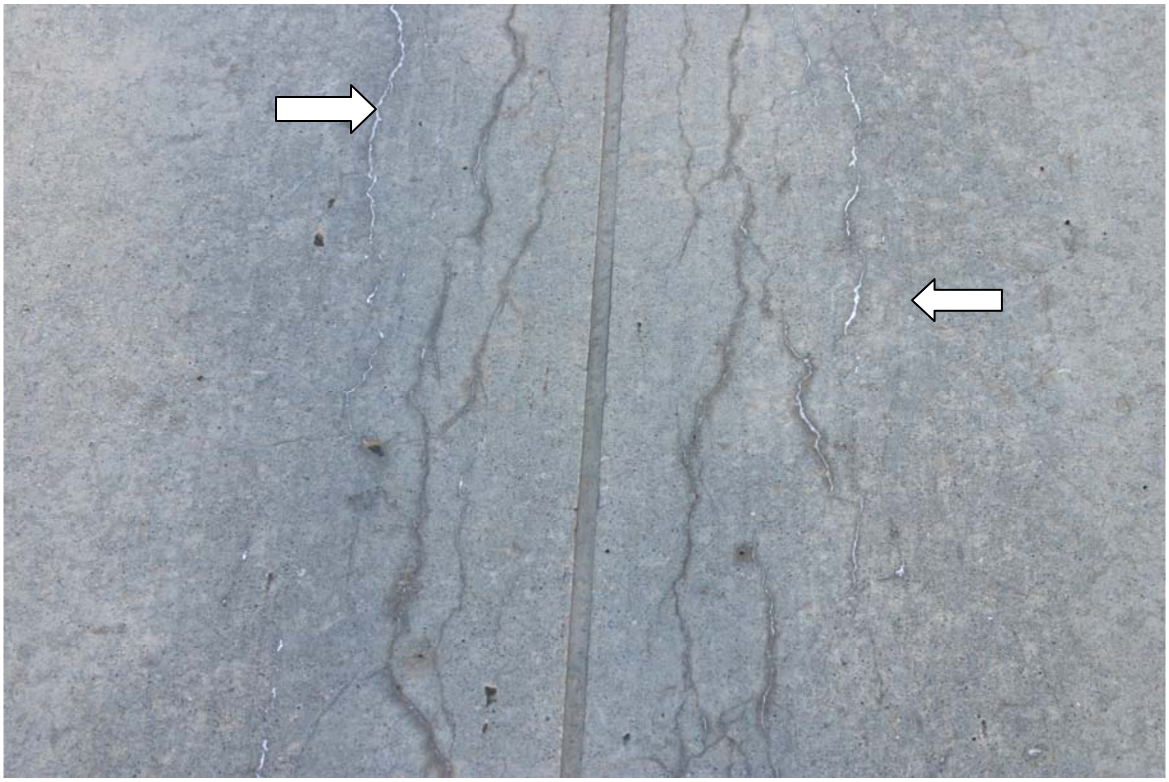

Figure 3. Cracking with white ASR exudate (arrows) in cracks.

It is widely accepted that the following three essential components are necessary for ASR-induced damage to occur in a concrete structure:

- Reactive aggregates – Reactive aggregates typically fall into one of two categories: 1) poorly crystalline or metastable silica materials, and 2) certain varieties of quartz. Note that ASR can even occur in limestone that contains reactive siliceous components (ACI 2008). Table 1 summarizes common examples of reactive rocks and minerals. For deleterious ASR to occur, sufficient reactive aggregate must be present to cause damage.

Table 1. Some examples of commonly reactive aggregate and mineral types (ACI 2008).

Rocks		**Minerals**
Shale	Chert	Opal
Sandstone	Quartzite	Tridymite
Silicified carbonate rock	Quartz-arenite	Crisobalite
Flint	Gneiss	Cryptocrystalline/microcrystalline Quartz
Argillite	Granite	Strained quartz
Greywacke	Siltstone	Volcanic glass
Arenite	Arkose	
Hornfels		

- Water – Deleterious ASR will not occur if water is not available within the concrete, since the expansion of ASR gel requires water. Available moisture is critical in considering a structure's susceptibility to ASR distress. In very dry environments, concrete made with highly reactive aggregates and high alkali cement may not exhibit deleterious expansion due to ASR. Even within a structure there may be varying amounts of expansion depending on exposure conditions. Unfortunately, concrete in contact with the ground, such as that within pavements and many transportation structures, will often maintain the minimum relative humidity of 80 percent required to cause significant expansion due to ASR. As a result, keeping a transportation structure "dry" is not considered a viable mitigation strategy to address ASR.

- Sufficient alkalis – Alkalis present in concrete pore solution can be contributed by the Portland cement, other constituents (e.g., aggregates, fly ash, slag, and silica fume), or may enter the concrete over time from external sources, such as deicing salts or ground water containing sulfates. The primary contributor is the alkalis in Portland cement. The alkali content of cement is expressed as "equivalent alkali content" (Na_2Oeq), determined by the following expression:

$$Na_2Oeq = Na_2O + (0.685 \times K_2O)$$

> where sodium oxide (Na_2O) and potassium oxide (K_2O) contents are expressed as percentages on the cement mill certificate. The use of low alkali cement (< 0.60 percent Na_2Oeq) is commonly cited as an effective mitigation strategy, yet it is better to calculate the total alkali loading in the mixture which accounts for the cement content as well as the addition of other components which may contribute alkalis (ACI 2008). Recently it has been concluded that limiting alkalis may be insufficient to mitigate ASR if highly reactive aggregates are present (Folliard et al. 2006).

The deleterious expansion associated with ASR gel formation and resulting pressure are still not fully understood. The first theory developed attributed the damage to the formation of osmotic pressure cells as water is imbibed, cracking the mortar structure (Hansen 1944). A second theory proposed that water is absorbed by the alkali-silica gel, swelling the gel and stressing the mortar structure (McGowan and Vivian 1952). And a third theory accounts for both previous theories' mechanisms, resulting in cracking depending on alkali-silicate complex (Powers and Steinor 1955). One aspect involving ASR and expansion that has received renewed interest in recent years is the important role of calcium. Although early proposed mechanisms (Hansen 1944; McGowan and Vivian 1952) did not recognize calcium's role in ASR, later studies have identified the presence of calcium in the reactive system as being essential to the deleterious process. Diamond (1989) proposed that, in the absence of calcium, silica simply dissolves in alkali-hydroxide solution and does not form alkali-silicate gel. Most recently, it has been proposed that in the absence of calcium, the gel formed is highly fluid and damage will only occur once the gel viscosity increases as it reacts with calcium from the cement paste (Ichikawa 2007).

ASR Test Methods

The current state-of-the-practice with regards to ASR testing has recently been published by the Federal Highway Administration (FHWA) (Thomas et al. 2008A). This document details the recommended test methods, procedures, and strategies for mitigating ASR.

The most widely used and accepted test methods for assessing the ASR potential of aggregates is ASTM C1260, *Standard Test Method for Potential Alkali Reactivity of Aggregates*. This test is also called the accelerated mortar bar test (AMBT). It is an empirical test in which mortar bars made with the aggregate source in question are immersed in a 1 M NaOH solution at 176^{o}F (80^{o}C) for a minimum of 14 days. According to the recently released FHWA guidance (Thomas et al. 2008), if the expansion does not exceed 0.10 percent at 14 days, the aggregate is considered non-deleteriously reactive. If the 14-day expansion exceeds 0.10 percent, the aggregate should be considered potentially reactive and tested in accordance with ASTM C 1293 as discussed later. A variation of this test is ASTM C1567, *Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate*, which is used to test the effectiveness of supplementary cementitious materials (SCMs), such as fly ash and slag, or lithium-based admixtures in mitigating ASR.

The AMBT has the advantage of being a relatively quick test that is easy to conduct with simple equipment. This allows the rapid assessment of aggregate sources without a large capital investment. But it does have a number of problems associated with it. One problem with this test is that it is considered severe for many aggregate types, rating aggregates as potentially reactive even though they may perform well in service. For example, some have recommended that the expansion limit of 0.10 percent is acceptable for quarried silicate and siliceous carbonate rocks, but should be adjusted to 0.20 percent for natural sands and gravels (Bérubé and Fournier 1992). Others have argued that the 14-day test yields too many false negatives, predicting good performance when in actuality failure results in field specimens (Stokes 2006). It was recommended that the test duration be extended to 28 days, keeping the failure criteria the same. After a thorough review of the available data, one study has suggested that a 14-day expansion criteria of 0.06 percent yields the same result as an expansion criteria of 0.13 percent at 28 days, avoiding the false negatives while minimizing false positives (when an aggregate is rejected for use even though it would have good field performance) (Malvar and Lenke 2008). Clearly more work is needed on establishing test duration and criteria for the AMBT.

As mentioned, if an aggregate is found to be potentially deleteriously reactive based on ASTM C1260, it is recommended that it be tested in accordance with ASTM C 1293, *Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction*. This test method is commonly referred to as the concrete prism test (CPT) and it is generally considered the most accurate test in predicting the field performance of aggregates (Folliard, Thomas, and Kurtis 2003) although some recent work has called this into question. In the test, concrete prisms are made at an increased alkali content and suspended above water at 100°F (38°C) for 1 year. Expansion is measured periodically and if it does not exceed 0.04 percent at one year, the aggregate is considered non-deleteriously reactive. If this test method is being used to assess the effectiveness of a mitigation strategy such as the use of fly ash, slag, or lithium-based admixture, the test duration is extended to 2 years. The long test duration of this test method has somewhat limited its use (Folliard, Thomas, and Kurtis 2003).

While there are a variety of other test methods available (see Table 2), the two mentioned above are the most common for identifying potentially reactive aggregate and form the basis for almost all current ASR test methods employed by state departments of transportation.

Table 2. ASR test methods.

Test Name	Purpose	Type of Test	Test Duration	Comments
ASTM C 227, Potential alkali-reactivity of cement-aggregate combinations (mortar-bar method)	To test the susceptibility of cement-aggregate combinations to expansive reactions involving alkalis	Mortar bars stored over water at 37.8°C (100°F) and high relative humidity	Varies: first measurement at 14 days, then 1, 2, 3, 4, 6, 9, and 12 months; every 6 months after that as necessary	Test may not produce significant expansion, especially for carbonate aggregate. Long test duration. Expansions may not be from alkali-aggregate reactivity.
ASTM C 289, Potential alkali-silica reactivity of aggregates	To determine potential reactivity of siliceous aggregates	Sample reacted with alkaline solution at 80°C (176°F).	24 hours	Quick results. Some aggregates give low expansions even though they have high silica content. Not reliable.
ASTM C 295, Petrographic examination of aggregates for concrete	To outline petrographic examination procedures for aggregates—an aid in determining their performance	Visual and microscopic examination of prepared samples—sieve analysis, microscopy, scratch or acid tests	Short duration—visual examination does not involve long test periods	Usually includes optical microscopy. Also may include XRD[1] analysis, differential thermal analysis, or infrared spectroscopy—see ASTM C 294 for descriptive nomenclature. Important to have an experienced petrographer perform the examination.
ASTM C 342, Potential volume change of cement-aggregate combinations	To determine the potential ASR expansion of cement-aggregate combinations	Mortar bars stored in water at 23°C (73.4°F)	52 weeks	Primarily used for aggregates from Oklahoma, Kansas, Nebraska, and Iowa.
ASTM C 441, Effectiveness of mineral admixtures or GBFS[2] in preventing excessive expansion of concrete due to alkali-silica reaction	To determine effectiveness of supplementary cementing materials in controlling expansion from ASR	Mortar bars—using Pyrex glass as aggregate—stored over water at 37.8°C (100°F) and high relative humidity	Varies: first measurement at 14 days, then 1, 2, 3, 4, 5, 9, and 12 months; every 6 months after that as necessary	Highly reactive artificial aggregate may not represent real aggregate conditions. (Pyrex "releases significant amounts of alkali," promoting reaction. Unlike natural aggregates which "rarely release significant amounts of alkalis into concrete" (Rogers and Hooton 1991).
ASTM C 856, Petrographic examination of hardened concrete	To outline petrographic examination procedures for hardened concrete—useful in determining condition or performance	Visual (unmagnified) and microscopic examination of prepared samples	Short duration—includes preparation of samples and visual and microscope examination	Specimens can be examined with stereo microscopes, polarizing microscopes, metallographic microscopes, and scanning electron microscope. Important to have an experienced petrographer perform the examination.

Table 2 (continued). ASR test methods

Test Name	Purpose	Type of Test	Test Duration	Comments
ASTM C 856 (AASHTO T 299), Annex uranyl-acetate treatment procedure	To identify products of ASR in hardened concrete	Staining of a freshly-exposed concrete surface and viewing under UV light	Immediate results	Identifies small amounts of ASR gel whether causing expansion or not. Opal, a natural aggregate, and carbonated paste can glow - interpret results accordingly. Tests must be supplemented by petrographic examination.
Los Alamos staining method	To identify products of ASR in hardened concrete.	Staining of a freshly-exposed concrete surface with two different reagents	Immediate results	Identifies small amounts of ASR alkali-rich gel whether causing expansion or not. Non-deleterious gel can stain positive - interpret results accordingly. Tests must be supplemented by petrographic examination.
ASTM C 1260 (AASHTO T303), Potential alkali reactivity of aggregates (mortar-bar method)	To test the potential for deleterious alkali-silica reaction of aggregate in mortar bars	Immersion of mortar bars in alkaline solution at 80°C (176°F)	16 days	Very fast alternative to C 227. Useful for slowly reacting aggregates or those that produce expansion late in the reaction.
ASTM C 1293, Determination of length change of concrete due to alkali-silica reaction (concrete prism test)	To determine the potential ASR expansion of cement-aggregate combinations.	Concrete prisms stored over water at 38°C (100.4°F)	Varies: first measurement at 7 days, then 28and 56 days, then 3,6,9,and 12 months; every 6 months as after that as necessary	Preferred method of assessment. Best represents the field. Requires long test duration for meaningful results. Use as a supplement to C 227,C 295, C 289, and C 1260.
ASTM C 1567, Potential alkali-silica reactivity of combinations of cementitious materials and aggregate (accelerated mortar-bar method)	To test the potential for deleterious alkali-silica reaction of cementitious materials and aggregate combinations in mortar bars	Immersion of mortar bars in alkaline solution at 80°C (176°F)	16 days	Very fast alternative to C 1293. Allows evaluation of effectiveness of supplementary cementitious materials.
Supplementary Test Methods				
ASTM C 294, Constituents of natural mineral aggregates	To give descriptive nomenclature for the more common or important natural minerals—an aid in determining their performance	Visual identification	Short duration—as long as it takes to visually examine the sample	These descriptions are used to characterize naturally-occurring minerals that make up common aggregate sources.

(Source: Farny and Kerkhoff 2007)

[1] XRD is X-ray diffraction.

[2] GBFS is ground blast furnace slag cement.

ASR Mitigation

There is considerable recent information on strategies to mitigate ASR in new construction (Farny and Kerkhoff 2007, ACI 2008, Thomas et al. 2008A). The primary methods for mitigating ASR in new concrete construction can be categorized as follows:

- Prescreen aggregate sources and eliminate the use of potentially reactive aggregates.
- Control/limit the alkali content in the concrete.
- Use supplementary cementitious materials (e.g., ground slag, fly ash, natural pozzolan, and silica fume) or alkali-silica reactivity inhibiting admixtures (lithium-based).

In the new FHWA report, specific guidance is provided on how to approach ASR mitigation in a prescriptive manner (Thomas et al. 2008A). The first step is to establish the aggregate reactivity class from the results of the CPT. Based on the aggregate reactivity class and the size of the concrete structure and exposure condition, a level of ASR risk is established. The level of prevention required is then determined from the level of ASR risk and importance of the concrete structure under consideration. From this prevention level, acceptable preventive measures are selected.

In the case where the aggregate is non-deleteriously reactive, no mitigation is required. In some cases where mitigation is required, ASR can be effectively mitigated by limiting the alkali content of the concrete (either in lbs/yd^3 or kg/m^3 Na_2Oeq) or through the effective use of SCMs. In severe cases, both limiting the total alkalis and the use of SCMs are required (Thomas et al. 2008A).

Additional guidance for mitigating ASR can also be found in other sources (Farny and Kerkhoff 2007, ACI 2008). Although not addressed in the new FHWA report, several documents provide guidance on using lithium admixtures to control ASR (Folliard et al. 2003, Farny and Kerkhoff 2007). Also, natural pozzolans have been found to be effective at mitigating ASR (ACI 2008). In all cases, the use of ASTM C1567 and C1293 can be used to determine the effectiveness of mitigation.

On a final note, it is important to understand that the ability of SCMs to mitigate ASR is highly dependent on the nature of the SCM. Typically, fly ash is added as a replacement for cement or as an addition at a rate of 15 to 40 percent to mitigate ASR. In general, Class F fly ash is much more effective than Class C fly ash in providing mitigation. Further, the CaO content of the fly ash is considered to be very important, with limits of 8, 15, or 18 percent being common. The maximum allowable alkali content of the fly ash is also commonly established (Malvar et al. 2008). As the CaO and alkali content of a fly ash increases, its ability to mitigate ASR decreases – in some cases it may even make ASR worse. Slag cement is also commonly used as a replacement for, or as an addition to the cement at a rate of 25 to 65 percent.

ASR in Arizona

A preliminary review of this problem with representatives of the concrete industry and public agency personnel indicates little immediate concern over ASR in Arizona. In general, there is a perception that the ASR problems center on a geographic area along the Salt River (and possibly the Gila River). The Phoenix metropolitan area is particularly affected. A number of structures in that area show some signs of MRD, but due to the long-term nature of the the MRD distress, few local structures have shown signs of distress that cause ADOT concern. While ASR has manifested itself on the upper reaches of the Salt River, where dams built and maintained by the Salt River Project are located, the difference between these two locations probably is related to the constant availability of moisture at the dam sites.

In a recent United States Geological Survey report, alluvial fans along the Santa Cruz River were analyzed for suitability as aggregate (Lindsey and Melick undated). It was found that gravel derived from the Tucson, Sierrita, and Tumacacori Mountains is composed mostly of volcanic rock, much of which is felsic in composition, and may be susceptible to ASR. In particular, the felsic volcanic composition of the Tucson Mountains gravel would likely indicate the presence of abundant unstable silica minerals and volcanic rocks from the Sierrita Mountains which include a high percentage of rhyolite crystal tuff and subordinate crystal-poor ignimbrite would require mitigation for ASR. The U.S. Air Force also cautions that glassy to crptocrystalline rhyolite to andesite volcanics and cherts may be encountered in the basin and range areas of the western U.S. including Arizona (Air Force 2006).

From this information, it seems reasonable to conclude that ASR is a potential problem for large areas of Arizona. ADOT has likely been fortuitous in avoiding obvious ASR problems due to standard use of relatively low alkali cement, standard use of fly ash, and the dry climatic conditions.

Regarding cement, the potential for an ASR problem was recognized early by the Portland cement producers in Arizona. Since the construction of the Glen Canyon Dam on the Colorado River in northern Arizona in 1960, the production of an ASTM Type II, low alkali cement has been standard practice. Cements used in Arizona that are produced in California and Mexico adhere to this requirement.

More importantly than the cement is the fact that fly ash is being used by ADOT in all PCC at a replacement/addition rate of 25 to 32 percent. For the most part, these are Class F fly ashes with CaO contents below 6 percent which makes them extremely effective in mitigating ASR. Phoenix Sky Harbor has a lot of old ASR problems in aprons that were constructed prior to the use of these fly ash limits. Fly ash has been used on all new pavements and there are no known ASR problems. It is important to recognize that fly ash characteristics are always changing due to changes in coal source, combustor technology, collection methodology, and increasing environmental demands. Thus there is no assurance that the effectiveness of the fly ash will be maintained into perpetuity and thus ADOT might want to evaluate its specifications to ensure future performance matches current good performance.

And finally, there is no question that Arizona has benefited from dry climatic conditions, as there is very little moisture available to drive ASR.

ASR Specifications in Arizona

Section 1006 (dated February 20, 2007) of the Arizona DOT specifications was reviewed as it pertains to ASR as well as other durability concerns. The following relevant sections have been extracted from the specifications. Underlined passages are new since the 2000 edition of the *Standard Specifications for Road and Bridge Construction.*

1006-2.01 Cement

Hydraulic cement shall consist of either Portland[1] cement or Portland-pozzolan cement. Portland cement shall conform to the requirements of ASTM C 150 for Type II, III, or V. However, at the option of the manufacturer, processing additions may be used in the manufacture of the cement, provided such processing additions have been shown to meet the requirements of ASTM C 465, and the total amount of such material used does not exceed one percent of the weight of the Portland cement clinker.

Portland-pozzolan cement shall conform to the requirements of ASTM C 595 for Type IP (MS).

Hydraulic cement shall not contain more than 0.60 percent total alkali. The word alkali as used in these specifications shall be taken as the sum of sodium oxide and potassium oxide calculated as sodium oxide (i.e., equivalent alkali content, Na_2Oeq).

1006-2.02 Water

The water used shall be free from injurious amounts of oil, acid, alkali, clay, vegetable matter, silt or other harmful matter. Water shall contain not more than 1,000 ppm of chlorides as Cl and not more than 1,000 ppm of sulfates as SO_4.

Water shall be sampled and tested in accordance with the requirements of AASHTO T 26. Potable water obtained from public utility distribution lines will be acceptable.

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[1] Note that in the ADOT specification, “Portland” is capitalized. In most U.S. literature, including that published by the ACI, AASHTO, and ASTM, portland is not capitalized in portland cement.

1006-2.03 Aggregates

When concrete is to be placed at elevations above 4,500 feet, the fine and coarse aggregate shall be subject to five cycles of the sodium sulfate soundness test in accordance with the requirements of AASHTO T 104. The total loss shall not exceed 10 percent by weight of the aggregate as a result of the test. Tests for soundness may be waived when aggregates from the same source have been approved and the approved test results apply to the current production from that source.

When aggregates show potential for alkali silica reaction (ASR), as indicated by expansions of 0.10 percent or greater at 16 days after casting when tested in accordance with ASTM C 1260, sufficient mitigation for the expansion shall be determined in accordance with ASTM C 1567.

1006-2.04 Supplementary Cementitious Material (Fly Ash, Natural Pozzolan, and Silica Fume)

Fly ash and natural pozzolan shall conform to the requirements of ASTM C 618 for Class C, F, or N mineral admixture, except that the loss on ignition shall not exceed 3.0 percent.

When a supplementary cementitious material with a calcium oxide content greater than 15 percent is used, or when the Special Provisions specify sulfate resistant concrete, the cement intended to be used shall be tested for sulfate expansion in accordance with ASTM C 1157 and ASTM C 1012. For moderate sulfate resistance, the maximum expansion shall be 0.10 percent at six months. For high sulfate resistance, the maximum expansion shall be 0.05 percent at six months and 0.10 percent at one year.

When Class C fly ash is used, the cement intended to be used shall be tested for sulfate expansion in accordance with ASTM C 1157 and ASTM C 1012 and shall have a maximum expansion of 0.05 percent at six months and 0.10 percent at one year.

The use of a supplementary cementitious material is not allowed for replacement of cement when Portland-pozzolan cement [Type IP (MS)] is used. A maximum of 25 percent of the required weight of Portland cement may be replaced with fly ash or natural pozzolan [at 1:1 replacement ratio]. If performance enhancement of the concrete, such as the mitigation of an alkali silica reaction or for increased sulfate resistance is necessary, additional quantities of fly ash or natural pozzolan may be incorporated into the concrete without a corresponding Portland cement replacement, if approved by the Engineer.

Comments on Arizona Specifications

ADOT is addressing the potential for ASR in a number of ways, as discussed below in the same order as presented in the specification:

- Cement alkalinity is limited to 0.60 percent Na_2Oeq. Further, there is allowance for the use of blended Portland-pozzolan cement (ASTM C 595 Type IP (MS)) which would likely be effective at mitigating ASR.
- The addition of aggregate testing using ASTM C1260 (14-day expansion limit of 0.10 percent) with the requirement to mitigate using ASTM C1567 is a good step in screening aggregates.
- The significantly expanded section on supplementary cementitious materials (SCMs) allows for a much broader category of materials to be considered, but few limits are placed. Most of the additions are directed at sulfate attack, which is discussed in the next chapter. A maximum allowable replacement of Portland cement of 25 percent does not ensure mitigation, but there is provision for additional use of SCMs if mitigation is sought.

ASR Specifications in Surrounding States

State Department of Transportation concrete specifications were reviewed from California, Colorado, Nevada, New Mexico, Texas, and Utah. The results with regards to ASR and sulfate attack are summarized in the appendix. Table 3 provides a brief summary of how each state addresses ASR. Below is a brief review of these specifications.

Cement

Most states approach specifying cement in a similar fashion, allowing the use of ASTM C150, C595, and in some cases, ASTM C1157 cements. Almost all limit the cements to low alkali, meaning < 0.60 percent Na_2Oeq. Some also have lists of pre-approved or pre-qualified cements. Some require the use of sulfate-resistant cements as discussed in the next chapter. Several agencies specify the use of blended cements to address ASR as well as sulfate attack issues.

Aggregate

The most common test employed by the various DOTs for assessing the ASR susceptibility of aggregates is ASTM C1260, with some requiring ASTM C1293 if a source fails ASTM C1260. All but Caltrans set the expansion limit at 0.10 percent at 14 days (Caltrans has set a limit of 0.15 percent at 14 days. Several states apparently have tested local aggregate sources, identified sources of reactive aggregate, and banned their use.

Water

The primary thrust of the specifications applicable to water used in concrete mixes is to ensure that it is generally free from contaminants. Several agencies specifically limit and or test for alkalis.

Table 3. Summary of surrounding state concrete specifications related to ASR.

State	Specification Recommendation			
	Cement	Water	Aggregates	SCMs
California	ASTM C150 Type II or C595 Type IP < 0.60% NaO_{eq}	< 300 parts per million NaO_{eq}.	ASTM C1260 (0.15@14 days) ASTM C1293 (0.040@1 yr)	Must use admixture to mitigate ASR. Fly ash, natural pozzolan, and silica fume allowed.
Colorado	ASTM C150, C595, and C1157 allowed < 0.90% NaO_{eq}	"Reasonably clean and free of alkalis."	ASTM C1260 (0.10@14 days) CPL 1402[1] (0.10@14 days)	Fly ash (Class C and F) and silica fume allowed. Must demonstrate the ability to mitigate.
Nevada	ASTM C150 Types I, III, and V and C595 < 0.60% NaO_{eq}	Water with a pH < 4.5 or > 8.5 must be tested.	ASTM C289 Historical basis.	Require 20 % cement replacement by fly ash or natural pozzolan to mitigate ASR.
New Mexico[2]	ASTM C150 Type II, C595, and C1157 allowed < 0.60% NaO_{eq}	"Free of acids and alkalis."	ASTM C1260 (0.10@14 days) ASTM C1293 (0.40@1 yr) ASTM C1567 (0.10@14 days)	Very comprehensive allowing Class F fly ash (> 85 % Fe, Si, and Al oxides and ≤ 8.0 % CaO), slag cement, silica fume and blended cements. Also allows lithium. Must be tested for effectiveness.
Texas	DMS-4600 Contribution of alkalis in mix from cement < 4 lb/yd^3 of concrete	< 600 parts per million NaO_{eq}.	ASTM C1260 (0.10@14 days)	Many options available. Allows fly ash, ultra-fine fly ash, slag cement, metakaolin, silica fume, and blends of these. Lithium is also allowed.
Utah	ASTM C150, C595, and C1157 allowed. < 0.60 % NaO_{eq}	No specific ASR requirements.[3]	No specific ASR requirements, but ASTM C1567 is limited to 0.10@14 days.	Allows fly ash, natural pozzolans, and silica fume. Limit CaO < 15 % for fly ash. Typical 20 % replacement of fly ash for cement.

[1] Colorado Procedure – Laboratory (CPL) 1402 is a CDOT modified ASTM C1567.

[2] New Mexico has very comprehensive ASR requirements which are the most thorough of any state reviewed.

[3] ASR not specifically addressed yet ASTM C1567 mentioned for mitigation.

Supplementary Cementitious Materials

Many states have detailed guidance in their specifications on the use of supplementary cementitious materials, either as a replacement for or as an addition to cement. New Mexico has the most rigorous approach to using SCMs to mitigate ASR, whereas Texas provides for numerous options for blending various SCMs. A summary of guidance associated with the use of supplementary cementitious materials includes limiting available alkalis in the mix, specifying the addition of pozzolans (20 to 25 percent minimum), and limiting the CaO content of the fly ash (8 to 15 percent maximum). Although not a supplementary material, it is noted that some states also allow the use of lithium-based admixtures to mitigate ASR.

Summary of ASR

Deleterious (damaging) ASR results from a reaction between the highly alkaline pore solution in concrete and certain reactive silica constituents in aggregate. This reaction forms a gel-like reaction product that swells when it imbibes water and thickens as it reacts with calcium from the paste. The combination of swelling and thickening creates pressures that are sufficient to fracture the aggregates and mortar, resulting in cracking and expansion of the structure.

ASR can be effectively prevented by using aggregates that do not contain reactive constituents. Unfortunately, many aggregates are at least mildly reactive when tested using ASTM C1260, and thus this strategy is often not an option. Mitigation strategies include the use of low alkali cements (e.g., < 0.60 percent Na_2Oeq) and/or limiting total alkalis in the concrete mix (e.g., 4.0 lb/yd^3 concrete), although this alone is often not found to be sufficient. The use of SCMs is thus commonly recommended, with 15 to 25 percent of low CaO fly ash (commonly classified as Class F) being used as a replacement for or in addition to cement being the most common mitigation strategy. The use of blends of fly ash, slag cement, silica fume, and/or natural pozzolans are also recommended. Some states also allow the use of lithium-based admixtures as a mitigation strategy. Testing using ASTM C1567 is often required to assess the effectiveness of the SCMs in mitigating ASR.

As important as the cement type is, the fact that fly ash is being used in all PCC at a replacement/addition rate of 25 to 32 percent has probably played an even larger role in the generally observed absence of durability problems. For the most part, these are Class F fly ashes with CaO contents below 6 percent which make them extremely effective in mitigating ASR. Phoenix Sky Harbor Airport has a lot of old concrete aprons that were constructed before fly ash was commonly used and ASR problems are rampant in these pavements. Fly ash has been used on all new pavements and there are no known ASR problems. It is important to recognize that fly ash characteristics are always changing due to changes in coal source, combustor technology, collection methodology, and increasing environmental demands. Thus there is no assurance that the effectiveness of the fly ash will be maintained in perpetuity and thus ADOT should consider reviewing their specifications to ensure future performance.

CHAPTER 3.
SULFATE ATTACK

Overview of Sulfate Attack

Sulfate attack occurs when sulfate ions attack constituents in the hydrated cement paste, which is the glue that holds the concrete together. It is a complicated distress mechanism which may have both physical and chemical mechanisms of attack, and may be due to internal or external sources of sulfate. Unless the source of sulfate is from the aggregate, the role of the aggregate in the occurrence of this distress is negligible.

In Arizona, the most common type of sulfate attack is caused by an external source of sulfate ions (e.g., naturally occurring sulfates of sodium, potassium, calcium, or magnesium that are found in soil or dissolved in groundwater) attacking cast-in-place concrete. These penetrating sulfate ions will chemically react with aluminum- and iron-rich cement hydration products. This is known as chemical sulfate attack from external sources (CSAES). CSAES is primarily thought to be caused by the formation of gypsum through the combination of the external sulfate ions and calcium ions present in hydration products and/or the formation of ettringite through the combination of external sulfate ions and hydrated calcium aluminate phases (DePuy 1994, ACI 2008). In either case, the formation of the deleterious reaction product leads to an increase in solid volume. In the former case, expansion due to gypsum formation may not be destructive, but gypsum has little cementing properties and thus the concrete loses integrity (DePuy 1994). In the case of the latter reaction, the expansive pressures exerted by ettringite formation can be very destructive. In concrete pavements, deterioration due to external sulfate attack initially appears as cracking near joints and slab edges, generally within a few years of construction. Fine longitudinal cracking may also occur parallel to longitudinal joints (Van Dam et al. 2002).

A physical form of sulfate attack, known as physical salt attack (PSA) or salt weathering, can result from naturally occurring salts of sodium, including sodium sulfate (Haynes et al. 2008). First noted in stone monuments, physical salt attack can lead to surface scaling in concrete just above the ground surface at the evaporative front. In the research conducted by Haynes et al. (2008), temperature and humidity conditions that promoted alternate cycles of conversion between thenardite (Na_2SO_4) and mirabilite ($Na_2SO_4 \cdot 10H_2O$) led to significant scaling. It was found that the formation of the mirabilite crystals was responsible for most of the scaling damage. Although indications of chemical sulfate attack were observed, including both ettringite and gypsum deposits, the damage was attributed almost exclusively to physical salt attack. It is noted that an ASTM C150 Type II, low calcium aluminate, moderately sulfate resistant cement was used in this study, along with a very high water-to-cementitious material ratio (*w/cm*) of 0.65.

A third type of sulfate attack is not commonly associated with pavements, but has been known to occur in mass concrete placements and precast/steam-cured structural elements (Thomas et al. 2008B). The source of the sulfate ions is internal and thus it is known as internal sulfate attack (ISA). Internal sources of sulfate ions include slowly soluble sulfate contained in the cement, aggregate, and admixtures (such as fly ash) or those that result from decomposition of primary ettringite during early hydration. The latter is primarily associated with high curing temperatures, and is known as delayed ettringite formation (DEF).

DEF can lead to destructive expansion within the paste, resulting in microcracking and separation of the paste from aggregate particles. DEF is most often associated with steam curing. At elevated temperatures (above 70°C), primary ettringite will not form properly (Scrivener 1996, Thaulow et al. 1996, Klemm and Miller 1999). After the concrete has cured and temperatures are reduced to ambient conditions, sulfates and aluminate phases in the paste may then react to form expansive ettringite, disrupting the concrete matrix. Recent work has confirmed that this phenomenon can also occur in mass placement of cast-in-place concrete that experienced sufficiently high temperatures due to ambient conditions and the heat generated through cement hydration (Thomas et al. 2008b).

Sulfate Attack Test Methods

There are no currently accepted standardized test methods that can be used to test the sulfate attack resistance of job-mix concrete. Further, testing does not separate CSAES, PSA, and DEF, primarily focusing on CSAES since it has been the focal point of concern until fairly recently. The testing that is done focuses exclusively on the cementitious binder.

DePuy (1994) reports that using a cement low in C_3A will generally decrease sulfate attack susceptibility, but exceptions exist where low C_3A cements show poor resistance to sulfate attack while some cements high in C_3A were observed to have good sulfate resistance. He recommends that performance testing using ASTM C 452 and C 1012 should be considered to examine the sulfate resistance of Portland cements and combinations of cements and SCMs including fly ash and slag, respectively. In ASTM C 452, mortar bars are made with Portland cement and gypsum in such proportions that the SO_3 content is 7 percent by mass. After mixing and casting, the mortar bars are cured under very controlled conditions. The initial length measurement is made at 24 hours, and the specimen is then water cured at 73^{o}F (23^{o}C). A second measurement is made at 14 days, and the change in length is reported. The test can be extended for longer periods of time. The maximum allowable expansion for ASTM C 150 Type V cement is 0.040 percent at 14 days.

In ASTM C 1012(Length Charge of Hydraulic Cement Mortars Exposed to a Sulfate Solution), mortar bars are prepared and immersed in a sulfate solution, and the resulting expansion measured. The cementitious material used can be Portland cement, or blends of Portland cement and fly ash or slags, or blended hydraulic cements. The mortar bars are immersed in the sulfate solution after attaining a compressive strength of 20 MPa. A standard exposure solution containing Na_2SO_4 can be used, or another sulfate solution simulating anticipated field conditions might be substituted. Length measurements are made at 1, 2, 3, 4, 8, 13, and 15 weeks, and at selected intervals thereafter depending on the observed rate of length change. The allowable expansion at 180 days is 0.10 percent for ASTM C595 cements.

Sulfate Attack Mitigation

Guidance is provided for mitigation of sulfate attack through a combination of the use of a low *w/cm* and certain cement types and SCMs (ACI 2008). Exposure is classified according to Class 0 through Class 3 based on the percent by mass water-soluble sulfate (SO_4) in the soil or as sulfate concentration in water in parts per million. As the concentration of sulfates increases and the exposure severity becomes more severe, the *w/cm* is reduced to limit the permeability of the concrete, thus hindering the ingress of the aggressive sulfate ions. In the most severe cases (Class 3), the maximum recommended *w/cm* is 0.40 (ACI 2008).

With regards to the recommendations on cementitious materials, ASTM C150 (AASHTO M 85) Type II (moderate sulfate resistant) and Type V (high sulfate resistant) are the two Portland cements that have some resistance to sulfate attack. Resistance is obtained by limiting the tricalcium aluminate content calculated from the oxide analysis to 8 percent and 5 percent for Type II and Type V cement, respectively. Type V cement also has a further restriction on the combination of all aluminate and ferrite phases. The purpose of these specifications is to limit the calcium aluminate hydration products that will form, thus minimizing the phases present to react with an external source of sulfate ions (ACI 2008). For a moderate sulfate environment (Class 1 exposure), the use of an ASTM C150 Type II cement or equivalent is recommended. As the severity of the sulfate environment increases, ASTM C150 Type V cement or equivalent is recommended for a Class 2 exposure and Type V with pozzolan or slag cement or equivalent is recommended for Class 3 exposure.

The need for high quality, impermeable concrete is a prerequisite for concrete resistance to external sulfate attack. Concrete with a low *w/cm* is consistently recommended, as it will have lower permeability and thus limit the amount of sulfate ions that can diffuse into the concrete to attack it. In addition, good workmanship and curing are essential. It is thought that air entrainment is beneficial only in that it makes the concrete more workable, so the *w/cm* ratio can be reduced. It is also commonly cited that the use of SCMs will reduce the permeability of concrete and thus improve the concrete's resistance to sulfate attack (ACI 2008).

Class F fly ash is generally found to be beneficial to sulfate resistance, whereas Class C fly ash may actually be detrimental. For these reasons, only high quality, Class F fly ash should be considered for use in improving sulfate resistance of concrete. It is thought that fly ash meeting ASTM C 618 and having less than 10 percent bulk CaO can be used to improve sulfate resistance. Fly ash containing 10 to 25 percent CaO should be tested with the actual materials to be used in the concrete.

The replacement of Portland cement with slag cement also has beneficial effects toward sulfate resistance through the reduction of the tricalcium aluminate content incurred by reducing the amount of Portland cement in the concrete. Slag cement will also reduce soluble calcium hydroxide, altering the environment required for the formation of ettringite, and will form additional calcium silicate hydrate in pore spaces normally occupied by alkalies and calcium hydroxide, reducing the permeability of the paste.

The sulfate resistance of concrete is decreased through the addition of calcium chloride, which is a common accelerating admixture. It therefore should not be added to concrete subjected to sulfate exposure conditions unless Type V cement is used (ACI 2008).

Due to variability in the effectiveness of various techniques to improve sulfate resistance, it is important that specific combinations of the cement and pozzolan be tested to verify sulfate resistance. ASTM C 1012 can be used to assess the sulfate resistance of blended cements or cement-pozzolan mixtures.

Unfortunately, assessing the sulfate resistance of concrete is difficult. There is currently no standard ASTM test for assessing the sulfate resistance of specified concrete made using the selected constituent materials and job mix formula. ASTM C 452 evaluates only the sulfate resistance of Portland cement and not that of the concrete. ASTM C 1012 is the most commonly recommended test to assess the sulfate resistance of Portland cement, blends of Portland cement with slags and fly ash, or blended hydraulic cements. Six-month expansion limits of 0.10 and 0.05 percent roughly translate to Class 1 exposure resistance and Class 2 exposure resistance, respectively. It is recommended that one year expansion tests, limiting expansion to 0.10 percent, are needed to qualify new sources of SCMs for Class 2 exposure. For Class 3 exposure, the test duration is extended to 18 months with an expansion limit of 0.10 percent.

Sulfate Attack in Arizona

Discussion with representatives of the concrete industry and public agency personnel indicates a great concern regarding sulfate attack in Arizona. This concern is validated through a review of USDA Natural Resources Conservation Service records (USDA 2008), which indicates that the potential for concrete corrosion (soil-induced corrosion or weakening of concrete due to sulfate and sodium content of soil) is widespread throughout the state. Specific soil reports for the State can be found on the USDA Natural Resources Conservation Service's web site. As summarized in table 4, this review indicates that approximately 14 percent of the almost 48,000,000 acres of land area surveyed in Arizona was either moderately or highly corrosive to concrete. Unfortunately, how the severity levels are defined is not evident in this data, but it still gives a clear indication that sulfate attack concerns exist in Arizona.

Table 4. Summary of risk of concrete corrosion (USDA 2008).

Area of Interest	Percent of Surface Area			
	Low	Moderate	High	N/A
Aguila-Carefree Area, Arizona, Parts of Maricopa and Pinal Counties	95.7%	3.0%	0.0%	1.2%
Apache County, Arizona, Central Part	68.4%	8.8%	3.1%	19.7%
Beaver Creek Area, Arizona	78.1%	0.0%	0.0%	21.9%
Cochise County, Arizona, Douglas-Tombstone Part	51.3%	36.8%	9.7%	2.2%
Cochise County, Arizona, Northwestern Part	50.0%	39.9%	8.9%	1.2%
Coconino County Area, Arizona, Central Part	97.9%	0.0%	1.4%	0.7%
Coconino County Area, Arizona, North Kaibab Part	81.4%	0.0%	5.3%	13.3%
Colorado River Indian Reservation, Parts of La Paz County, Arizona, and Riverside and San Bernardino Counties, CA	80.8%	16.0%	1.7%	1.4%
Eastern Maricopa and Northern Pinal Counties Area, Arizona	88.7%	0.0%	0.0%	11.3%
Fort Apache Indian Reservation, Arizona, Parts of Apache, Gila, and Navajo Counties	64.7%	35.2%	0.0%	0.1%
Fort Defiance Area, Parts of Apache and Navajo Counties, Arizona and McKinley and San Juan Counties, New Mexico	93.7%	1.3%	0.2%	4.9%
Gila Bend-Ajo Area, Arizona, Parts of Maricopa and Pima Counties	94.3%	0.2%	3.4%	2.1%
Gila-Duncan Area, Parts of Graham and Greenlee Counties, Arizona	90.8%	0.8%	0.0%	8.4%
Gila River Indian Reservation, Arizona, Parts of Maricopa and Pinal Counties	41.6%	5.0%	53.3%	0.0%
Grand Canyon Area, Arizona, Parts of Coconino and Mohave Counties	33.5%	0.3%	0.2%	66.0%
Hopi Area, Arizona, Parts of Coconino and Navajo Counties	71.0%	13.1%	0.1%	15.8%
Hualapai-Havasupai Area, Arizona, Parts of Coconino, Mohave, and Yavapai Counties	76.3%	0.0%	0.0%	23.7%
Long Valley Area, Arizona	0.2%	0.0%	0.0%	99.8%
Luke Air Force Range, Arizona, Parts of Maricopa, Pima and Yuma Counties	69.7%	2.0%	0.0%	28.3%
Maricopa County, Arizona, Central Part	88.1%	1.4%	8.6%	1.9%
Mohave County Area, Arizona, Northeastern Part, and Part of Coconino County	81.2%	0.4%	15.0%	3.4%
Mohave County, Arizona, Central Part	92.9%	1.2%	0.7%	5.2%
Mohave County, Arizona, Southern Part	94.9%	0.0%	0.1%	5.0%
Navajo County Area, Arizona, Central Part	67.7%	1.1%	19.0%	12.2%
Navajo Mountain Area, Arizona, Parts of Apache, Coconino and Navajo Counties	70.2%	12.7%	0.4%	16.7%
Oak Creek-San Francisco Peaks Area, Arizona, Part of Coconino County	99.2%	0.0%	0.0%	0.8%
Organ Pipe Cactus National Monument, Arizona	100.0%	0.0%	0.0%	0.0%
Pima County, Arizona, Eastern Part	89.0%	9.7%	0.0%	1.3%
Pinal County, Arizona, Western Part	75.1%	9.9%	14.7%	0.3%
Safford Area, Arizona	89.4%	1.3%	1.4%	7.9%
San Simon Area Parts of Cochise Graham and Greenlee Counties, Arizona	75.8%	13.2%	11.1%	0.0%
Santa Cruz and Parts of Cochise and Pima Counties, Arizona	91.9%	0.0%	1.1%	7.0%
Shiprock Area, Parts of San Juan County, New Mexico and Apache County, Arizona	37.4%	24.2%	32.5%	5.9%
Shivwits Area, Arizona, Part of Mohave County	81.2%	7.3%	11.5%	0.0%
Tohono O'Odham Nation, Arizona, Parts of Maricopa, Pima and Pinal Counties	89.9%	2.4%	7.7%	0.0%
Tucson-Avra Valley Area, Arizona	99.7%	0.3%	0.0%	0.0%
Virgin River Area, Nevada and Arizona	57.3%	1.3%	14.4%	27.0%
Willcox Area, Arizona Parts of Cochise and Graham Counties	68.1%	3.8%	20.3%	7.7%
Yavapai County, Arizona, Western Part	85.9%	3.0%	0.0%	11.1%
Yuma-Wellton Area, Parts of Yuma County, Arizona and Imperial County, California	62.2%	2.3%	30.9%	4.6%
Totals	77.4%	6.9%	5.9%	10.0%

In the 1950s, cements were designed so that they gave moderate sulfate resistance as a standard. This was the old ASTM C150 Type II (modified). They also produced a Type V cement to be used where there were problems. Today, there is very little Type V produced, unless a contractor is expecting a problem on a sizable project. However, Type V is widely used in the concrete pipe industry.

The Phoenix Cement Company started its cement plant in Clarkdale in 1959 in response to receiving the contract for the cement for the Glen Canyon Dam. At that time, it started using Type II cement. Later it began making a Type IP with fly ash ground directly into the cement. It is believed that Type IP is now only made on special request. The Phoenix Cement Company is now a division of the Salt River Materials Group and is still manufacturing Type II/V cement.

Other minor cement producers are Mitsubishi Cement, which owns a small plant in California that provides cement in Arizona, and the Lehigh Cement Company, which also owns a small plant in California that produces minimal amounts of cement used in Arizona. CEMEX is also active in Arizona, with two nearby plants in Mexico from which it is primarily providing Type II cements to Arizona. It is noted that cement plants change ownership frequently, especially under the current economic situation.

Arizona's sulfate problems are statewide and are not dependent on the aggregates involved. The available cements are "moderately sulfate resistant" per ASTM C150 Type II. This requirement has been important in reducing sulfate attack problems in most parts of the State. In the Yuma area, along the Colorado River, the sulfate problem is particularly aggressive and the U.S. Bureau of Reclamation has mandated the use of Type V cement for the past 50 years or more. The domestic cements available over the past few years have been blended to create Type II/V equivalent cement, and that blend is now being used successfully, both in that area and in the rest of the State.

The fact that fly ash is being used in all PCC used by ADOT at a replacement/addition rate of 25 to 32 percent is also extremely important. For the most part, these are Class F fly ashes with CaO contents below 6 percent which make them extremely effective in mitigating sulfate attack. Fly ash has been used on all new pavements and there are no known sulfate attack problems. As noted in the previous chapter, it is important to recognize that fly ash characteristics are always changing due to variations in coal source, combustor technology, collection methodology, and increasing environmental demands. Thus there is no assurance that the effectiveness of the fly ash will be maintained in perpetuity and ADOT should review their specifications to ensure future performance.

Sulfate Attack Specifications in Arizona

Section 1006 (dated February 20, 2007) of the Arizona DOT specifications was reviewed as it pertains to sulfate attack as well as other durability concerns. The following relevant sections have been extracted from the specifications. Underlined passages are new since the 2000 edition of the Standard Specifications.

1006-2.01 Cement

Hydraulic cement shall consist of either Portland cement or Portland-pozzolan cement. Portland cement shall conform to the requirements of ASTM C 150 for Type II, III, or V. However, at the option of the manufacturer, processing additions may be used in the manufacture of the cement, provided such processing additions have been shown to meet the requirements of ASTM C 465, and the total amount of such material used does not exceed one percent of the weight of the Portland cement clinker.

Portland-pozzolan cement shall conform to the requirements of ASTM C 595 for Type IP (MS).

1006-2.02 Water

The water used shall be free from injurious amounts of oil, acid, alkali, clay, vegetable matter, silt or other harmful matter. Water shall contain not more than 1,000 ppm of chlorides as Cl and not more than 1,000 ppm of sulfates as SO_4.

1006-2.04 Supplementary Cementitious Material (Fly Ash, Natural Pozzolan, and Silica Fume)

Fly ash and natural pozzolan shall conform to the requirements of ASTM C 618 for Class C, F, or N mineral admixture, except that the loss on ignition shall not exceed 3.0 percent.

When a supplementary cementitious material with a calcium oxide content greater than 15 percent is used, or when the Special Provisions specify sulfate resistant concrete, the cement intended to be used shall be tested for sulfate expansion in accordance with ASTM C 1157 and ASTM C 1012. For moderate sulfate resistance, the maximum expansion shall be 0.10 percent at six months. For high sulfate resistance, the maximum expansion shall be 0.05 percent at six months and 0.10 percent at one year.

When Class C fly ash is used, the cement intended to be used shall be tested for sulfate expansion in accordance with ASTM C 1157 and ASTM C 1012 and shall have a maximum expansion of 0.05 percent at six months and 0.10 percent at one year.

The use of a supplementary cementitious material is not allowed for replacement of cement when Portland-pozzolan cement [Type IP (MS)] is used. A maximum of 25 percent of the required weight of Portland cement may be replaced with fly ash or natural pozzolan [at 1:1 replacement ratio]. If performance enhancement of the concrete, such as the mitigation of an alkali silica reaction or for increased sulfate resistance is necessary, additional quantities of fly ash or natural pozzolan may be incorporated into the concrete without a corresponding Portland cement replacement, if approved by the Engineer.

1006-3.01 Water-to-Cement Ratio (*w/cm)*

For Class P Concrete, no *w/cm* is specified.

Comments on Arizona Specifications

ADOT is addressing the potential for sulfate attack in a number of ways, as discussed below in the same order as presented in the specification:

- Cement type is specified as either Type II or V, although Type III[2] is also allowed. Further, there is allowance for the use of blended Portland-pozzolan cement (ASTM C 595 Type IP (MS)) which would likely be effective at mitigating sulfate attack.
- The sulfate content in the mixing water is limited to not more than 1,000 ppm of sulfates as SO_4.
- The significantly expanded section on supplementary cementitious materials (SCMs) allows a much broader category of materials to be considered, but few limits are placed. Sulfate attack is addressed by testing cement/SCM blends through use of ASTM C1012, applying expansion limits of 0.10 percent at 6 months for moderate sulfate resistance and 0.05 percent at 6 months and 0.10 percent at 1 year for high sulfate resistance. Since the maximum allowable replacement of Portland cement of 25 percent does not ensure resistance to sulfate attack, there is provision for additional use of SCMs if mitigation is sought.

Sulfate Attack Specifications in Surrounding States

Concrete specifications were reviewed from Departments of Transportation in California, Colorado, Nevada, New Mexico, Texas, and Utah. The results are summarized in the appendix. Table 5 provides a brief summary of how each state addresses sulfate. Below is a brief review of those specifications.

Cement

Most states approach specifying cement in a similar fashion, allowing the use of ASTM C150, C595, and in some cases, ASTM C1157 cements. Almost all require that Type II or V cement be used if sulfate attack is of concern. Texas has very specific requirements for mitigating sulfate attack. Some also have lists of pre-approved or pre-qualified cements. Several agencies specify the use of blended cements to address ASR as well as sulfate attack issues.

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[2] Note that the ASTM C150 specification for Type III makes and allowance for moderate sulfate resistance if the C_3A content is less than 8 percent.

Water

The primary thrust of the specifications applicable to water used in concrete mixes is to ensure that it is generally free from contaminants. Several agencies specifically limit and or test for sulfates with the limits being set at 1,000 to 3,000 ppm.

Table 5. Summary of surrounding state concrete specifications as pertains to sulfate attack.

State	Specification Recommendation			
	Cement	*w/cm*	Water	SCMs
California	ASTM C150 Type II or V or C595 Type IP. Mortar shall not expand more than 0.010 when tested in conformance with California Test 527.	Not specified. Water content is controlled primarily based on workability.	< 1,300 ppm of sulfates as SO_4, when tested in conformance with California Test 417.	Fly ash, natural pozzolans, and silica fume are allowed. Use focuses on ASR, not sulfate attack, but amount varies depending on CaO content in fly ash.
Colorado	ASTM C150, C595, and C1157 allowed.	≤ 0.44 – Not related to sulfate resistance.	No specific mention of sulfate.	Fly ash (Class C and F) and silica fume allowed. Must demonstrate the ability of fly ash to mitigate sulfate attack through use of ASTM C1012.
Nevada	ASTM C150 Type V is to be used when sulfate protection is required.	≤ 0.47 – Not related to sulfate resistance.	No specific mention of sulfate.	Replacement of cement by fly ash or natural pozzolan only specified to mitigate ASR.
New Mexico	ASTM C150 Type II, C595, and C1157 allowed	Not specified.	< 1,000 ppm of sulfates as SO_4	Very comprehensive specifications for using fly ash, slag cement, silica fume, or blended cement. Class C fly ash cannot be used in sulfate-resistant concrete
Texas	Detailed guidance to mitigate sulfate attack using Type I/II, II, V, IP, or IS cement.	≤ 0.45 – Not related to sulfate resistance.	Sulfate content in accordance with ASTM D516 < 1,000 ppm.	Class C fly ash not allowed in sulfate-resistant concrete. Combinations of Class F fly ash, slag cement, and silica fume allowed.
Utah	ASTM C150 Type II, C595, and C1157 allowed.	≤ 0.44 – Not related to sulfate resistance.	< 3,000 ppm of sulfates as SO_4.	Allows fly ash, natural pozzolans, and silica fume. Limit CaO < 15% for fly ash. Typical 20% replacement of fly ash for cement.

Supplementary Cementitious Materials

Many states have detailed guidance in their specifications related to the use of supplementary cementitious materials, either as a replacement for or as an addition to cement. New Mexico has the most rigorous approach to using SCMs to mitigate ASR, but this approach would also be effective in mitigating sulfate attack. Texas forbids the use of Class C fly ash in sulfate-resistant concrete and provides for numerous options for blending various SCMs. A summary of guidance associated with the use of supplementary cementitious materials for addressing sulfate attack includes specifying the addition of pozzolans (20 to 25 percent minimum), limiting the CaO content of the fly ash (8 to 15 percent maximum), and the use of ASTM C1012 expansion testing.

Water-to-Cementitious Material Ratio (*w/cm)*

In no case was the *w/cm* limit established to specifically address sulfate attack. Most states set limits (from 0.44 to 0.47), but two did not. The main concern in establishing *w/cm* was primarily to achieve strength, but permeability requirements were also considered. The latter has a direct bearing on sulfate attack resistance.

Summary of Sulfate Attack

Deleterious (damaging) sulfate attack most commonly occurs due to the ingress of external sulfate ions from soils (e.g., naturally occurring sulfates of sodium, potassium, calcium, or magnesium that are found in soil or dissolved in groundwater). These ions will react with normal cement hydration products to form ettringite and/or gypsum. In the former case, expansion of the paste results in cracking and degradation and in the latter, the paste loses strength and becomes soluble. A purely physical mechanism, commonly referred to as physical salt attack or salt weather, can also cause concrete degradation as a result of sulfate salts present in the soil being wicked up to the surface and then evaporating just above the ground level. This causes salt crystallization and scaling of the concrete at the surface.

Concrete can be made resistant to sulfate attack by limiting its permeability and/or limiting the hydration products that react with the sulfates. Permeability is most directly influenced by the *w/cm*, with limits of 0.45 or below recommended to assist in preventing ingress of external sulfate ions (ACI 2008). The use of pozzolans (e.g., low CaO fly ash, silica fume, and so on) or slag cement has also been shown to be very effective in reducing the permeability of concrete and are thus often recommended to increase concrete's resistance to sulfate attack. The two hydration products most directly affected by sulfate attack are phases containing aluminum and calcium hydroxide. Limits on the calculated tricalcium aluminate content of the cement are the basis for improving cement resistance to sulfate attack (e.g., Types II and V Portland cement). Calcium hydroxide is often limited through the addition of pozzolans or slag cement.

Guidance to mitigate sulfate attack is provided by ACI (2008). The severity of the sulfate environment is assessed based on determining the water soluble sulfate ion concentration present in the soil, but it is recognized that many factors contribute to the aggressiveness of the environment. For example, all things equal, soils containing calcium sulfate are less aggressive than those containing sodium sulfate, which again are less aggressive than those containing magnesium sulfate. Depending on the severity of the environment, the guidelines recommend reducing the *w/cm* and the use of sulfate resistant cements.

In Arizona, in addition to the cement type, the fact that high quality Class F fly ash is being used in all PCC at a replacement/addition rate of 25 to 32 percent plays a large role in controlling sulfate attack. For the most part, these fly ashes have CaO contents below 6 percent which make them extremely effective in mitigating sulfate attack. Fly ash has been used on all new pavements and there are no known sulfate attack problems. It is important to recognize that fly ash characteristics are always changing due to changes in coal source, combustor technology, collection methodology, and increasing environmental demands. Thus there is no assurance that the effectiveness of the fly ash will be maintained in perpetuity and thus ADOT should review their specifications to ensure future performance.

CHAPTER 4.
SUMMARY OF FINDINGS AND RECOMMENDATIONS

The findings of this study can be summarized as follows:

- Both ASR and sulfate attack can potentially impact concrete transportation structures in Arizona, although little evidence exists that links either mechanism to degradation in newly constructed pavements or bridges.

- In particular, there is little immediate concern over ASR, although it is known that reactive aggregates can be found over a broad geographic area including in the vicinity of the Salt River (and possibly the Gila River as well) and along the Santa Cruz River. ADOT has likely avoided obvious ASR problems due to routine use of relatively low alkali cement (0.60 percent Na2Oeq) and the use of low CaO content Class F fly ash (at 25 to 32 percent replacement for cement). ADOT also has allowance for the use of blended Portland-pozzolan cement (ASTM C 595 Type IP (MS)) which would also likely be effective at mitigating ASR.

- The addition of aggregate screening testing to the ADOT specification through the use of ASTM C1260 (14-day expansion limit of 0.10 percent) is a good step in identifying susceptible aggregates. Mitigation of potentially reactive aggregates follows the current state-of-the-practice of requiring testing using ASTM C1567, in which the cementitious system is a blend of the Portland cement and SCM(s) to be used in the job mix.

- Although ADOT now requires aggregate screening, many of the surrounding states have more detailed guidance in their specifications related to the use of supplementary cementitious materials, either as a replacement for or as an addition to Portland cement. New Mexico has the most rigorous approach to mitigate ASR using SCMs, whereas Texas provides numerous options for blending various SCMs. Guidance associated with the use of SCMs includes limiting available alkalis in the mix, specifying the addition of pozzolans (20 to 25 percent minimum), and limiting the CaO content of the fly ash (8 to 15 percent maximum). Although not a supplementary material, it is noted that some states also allow the use of lithium-based admixtures to mitigate ASR.

- The potential for sulfate attack exists over a wide geographical area, with 6.9 and 5.9 percent of the surface area of Arizona considered as having moderate to high potential for concrete corrosion (including sulfate attack), respectively. ADOT specifies either Type II or V cements, which have moderate or high resistance to sulfate attack, respectively. Further, there is allowance for the use of blended Portland-pozzolan cement (ASTM C 595 Type IP (MS)) which would likely be effective at mitigating sulfate attack.

- The significantly expanded section in the ADOT specifications on supplementary cementitious materials (SCMs) allows a much broader category of materials to be considered, but few limits are placed. Sulfate attack is addressed by testing cement/SCM blends through use of ASTM C1012, applying expansion limits of 0.10 percent at 6 months for moderate sulfate resistance and 0.05 percent at 6 months and 0.10 percent at 1 year for high sulfate resistance. Since the maximum allowable replacement of Portland cement with an SCM is 25 percent, resistance to sulfate attack is not ensured, but there is provision for the use of additional SCMs if mitigation is sought.

- ADOT's approach to mitigating sulfate attack is consistent with that of most surrounding states which also specify the use of Type II and V cements. Further, guidance associated with the use of supplementary cementitious materials for addressing sulfate attack includes specifying the addition of pozzolans (20 to 25 percent minimum), limiting the CaO content of the fly ash (8 to 15 percent maximum), and the use of ASTM C1012 expansion testing.

Based on this study, ADOT's current practices are consistent with that of its neighbors, but by no means are they the most rigorous, particularly related to controlling ASR. The following recommendations are made to improve ADOT's approach to ASR and sulfate attack mitigation to ensure success in the future:

- Although ADOT has benefited from abundant sources of low CaO Class F fly ash, it is important to recognize that fly ash characteristics are changing as the coal source, combustor technology, collection methodology, and increasing environmental demands change. Thus there is no assurance that the effectiveness of the fly ash ADOT is currently using will be maintained in perpetuity. ADOT should review their SCM specifications to ensure that those materials being used in their concrete have the desired effect of mitigating ASR and sulfate attack. Of the specifications reviewed, those currently employed by New Mexico are the most thorough.

- For the most part, ADOT's specifications for cement are similar to those of the surrounding states with one exception: a number of neighboring states also permit the use of ASTM C1157 performance specified cements. ADOT should investigate allowing the use of these cements as well.

- With regards to aggregate screening for ASR, ADOT is following the current state-of-the-practice utilizing accelerated mortar bar testing in compliance with ASTM C1260/C1567. This test has some limitations, but its short duration (16 days from casting to completion) makes it extremely attractive for project use. The new FHWA guidelines (Thomas et al. 2008A) recommend that long-term concrete prism testing be conducted in accordance with ASTM C1293 to establish an empirical relationship with the ASTM C1260 test results to ensure mitigation. This would require ADOT to embark on a long-term study to test its most common ASR-susceptible aggregates, but it is the only currently acceptable approach to establishing confidence that the ASTM C1260/C1567 results accurately predict field performance.

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APPENDIX
SUMMARY OF SPECIFICATIONS USED BY NEIGHBORING STATES TO AID IN ASR AND SULFATE ATTACK MITIGATION

California

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Link to State Specifications Website:
http://www.dot.ca.gov/hq/esc/oe/specifications/std_specs/2006_StdSpecs/

The following sections contain excerpts from the specifications that relate to mitigation of Alkali Silica Reactivity (ASR) and Sulfate Attack in Portland Cement Concrete (PCC):

Aggregate

- Aggregates shall have not more than 10 percent loss when tested for soundness in conformance with the requirements in California Test 214.
- When the aggregate is tested in conformance with the requirements in California Test 554 and ASTM Designation C 1293, the average expansion at one year shall be less than or equal to 0.040 percent.
- When the aggregate is tested in conformance with the requirements in California Test 554 and ASTM Designation C 1260, the average of the expansion at 16 days shall be less than or equal to 0.15 percent.

Water

- Water shall not contain more than 1,300 parts per million of sulfates as SO_4, when tested in conformance with California Test 417.
- Water shall not contain coloring agents or more than 300 parts per million of alkalis ($Na_2O + 0.658\ K_2O$)

Cement

- “Type II Modified" Portland cement shall conform to the requirements for Type II Portland cement in ASTM Designation C 150-02a.
- "Type IP (MS) Modified" cement and "Type II Modified" Portland cement shall conform to the following requirements:
  A. The cement shall not contain more than 0.60 percent by weight of alkalis, calculated as the percentage of Na_2O plus 0.658 times the percentage of K_2O, when determined by either direct intensity flame photometry or by the atomic absorption method. The instrument and

procedure used shall be qualified as to precision and accuracy in conformance with the requirements in ASTM Designation C 114;

B. The autoclave expansion shall not exceed 0.50 percent; and

C. Mortar, containing the cement to be used and Ottawa sand, when tested in conformance with California Test 527, shall not expand in water more than 0.010 percent and shall not contract in air more than 0.048 percent, except that when cement is to be used for precast prestressed concrete piling, precast prestressed concrete members, or steam cured concrete products, the mortar shall not contract in air more than 0.053 percent.

Supplementary Cementitious Materials

- The amounts of cement and mineral admixture used in cementitious material shall be sufficient to satisfy the minimum cementitious material content requirements specified in Section 90-1.01, "Description," or Section 90-4.05, "Optional Use of Chemical Admixtures," of the Standard Specifications.
- Coal fly ash; raw or calcined natural pozzolan, or silica fume may be used as mineral admixtures.
- When admixtures are used, the available alkali content (as sodium oxide equivalent) shall not exceed 1.5 percent when determined in conformance with the requirements in ASTM Designation C 311, or the total alkali content (as sodium oxide equivalent) shall not exceed 5.0 percent when determined in conformance with the requirements in ASTM Designation D 4326.
- Admixture materials shall conform to the requirements in the following ASTM Designations:
    A. Chemical Admixtures—ASTM Designation C 494.
    B. Air-entraining Admixtures—ASTM Designation C 260.
    C. Calcium Chloride—ASTM Designation D 98.
    D. Mineral Admixtures—Coal fly ash; raw or calcined natural pozzolan as specified in ASTM Designation C 618; silica fume conforming to the requirements in ASTM Designation C 1240, with reduction of mortar expansion of 80 percent, minimum, using the cement from the proposed mix design.
- Unless otherwise specified in the special provisions, mineral admixtures shall be used in conformance with the provisions in Section 90-4.08, "Required Use of Mineral Admixtures.”

Colorado

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Link to State Specifications Website:
http://www.dot.state.co.us/DesignSupport/Construction/2005SpecsBook/2005index.htm

The following sections contain excerpts from the specifications that relate to mitigation of Alkali Silica Reactivity (ASR) and Sulfate Attack in Portland Cement Concrete (PCC):

Aggregate

Any aggregate with expansion of 0.10 percent at 16 days as determined by ASTM C 1260 shall not be used unless mitigative measures are included and subsequent results of CPL 4202 show an expansion less than 0.10 percent at 16 days. [Note: CPL 4202 is a department modified version of ASTM C 1567.]

Coarse Aggregate

Coarse aggregate shall conform to the requirements of AASHTO M 80.

Fine Aggregate

The fine aggregates should meet the requirements of AASHTO M 6.

Water

- Water will be tested in accordance with, and shall meet the suggested requirements of AASHTO T 26.
- Water used in mixing or curing shall be reasonably clean and free of alkali.

Cement

- Cement shall be from a preapproved source listed on the department's Approved Products List.
- Portland cement shall conform to the requirements of ASTM C 150.
- Blended cement shall conform to the requirements of ASTM C 595.
- Hydraulic cement shall conform to the requirements of ASTM C 1157 (Standard Performance Specification for Hydraulic Cement).
- Maximum percent of equivalent alkalis ($Na_2O + 0.658\ K_2O$) shall not exceed 0.90 percent.
- Type IP or IP(MS) may be used in place of Type I or II. Blended cement shall consist of no less than 70 percent Portland cement. Hydraulic cement according to ASTM C 1157, Type GU or MS may also be used.

Supplementary Cementitious Materials

- Fly ash for concrete shall conform to the requirements of ASTM C 618, Class C or Class F.
- Where Class F fly ash is required, Type IP or IP(MS) cement may be used, except blended cement shall consist of no less than 70 percent Portland cement and no less than 20 percent fly ash.
- Fly ash used to enhance sulfate resistance, shall be used in a proportion greater than or equal to the proportion tested in accordance to ASTM C1012 and it shall have a calcium oxide content no more than 2.0 percent greater than the fly ash tested according to ASTM 1012.
- Silica fume for concrete shall conform to the requirements of ASTM C 1240.

Structural Concrete

- The Contractor shall provide protection against sulfate attack on concrete structures by providing concrete structures manufactured with requirements according to Table 601-4. The exposure Class will be stated on the plans. Table 601-4—Requirements to protect against damage to concrete by sulfate attack from external sources of sulfate—provides criteria for severity of potential exposure (percent of water soluble sulfate in dry soil, sulfate in water, water cement ratio) and specifies the type of cement to be used.
- The Concrete Mix Design Report shall state what mitigative measures were included in the concrete mix design and include results for CPL 4201 and CPL 4202.

Nevada

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Link to State Specifications Website:
http://www.nevadadot.com/business/contractor/standards/

The following sections contain excerpts from the specifications that relate to mitigation of Alkali Silica Reactivity (ASR) and Sulfate Attack in Portland Cement Concrete (PCC):

Aggregate

- Aggregates should be innocuous when tested for 'Potential Reactivity' under ASTM C289.
- Aggregates from any source having a history of alkali-silica reactivity in concrete will not be approved for use.

Coarse Aggregate

Coarse aggregate shall be tested in accordance with AASHTO T104 and shall have a 5-cycle sodium sulfate soundness loss of not more than 12 percent.

Fine Aggregate

Fine aggregate shall be tested in accordance with AASHTO T104 and shall have a 5-cycle sodium sulfate soundness loss of not more than 12 percent.

Water

Water with a pH less than 4.5 or greater than 8.5 and a resistivity less than 500 ohm.cm will be tested according to AASHTO T26.

Cement

- Type II, Type III, and Type V Portland cements shall conform to ASTM C150
- Type IP blended hydraulic cement shall conform to ASTM C595
- The cement shall not contain more than 0.60 percent by mass of alkalies calculated as Na_2O plus 0.658 K_2O.
- Type IP cement which exceeds the allowable alkali content may be used if mortar bars made and tested according to ASTM C227, using the proposed cement and a selected highly alkali-reactive aggregate, show no more than 0.05 percent expansion at 6 months.
- Type V cement is to be used when sulfate protection is required for concrete structures

Supplementary Cementitious Materials

- If the proposed aggregate fails the test requirement for “Potential Reactivity” under ASTM C289, the aggregate may still be used for concrete provided that it is incorporated in an approved mix design with an approved Type F or Type N pozzolan, or with a Type IP cement. If a pozzolan is used for this purpose, use 1 part pozzolan to 4 parts of cement by mass. The pozzolan quantity shall be considered as cement in meeting the required minimum cement content.
- Pozzolan shall conform to Subsection 702.03.05. The pozzolan constituent shall be limited to a maximum of 20 percent by mass of the blended cement.

New Mexico

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The following sections contain excerpts from the specifications that relate to mitigation of Alkali Silica Reactivity (ASR) and Sulfate Attack in Portland Cement Concrete (PCC):

Aggregate

- The Department's State Materials Bureau maintains a list of reactive, potentially reactive, and non-reactive (innocuous) aggregate sources.
- All aggregates shall be evaluated for reactivity by AASHTO T 303 or by ASTM C 1293. The initial "Proof-of-Reactivity-Potential" test will be performed utilizing a standard Rio Grande Type I-II low alkali cement. This cement shall have alkali content between 0.5 to 0.6 percent. Aggregates that exhibit mean mortar bar expansions at 14 days greater than 0.10 percent shall be considered potentially reactive. Aggregates will be considered innocuous if their maximum expansion is less than 0.10 percent at 14 days unless ASTM C 1293 is used, then the aggregate shall be considered to be innocuous if the average expansion measured at the end of one (1) year is less than 0.04 percent.

Coarse Aggregate

Coarse aggregate shall have an Aggregate Index (A.I.) of 25 or less, when calculated in accordance with Section 910, "Aggregate Index."

Fine Aggregate

Fine aggregate shall have a soundness loss of 12 or less when tested in accordance with AASHTO T104 using magnesium sulfate solution with a test duration of five (5) cycles.

Water

- Water shall be sampled and tested in accordance with AASHTO T 26 and be free of acid and alkali.
- The sulfate content and the chloride content each shall not exceed 1,000 ppm.

Cement

- Portland cement shall be "low-alkali" and shall meet the requirements of ASTM C 150 for the type required. Type II cement is required unless otherwise specified.
- ASTM C595 and C1157 also allowed.
- If the ASR mitigation test required in subsection 509.2.4.5 is less than 0.10 percent for each aggregate, then the requirement for low-alkali shall be waived.

Supplementary Cementitious Materials

- Minimum 20 percent fly ash in blended cement. Use Class F fly ash if either aggregate is reactive. Class C fly ash may be used if neither aggregate is reactive.
- Fly ash shall conform to the physical and chemical requirements of ASTM C 618, including the optional requirements for available alkalis and reactivity with cement alkalis.
- If the Contractor elects to use an aggregate source which has been designated as potentially reactive or known reactive, a combination of one or more of the following ASR inhibiting admixtures, shall be used to provide a concrete mixture that meets the maximum expansion requirements:
  - Fly Ash (Class F):

    20 percent (minimum) by weight of cement only for binary blends
    12 percent (minimum) by weight for ternary blends as long as the total pozzolan dosage is at least 20 percent.
  - Blended Cement:

    20 percent (minimum) by weight of cement only
    Proof shall be provided that the blended cement contains the appropriate percent of fly ash to mitigate ASR.
  - GGBFS:

    Not less than 25 percent by weight of cement only
  - Silica Fume:

    Not less than 10 percent by weight of cement only
  - Lithium

    The Contractor may use lithium nitrate ($LiNO_3$) as an admixture to control expansions caused by reactive aggregate. Lithium shall be used in the form of a solution consisting of 30 percent, by weight, $LiNO_3$. If used, it shall be used at a dosage rate of 4.6 L of solution for each kg (0.55 gal. /lb) of sodium equivalent, as determined from the cement mill certificate.
- The effectiveness of the admixture(s) in controlling deleterious expansion shall be determined by mortar bars made and tested using the cement, fly ash, other mitigating admixtures and the proposed aggregate intended for use in the proposed concrete mixture.

Texas

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The following sections contain excerpts from the specifications that relate to mitigation of Alkali Silica Reactivity (ASR) and Sulfate Attack in Portland Cement Concrete (PCC):

Aggregate

- Supply aggregates that meet the definitions in Tex-100-E.
- Aggregates should be free from injurious amounts of alkali.
- Test both coarse and fine aggregate separately in accordance with ASTM C 1260. The test result for each aggregate should not exceed 0.10 percent expansion.

Coarse Aggregate

Coarse aggregate shall be tested in accordance with Tex-411-A and shall not have a 5-cycle magnesium sulfate soundness of more than 18 percent. Crushed recycled hydraulic cement concrete is not subject to the 5-cycle soundness test.

Fine Aggregate

Limit recycled crushed concrete fine aggregate to a maximum of 20 percent of the fine aggregate.

Water

- Furnish mixing and curing water that is free from oils, acids, organic matter, or other deleterious substances.
- Water should be free from alkali.
- Sulfate concentration tested according to ASTM D516 should be less than 1,000 ppm.
- Alkalies ($Na_2O + 0.658K_2O$) concentration tested according to ASTM D 4191 and D 4192 should be less than 600 ppm.

Cement

- Furnish cement conforming to DMS-4600, “Hydraulic Cement.”
- When using hydraulic cement only, ensure that the total alkali contribution from the cement in the concrete does not exceed 4.00 lb/yd^3 of concrete.

- When sulfate-resistant concrete is required, use mix design options 1, 2, 3, or 4 given in Section 421.4.A.6, “Mix Design Options,” using Type I/II, II, V, IP, or IS cement.
- Do not use Class C fly ash in sulfate-resistant concrete.

Supplementary Cementitious Materials

- Furnish fly ash conforming to DMS-4610, “Fly Ash.”
- Furnish Ultra-Fine Fly Ash (UFFA) conforming to DMS-4610, “Fly Ash.”
- Furnish Ground Granulated Blast-Furnace Slag GGBFS conforming to DMS-4620, “Ground Granulated Blast- Furnace Slag,” Grade 100 or 120.
- Furnish silica fume conforming to DMS-4630, “Silica Fume.”
- Furnish metakaolin conforming to DMS-4635, “Metakaolin.”
- Furnish chemical admixtures conforming to DMS-4640, “Chemical Admixtures for Concrete.” Do not use calcium chloride.
- For structural concrete designed using more than 520 lb/yd^3 of cementitious material, use one of the mix design Options 1–8 shown below.
- For concrete classes not identified as structural concrete and designed using less than 520 lb/yd^3 of cementitious material, use one of the mix design Options 1–8, except that Class C fly ash may be used instead of Class F fly ash for Options 1, 3, and 4 unless sulfate-resistant concrete is required.

Option 1. Replace 20 to 35 percent of the cement with Class F fly ash.

Option 2. Replace 35 to 50 percent of the cement with GGBFS.

Option 3. Replace 35 to 50 percent of the cement with a combination of Class F fly ash, GGBFS, or silica fume. However, no more than 35 percent may be fly ash, and no more than 10 percent may be silica fume.

Option 4. Use Type IP or Type IS cement. (Up to 10 percent of a Type IP or Type IS cement may be replaced with Class F fly ash, GGBFS, or silica fume.)

Option 5. Replace 35 to 50 percent of the cement with a combination of Class C fly ash and at least 6 percent of silica fume, UFFA, or metakaolin. However, no more than 35 percent may be Class C fly ash, and no more than 10 percent may be silica fume.

Option 6. Use a lithium nitrate admixture at a minimum dosage of 0.55 gal of 30 percent lithium nitrate solution per pound of alkalis present in the hydraulic cement.

Option 7. When using hydraulic cement only, ensure that the total alkali contribution from the cement in the concrete does not exceed 4.00 lb/yd^3 of concrete.

Option 8. For any deviations from Options 1–7, perform the following:

- Test both coarse and fine aggregate separately in accordance with ASTM C 1260, using 440 g of the proposed cementitious material in the same proportions of hydraulic cement to supplementary cementing material to be used in the mix.
- Before use of the mix, provide the certified test report signed and sealed by a licensed professional engineer demonstrating that the ASTM C 1260 test result for each aggregate does not exceed 0.10 percent expansion.

Utah

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The following sections contain excerpts from the specifications that relate to mitigation of Alkali Silica Reactivity (ASR) and Sulfate Attack in Portland Cement Concrete (PCC):

Aggregate

Coarse Aggregate

Determine the suitability of coarse aggregate sources using the requirements for soundness, percentage of wear, and potential reactivity as specified in AASHTO M 80.

Fine Aggregate

The fine aggregates should meet the requirements of AASHTO M 6.

Water

- Limit maximum sulfate concentration as SO_4 to 3000 ppm.
- Use potable water or water meeting ASTM C 1602, including Table 2.

Cement

- Use Type II Portland cement, or blended Portland cement, unless otherwise specified.
- Follow the requirements of Table 2 of ASTM C 150 for low-alkali cement.
- When blended cement is substituted for Portland cement, use ASTM C 1567 to verify that expansion is less than 0.1 percent at 16 days.
- Use cement from the list of UDOT pre-qualified sources maintained by the UDOT Materials Quality Assurance Section.

Supplementary Cementitious Materials

- May use Class N natural pozzolan instead of fly ash provided that the 14-day expansion test (ASTM C 1567) with job aggregates and job cement does not exceed 0.1 percent.
- May use silica fume conforming to ASTM C 1240.
- Maximum allowable CaO content in fly ash not to exceed 15 percent.
- Use Class F fly ash to replace 20 percent of Portland cement by weight.