Understanding AAR in Watertight Structures

By Paolo Benedetti & Charles Hanskat

Although Alkali Aggregate Reactions (AAR) have probably been around since the Romans first used concrete, they were not formally identified until the 1930s by California DOT engineer Thomas Stanton. Stanton published the first comprehensive study of ASR (one form of AAR) in the 1940s, and countless studies on AAR have been published in the 85 years since. The Federal DOT published a series of studies from 2006-2013 as guidance to the state DOTs. Additionally, numerous state DOTs, universities, and trade associations have studied AARs.

There are two primary forms of AAR; Alkali Silica Reaction (ASR) which forms as a reaction with silica-based minerals, and Alkali Carbonate Reaction (ACR) caused by carbonate or dolomite minerals. A less common concrete defect is Delayed Ettringite Formation (DEF), which is caused by a reaction of sulfates with aluminates in the cement. In this article, I will use the generic term AAR to broadly discuss these destructive chemical reactions. Essentially, each form of AAR is a chemical reaction that creates a substance that expands when exposed to moisture or by the chemical reaction. The expansion of the material within the concrete matrix results in fine cracking which compromises the structural integrity of concrete leading to a more rapid deterioration and reduced lifespan of the structure. The destructive forces are so prevalent, it is sometimes referred to as "concrete cancer."

Everyone who works with concrete should understand basic concrete chemistry. When designers use ACI Codes for design of pools they must address the potential for AAR in concrete exposed to water. ACI 318-19 Section 26.4.2 Concrete mixture requirements, subsection (12) requires all concrete for sections with W1 or W2 exposures must be evaluated for potential for alkali-aggregate reactivity. ACI 350-20 Chapter 4 has extensive requirements for considering AAR potential in liquid-containing structures.

However, in areas where a licensed professional engineer is not required or even retained for a pool design and there is no competent engineering support, the burden for using proper concrete materials for the project falls on the pool builder or the owner.

Aggregates are usually sourced and consumed locally due to their high transportation costs. Quarries are generally not highly sophisticated operations, so the purchaser may need to investigate the quality and specific chemical composition of their locally sourced aggregates and the impact on their use in concrete for a project.

REACTIVE AGGREGATES

ASR

ASR is a reaction between the alkali components of cement and aggregates containing amorphous silica. According to the Portland Cement Association: "Aggregates containing certain forms of silica will react with alkali hydroxide in concrete to form a gel that swells as it absorbs water from the surrounding cement paste or the environment. These gels can induce enough expansive pressure to damage concrete." ASR is the most common form of AAR, due to the high percentage of silica present in most aggregates.

ACR

ACR is a chemical reaction between dolomite in carbonate aggregates and the alkali components of the cement. The soluble salts, calcite, and brucite formed by this reaction can also induce enough pressure to damage the concrete. The reaction will continue until the dolomite is consumed.

DEF

DEF is caused when the sulfate ions attack the aluminate compounds in the cement, and the resulting ettringite crystals can exert sufficient pressures to damage concrete. The sulfate ions can be present in the cement paste, supplementary cementitious materials (SCM), some admixtures and high sulfate aggregates High internal concrete temperatures above 160°F (70°C), as often found in mass concrete structures, are the most common reason that DEF forms in concrete.

Each of these destructive chemical reactions can be prevented with a thorough understanding of the reaction causes, as well as the limitations of material testing protocols, careful selection of raw materials, utilization of supplemental cementitious materials (SCMs), competent concrete mixture designs, and specification of competent prophylactic measures.

MATERIAL TESTING LIMITATIONS

Because of the many factors and extensive time required to aggravate AAR conditions, numerous testing standards are generally inconclusive or inaccurate. Two generally accepted tests, ASTM C 1260: *Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)* and ASTM C 1293: *Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction*, stand out as the industry standards.

The ASTM 1260 test is an accelerated testing method that can produce significant false negative results. As such, the DOT only recommends that it be utilized to reject aggregates.[1]

While the ASTM C 1293 concrete prism test provides a higher level of accuracy and confidence, it requires a minimum of one year to complete the test. "When testing SCMs or lithium compounds, the test typically is carried out for two years. This relatively long period for conducting ASTM C 1293, either one or two years, has been the major drawback for the test and has somewhat limited its use."[1]

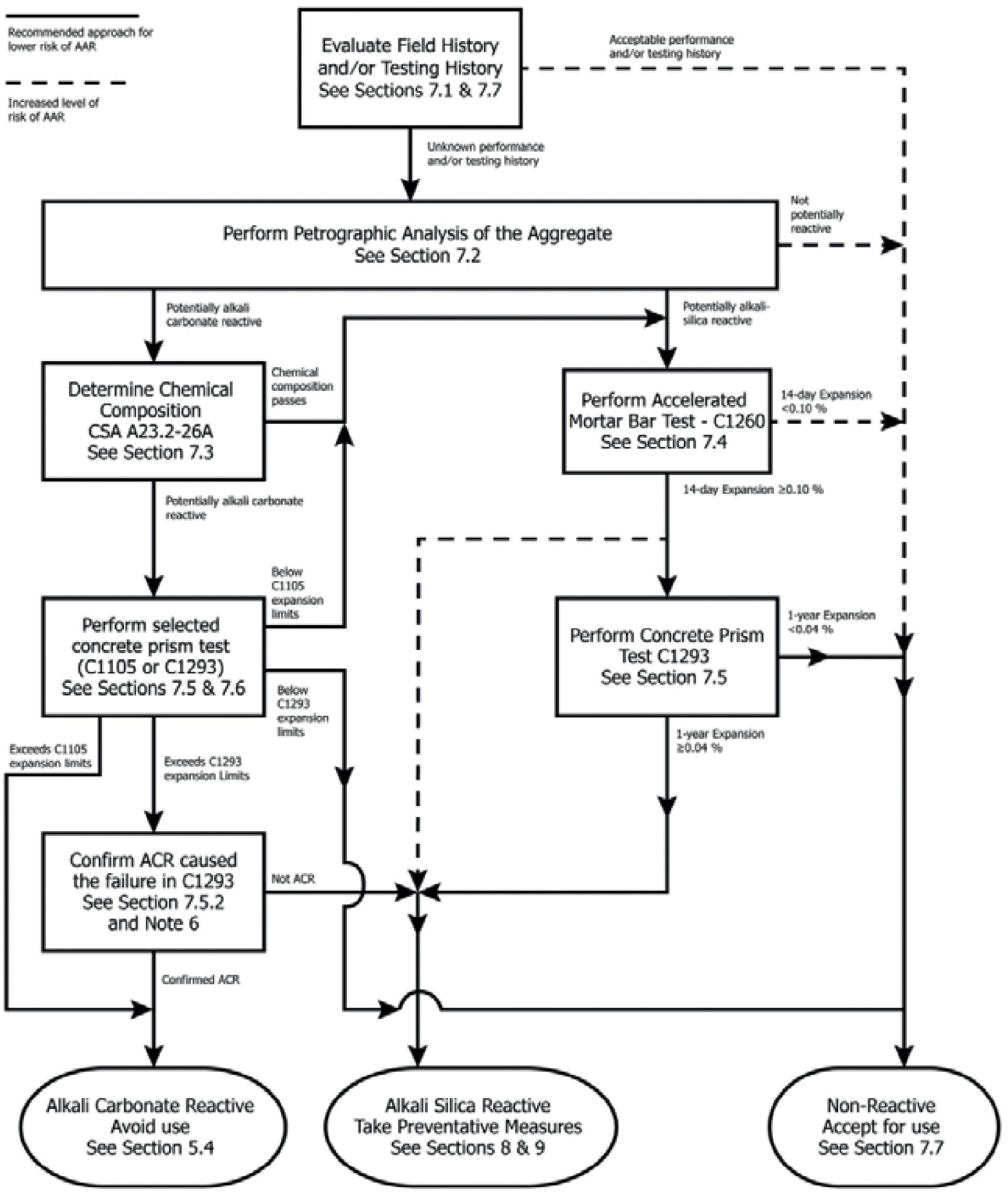


Fig. 1 Sequence of Laboratory Tests for Evaluating Aggregate Reactivity (ASTM C1778-22).

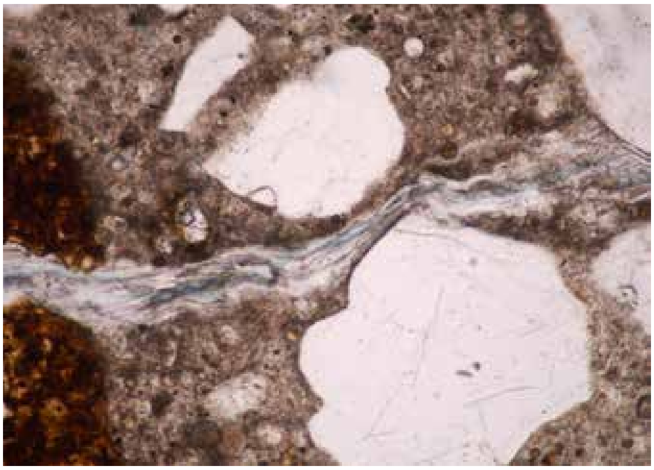
MITIGATION

Per ASTM 1778-22 Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete, "There are no proven measures for effectively preventing damaging expansion with alkali carbonate reactive rocks in concrete and such materials."[2] So the most obvious means to avoid AAR is to steer clear of reactive minerals. This is often easier said than done due to the economy and ease of using locally sourced aggregates. Knowing the chemical composition of the aggregates is paramount in mitigating the risks of these destructive forces. One must have a high level of confidence in their testing protocol to rely solely upon the test results identifying an aggregate as non-reactive.

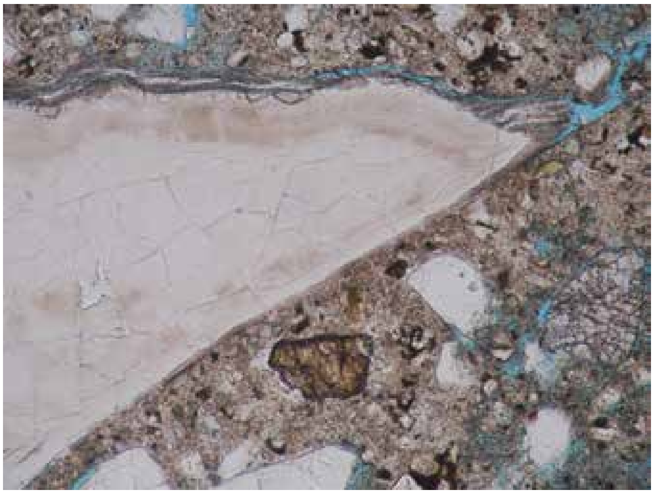
When avoiding using AAR-susceptible aggregates is not practical, other measures can be implemented to help mitigate the impact of AAR. This includes use of low alkali cements, supplementary cementitious materials like fly ash, silica fume and slag, and lithium admixtures.

ASTM C1778 is a key reference in designing concrete mixtures that can help mitigate the impact of AAR in concrete structures. The standard delineates a prescriptive approach in four steps:

1. Classify the aggregates reactivity using ASTM C1293 or ASTM C1260 (Fig. 1). Aggregates are classified as non-reactive (R0), moderately reactive (R1), highly reactive (R2) or very highly reactive R3).
2. Decide on the level of ASR risk. Pools will always fall into the category "All concrete exposed to humid air, buried or immersed and have a Risk Level from 3 to 5 with increasing reactivity of the aggregate (R1, R2 and R3).
3. Assign a structure classification. Generally pools would fall into an SC3 classification where a minor risk of ASR is acceptable though service life may reduce to 40 to 74 years. An SC4 classification is generally used for lifeline structures but may be used if the owner desires a service life of greater than 75 years.



Thin section photomicrograph of alkali-silica reaction of a glassy volcanic rock (on the left) with copious quantities of ASR gel completely filling the fracture that propagates through the paste. Photo courtesy of Mark Lukkarila, F.ACI.



Thin section photomicrograph of an ASR in a chalcedonic chert. Photo courtesy of Mark Lukkarila, F.ACI.

4. Decide on the level of prevention. This varies from V (no prevention needed) to W, X, Y, Z and ZZ (with increasing levels of mitigation. Most pools would fall between the X and ZZ level.

Once a level of prevention (X-ZZ) is selected C1778 provides Table 1 that lists the minimum levels of SCM required to replace the portland cement in the concrete mixture to achieve the desired level of prevention. The CSA guidelines for controlling ASR, shown in ASTM C1778, also provide an alternative method for performance testing that may be useful if using SCMs that are not included the standard.

There are currently no ASTM standards that address the use of lithium to mitigate AAR. However, several government agencies including the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and Canadian Standards Association (CSA) have testing procedures that can be used to evaluate the effects of lithium admixtures on AAR.

SUPPLEMENTARY CEMENTITIOUS MATERIALS

SCMs have proven to be the most cost effective alternative means of preventing AAR in concrete. Lower lime content fly ash has proven to be the most effective in controlling AAR, due to its improved alkali binding ability.[3] Class-F fly ash is better at mitigating AAR than Class-C fly ash. Though less fly ash is being produced by coal-fired power plants, supplemental processing of waste fly ash for concrete is helping to maintain availability. However, the extra processing adds to the cost of fly ash processed for use in concrete.

CONTROL OF AAR IN NEW CONCRETE

ASR CAN BE CONTROLLED BY:

- Use of low alkali reactive aggregates (both coarse and fine)
- Low alkali cement (reduces the potential for alkali-silica reactions)
- High compressive value concrete (decreased permeability)

Type of SCM	Total Alkali Content of SCM (% Na_2O_e)*	Chemical Composition Requirement (% oxides)	Cement Replacement Level (% by mass)[a]		
			Prevention Level W (mild)	Prevention Level X (moderate)	Prevention Levels Y and Z (strong-Y) (exceptional-Z)
Fly Ash	< 3.0	CaO < 8%	≥ 15	≥ 20	≥ 25
		CaO = 8% - 20%	≥ 20	≥ 25	≥ 30
		CaO > 20%	See note *b*	See note *b*	See note *b*
	3.0 - 4.5	CaO < 8%	≥ 20	≥ 25	≥ 30
		CaO = 8% - 20%	≥ 25	≥ 30	≥ 35
		CaO > 20%	See note *b*	See note *b*	See note *b*
	> 4.5			See note *b*	
Blast Furnace Slag	< 1.0[b]	None	≥ 25	≥ 35	≥ 50
Silica Fume	< 1.0[b]	SiO_2	2.0 alkali content[c]	2.5 alkali content[c]	3.0 alkali content[c]
Natural Pozzolans	Natural pozzolans that meet the requirements of CSA A23.5 may be used provided thtat their effectiveness in controlling expansion due to ASR is demonstrated according to CSA Recommended Practice A23.2-28A.				
Ternary Blends	When two or more SCMs are used together to control ASR, the minimum replcement levels given in Table 5 of CSA, 2004 for the individual SCMs may be reduced partially, provided that the sum of the parts of each SCM is 1. For example, when silica fume and slag are combined, the silica fume level may be reduced to one-third of the minimum silica fume level given in Table 5, provided that the slag level is at least two-thirds of the minimum slag level given in Table 5.				

*Na_2O_e = socium oxide content = $Na_2O + 0.658 * K_2O$

Table 1: Interim Recommendations for the Use of Lithium to Mitigate or Prevent Alkali-Silica Reaction (ASR), Publication Number: FHWA-HRT-06-073, Date: July 2006 Table 3.

- Mitigating concrete mixture designs:
  - SCMs
  - Lithium compounds
- Improved site drainage (negative side water)

ACR CAN BE CONTROLLED BY:

- Use of silica-free dolomite aggregates
- Low alkali cement (reduces the potential for alkali-silica reactions)
- High compressive value concrete (decreased porosity)
- Mitigating concrete mixture designs:
  - SCMs
  - Lithium compounds
- Improved site drainage (negative side water)

DEF CAN BE CONTROLLED BY:[4]

- Controlling the heat of hydration (excessive heat over 160°F (70°C) during the early stages of hydration accelerates DEF formation)
- Use of low-sulfate aggregates
- Lower aluminum content concrete
- Controlled cooling after concrete placement
- Low alkali cement

SHOTCRETE WORKMANSHIP

Poor shotcrete placement practices can result in reduced compressive strength and increased permeability, even when placing high-quality concrete. Insufficient air volumes resulting in low velocity, utilization of unconsolidated trimmings and rebound, over working placed concrete, or improper curing and temperature control can impact the in-place properties of the concrete and the watertightness. The primary benefit of proper shotcrete placement of concrete for reducing the potential for AAR is the higher strength and lower permeability of the hardened concrete keeping water from permeating the concrete as easily.

REINFORCING STEEL

Water migration into structures containing reactive aggregates is also a contributing factor to the formation of AARs. The reinforcing steel for swimming pools is usually specified solely for structural purposes. Per ACI 318-19(22), the minimum concrete/steel ratios are 0.18 - 0.20%. Yet this quantity of steel is rarely sufficient to prevent drying shrinkage cracks. Per ACI PRC 224-01 Control of Cracking of Concrete Structures, “To control cracks to a more acceptable level, the percentage requirement needs to exceed about 0.60%.” Note that this recommendation is THREE times the minimum steel required by ACI 318. If the pool shell does not contain enough reinforcing steel to control drying shrinkage cracks, these through wall cracks can allow water to more easily reach deeper and more extensive sections of the concrete and promote additional AAR damage.

SUMMARY

In existing concrete containing AAR reactive-aggregates, only by keeping the concrete dry can AAR damage be fully mitigated. Unfortunately, this is impractical in most pools and watershapes. Thus, the best solution is addressing the potential for AAR when the concrete mixture design is developed. A knowledgeable pool builder should investigate the concrete supplier's attention to the potential of AAR in their aggregates and methods that may be implemented to mitigate potential damage in their pools.

Potential AAR damage can be mitigated by selecting appropriate concrete materials for the fresh concrete. Understanding the contributing factors and careful attention to materials used in the mixture design, proper reinforcement and skilled shotcrete placement can all play a role in controlling, if not preventing, AAR harm.

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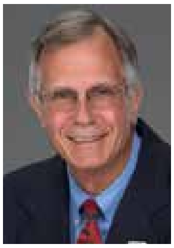

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