Advisory Circular

U.S. Department of Transportation
Federal Aviation Administration

Subject: HANDBOOK FOR IDENTIFICATION OF ALKALI-SILICA REACTIVITY IN AIRFIELD PAVEMENTS	**Date:** DRAFT **Initiated by:** AAS-100	**AC No:** 150/5380-8A **Change:**

1. PURPOSE. This Advisory Circular (AC) provides guidance on understanding, identifying, preventing, and mitigating alkali-silica reactivity (ASR) in fresh and hardened Portland cement concrete airfield pavements.

2. BACKGROUND. The Federal Aviation Administration (FAA) conducted a study on the impact of ASR distress on airport runways and taxiways in response to Section 743 of the Wendall H. Ford Aviation Investment and Reform Act for the 21st Century (P.L. 106-181). The study involved a determination of ASR distress based on in-the-field inspections followed by petrographic analysis and other techniques. The study confirmed that ASR distress can negatively impact the long-term performance of airfield pavements.

This handbook was developed as an integral part of the study. It was prepared by the Texas Transportation Institute, Texas A&M University, through a cooperative agreement between the FAA and the National Safe Skies Alliance. Deletions to the handbook are the result of recent research funded through a cooperative agreement between the FAA and the Innovative Pavement Research Foundation.

3. APPLICATION. The FAA recommends the information and procedures contained in the handbook for use during the engineering and design phase of paving projects. This AC is not binding or regulatory.

The handbook provides decision makers with a framework for the definite identification of ASR in airfield pavements. It summarizes ways to prevent and mitigate these effects, including using lithium.

The handbook is included as Appendix 1 of this AC.

4. CANCELLATION. This AC cancels AC 150/5380-8, Handbook for Identification of Alkali-Silica Reactivity in Airfield Pavements, dated February 2, 2004.

5. PRINCIPAL CHANGES. Chapter 8 of Appendix 1 is deleted to remove all reference to the dilatometer. The test protocol may be reinstated when fully developed.

6. RELATED READING MATERIAL. AC 150/5380-6, Guidelines and Procedures for Maintenance of Airport Pavements, provides further guidance and technical information for identifying distresses in airfield pavements.

7. ONLINE AVAILABILITY. To view and download this AC, visit the FAA Web site at http://www.faa.gov/.

Michael J. O'Donnell
Director, Office of Airport Safety and Standards

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APPENDIX 1—HANDBOOK FOR IDENTIFICATION OF ALKALI-SILICA REACTIVITY IN AIRFIELD PAVEMENT
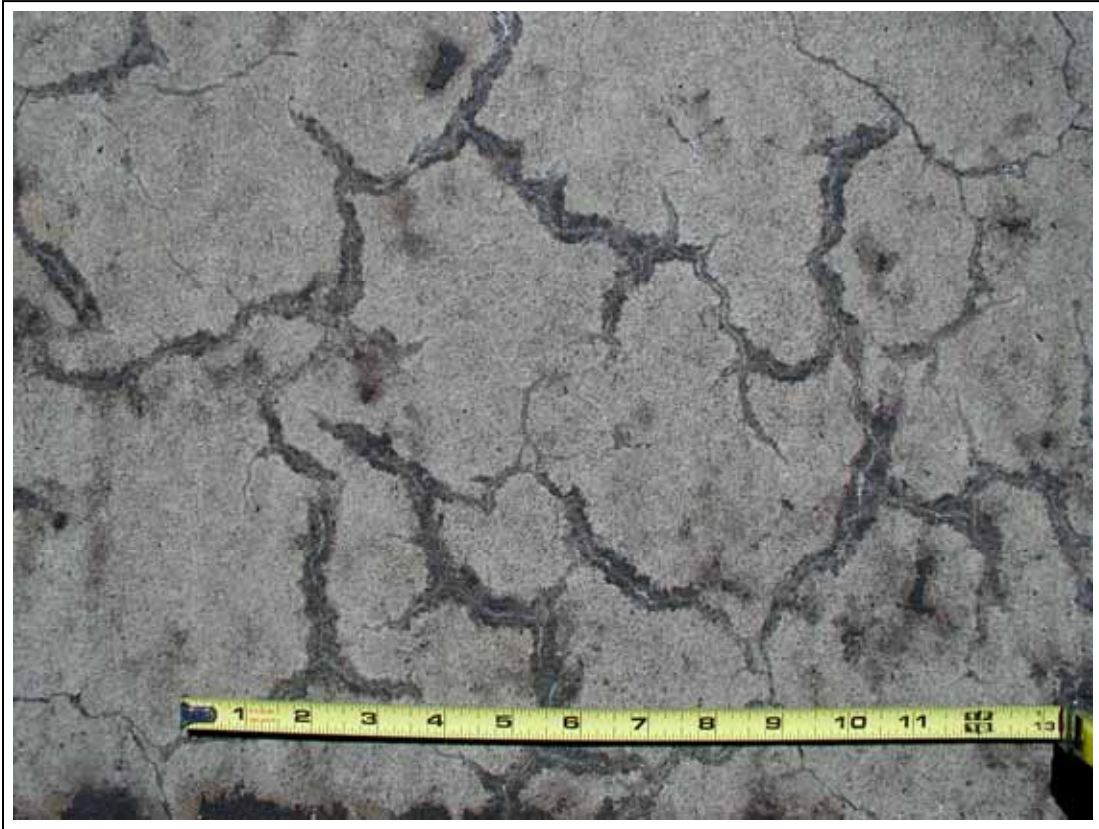
Map Cracking Due to Alkali-Silica Reactivity (ASR) in an Airfield Pavement

Shondeep L. Sarkar, Ph.D., P.E.
Research Scientist

Dan G. Zollinger, Ph.D., P.E.
Associate Research Engineer

Anal Kanti Mukhopadhyay, Ph.D.
Research Associate

Lim Seungwook
Graduate Research Assistant

Chang-Seon Shon
Graduate Research Assistant

Texas Transportation Institute
Texas A&M University
College Station, Texas 77843-3135

DISCLAIMER

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FOREWORD

This handbook has been prepared for airfield engineers and other personnel associated with maintenance of airfield pavements. Alkali-silica reactivity (ASR) continues to be a detriment to the long-term performance of airfield pavements. Deleterious reaction between alkali and reactive aggregate in concrete causes expansion and subsequent cracking in pavements. However, damage due to ASR is often difficult to differentiate from damage caused by other deleterious mechanisms. The objective of this handbook is to provide step-by-step guidance on how to identify ASR in airfield pavements based on field inspection and laboratory investigation, and then perform ASR distress rating. Total reliance on field observation for identification of ASR is not recommended. Laboratory investigation, particularly petrography of core samples, needs to be performed to precisely identify ASR and to assess the extent of damage caused by ASR. This handbook essentially consists of a framework for definite identification of ASR and ASR-induced damage in airfield concrete pavements.

The use of a special dye can often help to indicate the possible existence of ASR but must not be accepted as a decision-making tool for assessing damage caused by ASR.

Following identification of ASR and evaluation of the degree of distress, it is then necessary to consider mitigation and preventive measures. These are summarized in Chapter 5.

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Chapter 1: Understanding Alkali-Silica Reactivity

1.1 Definition

Alkali-silica reactivity (ASR) occurs either in mortar or concrete. A deleterious chemical reaction between hydroxyl (OH^-) ions associated with alkalis (sodium and potassium) present in cement or other sources and certain reactive siliceous components that may be present in coarse or fine aggregates, produces a gel. When this alkali-silica gel absorbs moisture, it expands, and eventually produces cracks in aggregate particles as well as in the cement paste in concrete.

Three conditions must be satisfied for expansive ASR to occur.

1. A reactive form of silica or silicate must be present in the aggregate.

2. Sufficient alkali, sodium (Na) and/or potassium (K), mainly from cement, must be available.

3. Sufficient moisture, i.e., not less than 85% relative humidity (RH) in the pore structure of the concrete or mortar, is required.

If any of the above conditions is lacking, detrimental expansion due to ASR cannot occur.

1.2 Essential parameters for ASR

1.2.1 Reactive aggregate

What is reactive aggregate?

A simplified example of different forms of silica is provided to explain this.

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                    ┌─────────────────────┐
                    │   Silica (SiO₂)     │
                    └─────────────────────┘
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$$Silica\ (SiO_2)$$

Crystalline, e.g., Quartz	Crypto-crystalline, i.e., extremely fine crystalline, e.g., Chalcedony	Amorphous or glassy, i.e., non-crystalline, e.g., Opal

Usually non-reactive (Figure 1), but strained quartz can be reactive (Figure 2)	Reactive (Figure 3)	Highly reactive
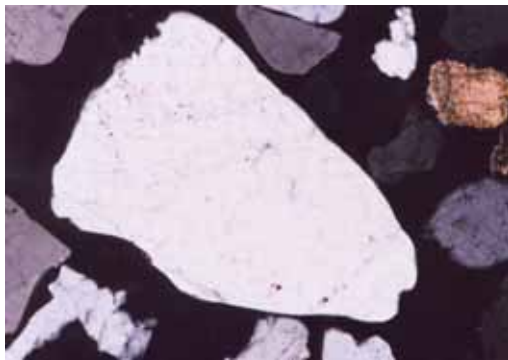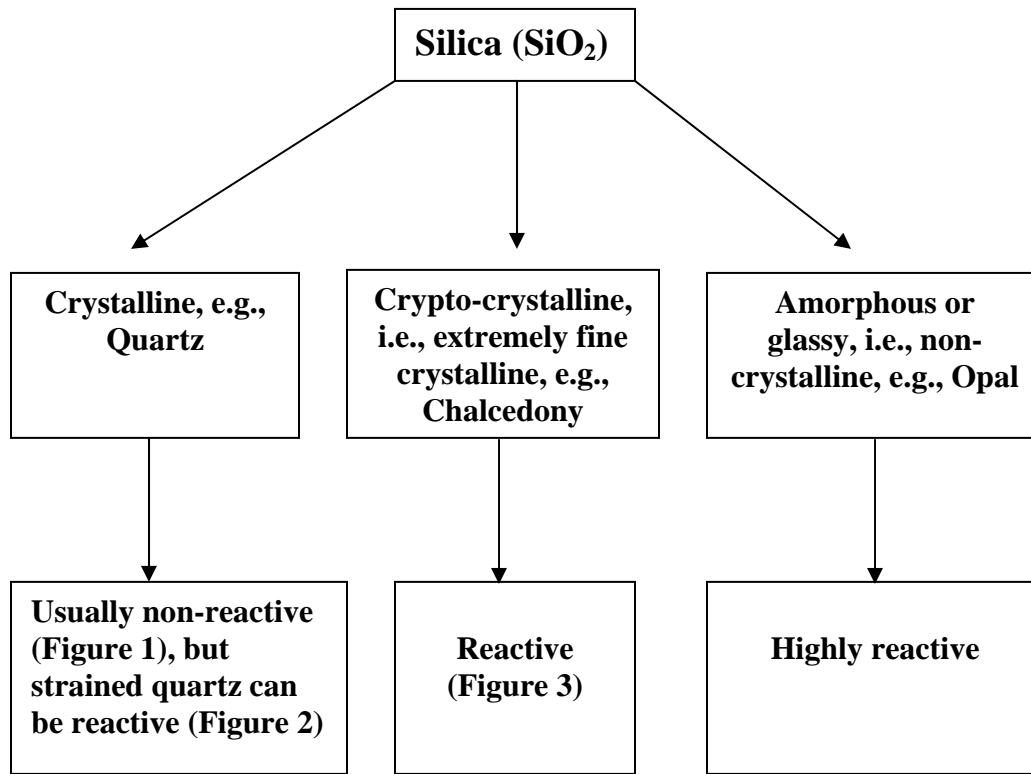
(A)   (B)

Figure 1-1. Non-reactive quartz. The entire quartz grain is either uniformly bright (A) or totally dark (B) under cross-polarized light when the microscope stage is rotated 360°.
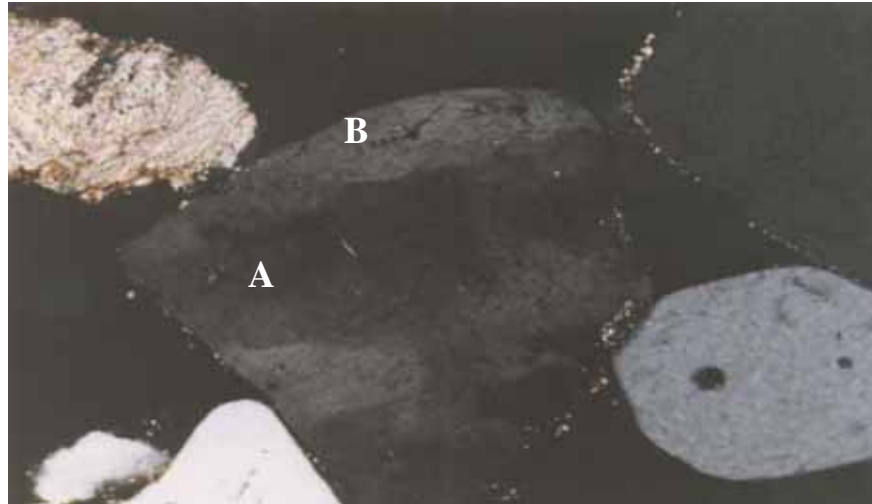
Figure 1-2. Reactive or strained quartz exhibits dark (A) and light bands (B) within a single grain.
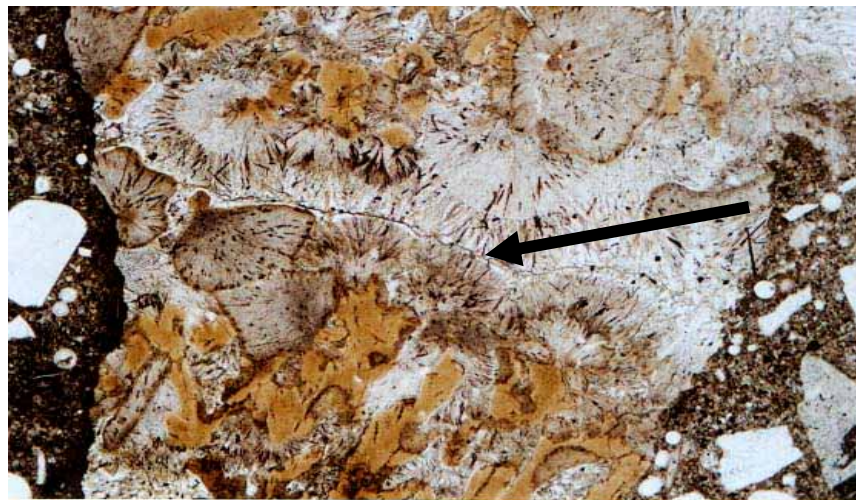
Figure 1-3. Photomicrograph of a very fine grained (cryptocrystalline) chalcedony aggregate in concrete. Note the characteristic acicular crystals of chalcedony. ($\rightarrow$)

Thus, it is the form of silica that determines whether a siliceous aggregate is reactive or not. Many of the coarse aggregates used in the U.S.A. are siliceous in composition, i.e., high in silica (SiO_2) content. However, they are not necessarily reactive.

Certain reactive aggregates do not exhibit maximum expansion unless the aggregate is present in a critical range. The proportion of reactive aggregate particles that produces maximum expansion for a given alkali content and water-cementitious ratio (W/C) in concrete is known as the pessimum proportion. For example, 3% opal in aggregate shows maximum expansion. With parameters such as alkali content, W/C, etc. being constant, the

difference in expansion of different potentially reactive aggregates mainly depends on (i) the inherent reactivity of their constituent mineral phases or rock types, (ii) grain size of the reactive particle, and (iii) the proportion of these reactive phases within the reactive aggregate. Not all aggregates that are susceptible to ASR, however, show the pessimum effect. Aggregates without this pessimum effect exhibit increasing expansion as a function of the amount of reactive particles present in the aggregate.

Fine aggregate is more susceptible to ASR because of its higher surface area.

1.2.2 Higher concentration of alkali

What is alkali?
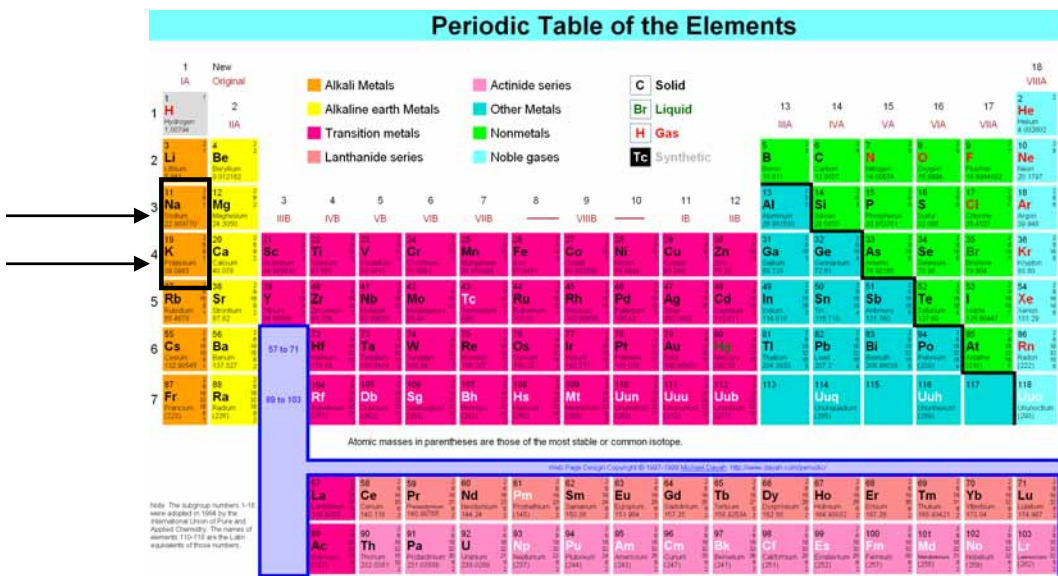
The periodic table shows the position (→) of alkalis (sodium [Na] and potassium [K]), i.e. second and third elements in Group I, the alkali metal group.

Concrete consists of innumerable pores that are often filled with solution containing alkalis (Na^+, K^+) and hydroxyl (OH^-) ions. The alkali level in the pore solution must be high for ASR to occur. Following are the sources of alkalis in concrete.

1. *Alkalis from cement* — Cement is the major source of soluble alkalis due to hydration of cement minerals. According to the American Society for Testing and Materials (ASTM) C 150, 0.6% is the standard option when specifying low-alkali cement. However, it is reported that even this value may be high when used with reactive aggregate.

2. *Alkalis from de-icing salts* — these salts are a common source of alkalis in areas where de-icing salts are used. However, airport authority takes painstaking efforts to

subject all chemicals to tests that preclude those that would harm the aircraft and airport support infrastructure. This potential is minimal to rare on the airside.

3. ***Supplementary cementing materials*** — For example, fly ash with a high alkali content can introduce alkali.

4. ***Aggregates*** — Some aggregates themselves may be a potential source of alkalis. Typically, alkalis are released when the aggregate's lattice structure begins to break down during ASR. These alkalis later provide an additional source for further ASR.

1.2.3 Environmental factors

Availability of sufficient moisture — Moisture is an essential ingredient for ASR; this reaction cannot occur in the absence of moisture. Moisture can have a significant impact on the severity of distress as well. The ASR gel is hygroscopic, i.e., it absorbs moisture. Therefore, higher humidity can increase moisture absorption and thus cause greater expansion in concrete.

Effect of temperature — The rate of ASR development increases with increasing temperature.

Combination of factors — ASR-induced deterioration is more severe in portions of a concrete structure subjected to repeated wetting and drying or freeze-thaw cycles, in addition to the effects of higher temperature and higher moisture.

1.3 Mechanism of ASR

Broadly, the ASR mechanism can be divided into two parts: (1) the actual chemical reaction, and (2) distress arising from the chemical reaction.

(1) Reaction mechanism

The chemical reaction between the alkali hydroxides and reactive silica is essentially a dissolution reaction, i.e., solubility of reactive silica in high-alkaline (high pH) solution. Basically, the hydroxyl (OH^-) ions attack the stronger siloxane bridge (Si-O-Si) near the surface of the reactive siliceous component and break it down. The negative charge created by this breakdown is balanced by the positively charged alkali ions, such as Na^+ or K^+.

$$Si\text{-}O\text{-}Si + 2NaOH\ (KOH) \longrightarrow 2\ Si\text{-}O^-\text{-}Na^+\ (K^+) + H_2O \text{ ------------------(i)}$$

As the reaction proceeds, alkali hydroxides penetrate into the siliceous particle, thus loosening the lattice structure. This type of breakdown of the lattice structure by alkali hydroxide is practically impossible in well-crystallized silica (quartz), but is much greater in crypto-crystalline and amorphous silica because of increased surface area and a disordered,

open lattice structure. The breakdown of the silica lattice due to alkali attack is illustrated in Figure 1-4.
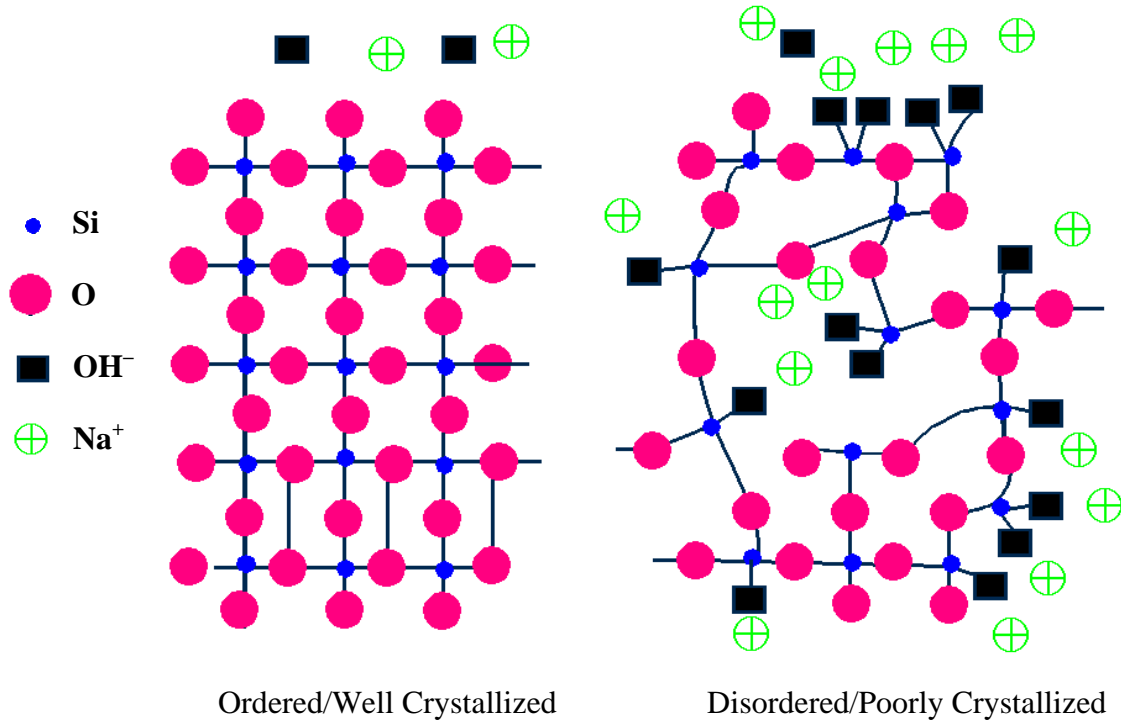
Figure 1-4. Attack of alkali solution on silica lattice.

In the case of non-reactive quartz, the alkali ions cannot penetrate the well-ordered crystal lattice. However, silica minerals with poorly crystallized, disordered crystal lattice such as strained quartz, chalcedony are susceptible to alkali attack, as shown in Figure 1-4.

(2) Distress mechanism

The distress mechanism can be explained by the following flow chart.

Development of a high concentration of alkali hydroxide in the pore solution of concrete or mortar and migration of alkalis through the pore solution to reactive aggregate sites.

Absorption of water by this gel creates expansive forces on the surrounding cement paste, which is in a state of constraint.
Gel reaction product + Moisture → Expansion

mponent within gel **(a viscous** assium], **calcium, and water).**

Stress develops by expansive forces that exceed the tensile strength of the cement paste, thus causing cracks.

Movement of the gel from the aggregate into the paste through cracks is enhanced by calcium absorption from calcium hydroxide. Later, the gel fills these cracks and exerts more expansive pressure, causing further distress.

Chapter 2: Field Diagnosis of ASR

It is preferable that qualified personnel carry out diagnosis in the field. In order to undertake field inspection of airfield pavement, it is essential for the inspector to have a basic knowledge of the different types of distress that occur in pavements. The most readily identifiable distress feature is cracking. Cracking, however, can be of several types, such as:

Linear or longitudinal/transverse cracking
Map cracking
Corner break
D-cracking

Each of these has been cited later in this chapter. One must recognize that several factors can cause cracking in pavement.

2.1 Background information

The following data should be recorded before inspection.

1. Concrete mixture proportions, if available. Otherwise, whether fly ash or slag was used in the concrete.
2. Approximate dates of construction, because segments of airfield pavements may have been constructed at different times.
3. Average relative humidity at the airfield.
4. Annual precipitation.
5. Temperature variation.
6. Use of de-icing chemicals and type, if any.
7. Water runoff.
8. Freezing and thawing, if any.

2.2 Visual manifestation of ASR in airfield pavements

A detailed field survey is normally the first stage for identifying the possible presence of ASR, and the extent of deterioration. The visual signs to be considered in an airfield pavement include the following.

1. *Laddering* — Fine, short, parallel cracks that are perpendicular to joints and normally appear on both sides of a joint at the initial stage of ASR (Figures 2-1 and 2-2).

Figure 2-1. Laddering (→) along a joint due to ASR

Figure 2-2. A close-up view of laddering (→).

2. *Map-cracking* — A matrix of fine cracks in non-reinforced concrete slab in pavements. Map cracking is never distributed uniformly on the surface of a pavement. Its appearance can vary from just a few cracks (Figure 2-3) to isolated areas of pattern cracking to fairly severe, closely spaced extensive map cracking (Figures 2-3 and 2-4), i.e., the crack density on the surface may vary. It must be noted that it is often difficult to distinguish map cracking from crazing, the latter arises from improper finishing and curing and do not affect the structural integrity of concrete.
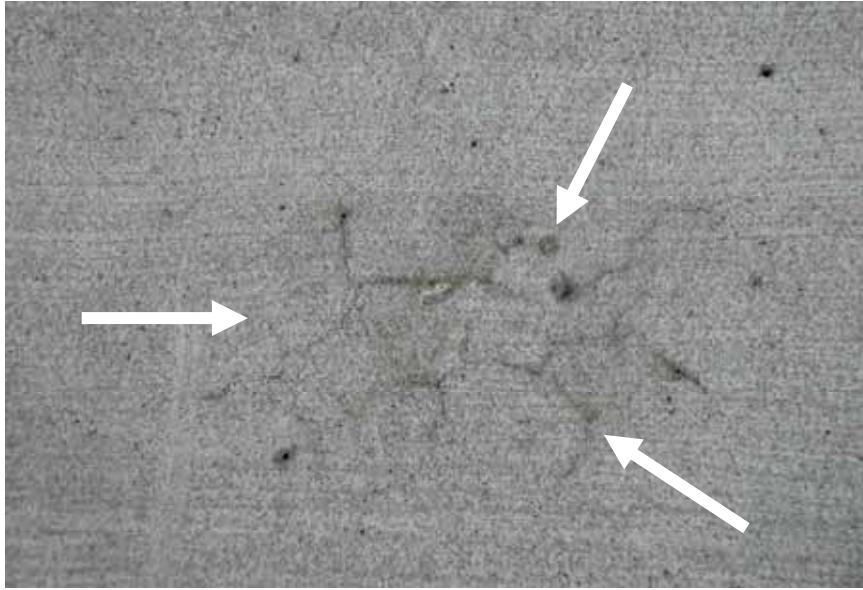
Figure 2-3. Only a few map cracks (→).
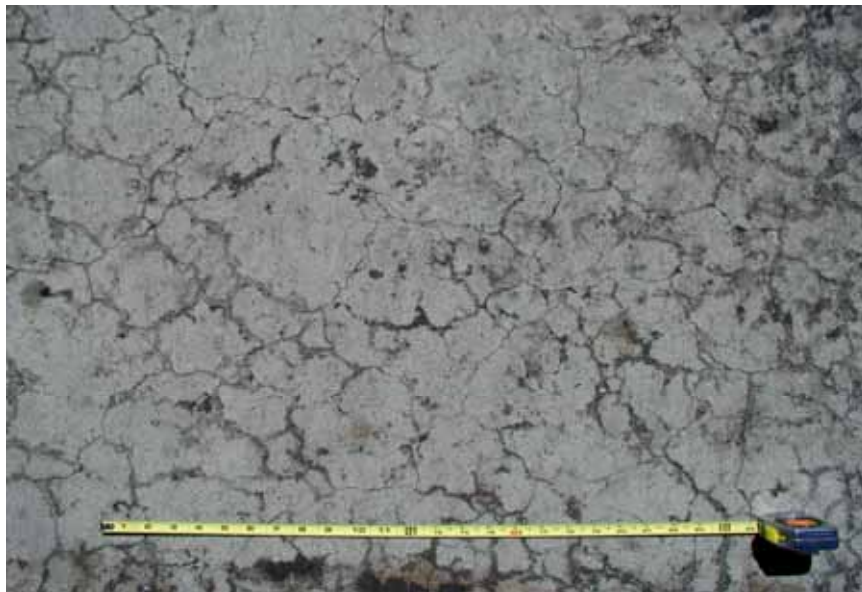
Figure 2-4. Widespread map cracking.

Figure 2-5. Severe map cracking.

3. ***Aggregate pop-out*** — it can occur at the pavement surface due to swelling of the gel.
   Typically, a portion of an affected, exposed aggregate particle breaks away.
   Sometimes, part of the mortar attached to the aggregate is also removed with it,
   leaving a conical-type depression at the surface of the concrete pavement (Figures 2-6
   and 2-7). Aggregate pop-out is not typical of ASR, and can also occur due to frost
   action on shale particles or porous chert particles.

Figure 2-6. Aggregate pop-out (→).

Figure 2-7. Several aggregate particles (A) have been dislodged ($\rightarrow$) along with some neighboring paste.

4. ***Reaction rims around aggregate particles*** — A reaction rim can be described as a peripheral discoloration of aggregate. This feature is often visible to the naked eye or under a hand lens. When examined under a petrological microscope, reaction rims are more positively identifiable (see Chapter 3 for details).

5. ***Open or gel-filled cracks in aggregate particles*** — Usually this is associated with an aggregate reaction rim. An illustration is provided in Figure 2-8.

Figure 2-8. An open internal crack ($\rightarrow$) in an ASR-affected aggregate particle (A).

6. ***Exudation*** — Moisture movement through pores and cracks in concrete transport the ASR gel to the surface, where it exudes. However, ASR gel exudation is not very common, and where present, indicates that there has been sufficient moisture to carry the gel to the surface. This exuded gel is usually grayish white (Figures 2-9 and 2-10). Eventually, the original gel can become a white crystalline material due to carbonation.

Figure 2-9. Gel exudation through cracks.
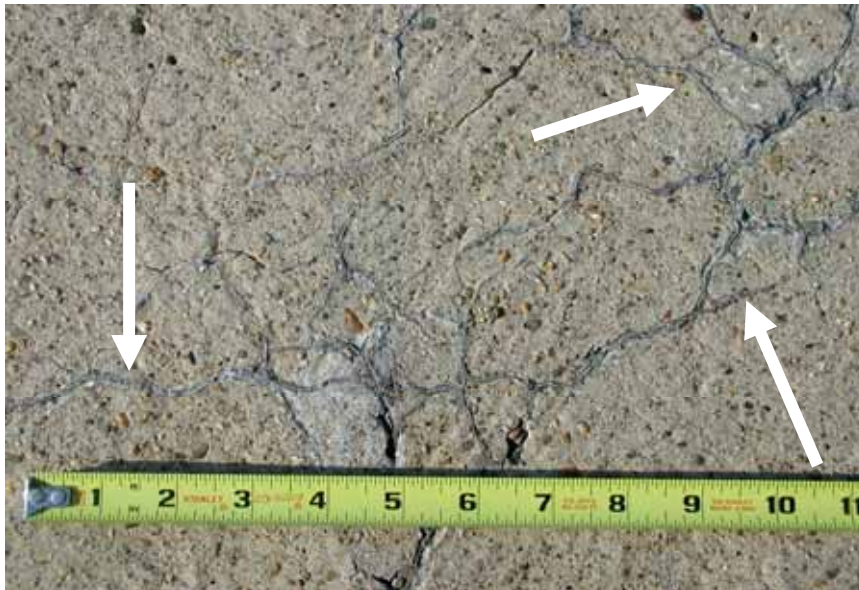
Figure 2-10. Gel exudation (→) through cracks.

2.3 Structural evidence of expansion due to ASR

1. *Closure of joints* — Some of the expansion joints in a pavement may close or become compressed due to horizontal slab movement. (Figure 2-11). This compression may give rise to joint sealant damage, e.g., squeezing out joint sealant because of high compression. Figure 2-12 clearly shows the heaving of an asphalt shoulder due to expansive movement of the adjoining concrete pavement slab in an airfield severely affected by ASR.
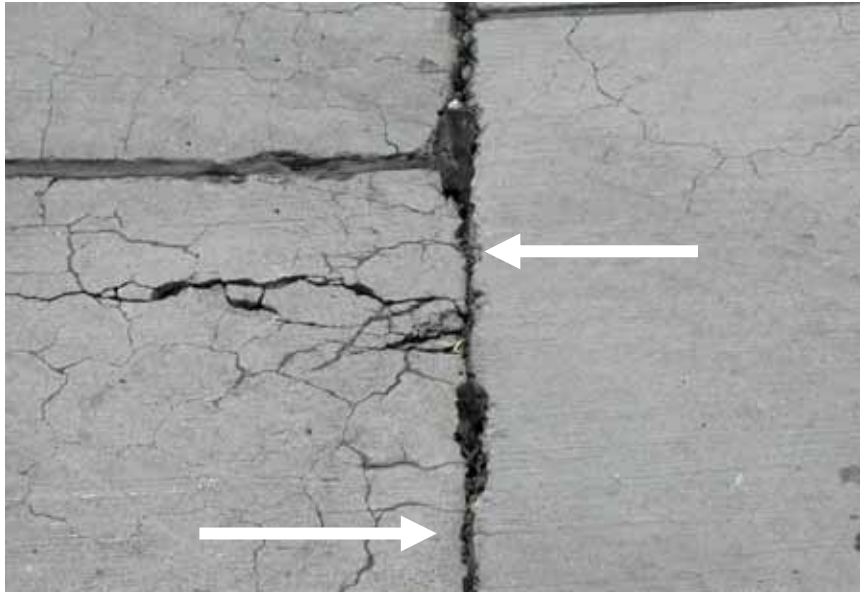
Figure 2-11. Joint compression due ($\rightarrow$) to slab movement.

Figure 2-12. Heaving ($\rightarrow$) of an asphalt shoulder due to movement of adjoining concrete slab affected by ASR. Movement has been so severe that it has distorted the concrete columns (┈▶) of a neighboring building.

(b) Joint misalignment — Further compression on the joint causes misalignment of joints (Figures 2-13)
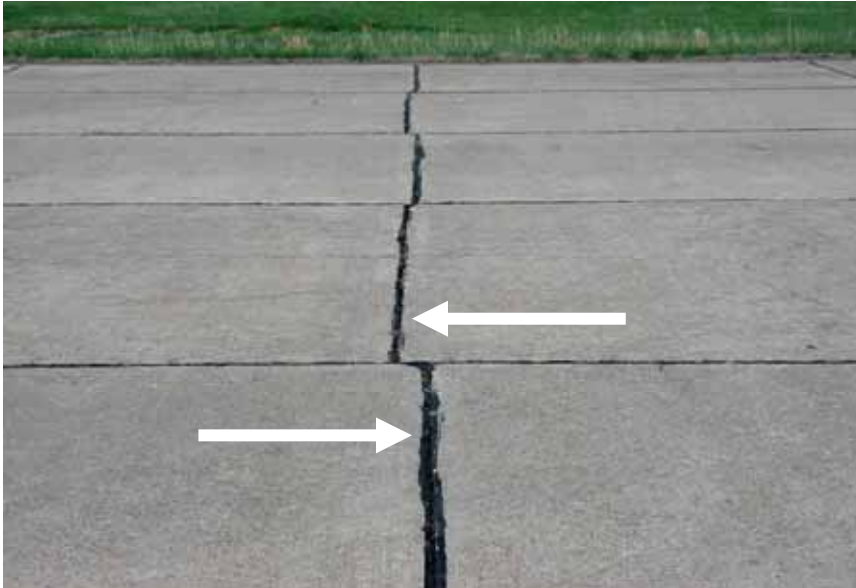
Figure 2-13. Misalignment of joint (→) caused by slab movement.

2. *Blowup/buckling/heaving* — Expansion due to ASR can cause a concrete slab to move upward to relieve compression restraint (Figure 2-14). When one slab heaves up relative to an adjoining slab in a runway, it can become a source of potential hazard for aircraft landing. Slabs are reported to have been ground down a few times during their service life to provide a smooth and level runway surface.

Figure 2-14. Heaving of a slab relative to another

Restraint can influence the development of cracks due to ASR. Cracking may not occur uniformly throughout a structure if expansive forces are less than restraining forces. Most commonly, cracking will be partially or completely suppressed in the direction of the restraint (e.g. steel reinforcement in one direction).

2.4 Distinction between ASR distress features and other types of distress features in airfield pavements

Deterioration arising from ASR and other mechanisms often looks very similar. This similarity makes positive identification of ASR virtually impossible from visual inspection alone. Nevertheless, the visual indicators of ASR listed in sections 2.2 and 2.3 should be considered as preliminary evidence. However, laboratory investigation is essential to confirm ASR. The roles of structural design of the pavement, concrete mixture proportions, age of the pavement, and climatic factors in the deterioration process should be evaluated before considering the influence of other major distress mechanisms, such as freeze-thaw, sulfate attack, carbonation, leaching, etc.

One deterioration mechanism often complements another to accelerate concrete deterioration, e.g., (a) initial cracks formed by freeze-thaw or shrinkage can generate better access for moisture to migrate deeper, and thus increase the risk of further damage; (b) portland cement may provide the alkali necessary for ASR to initiate, but the reaction may be aggravated by other sources of alkalis described earlier in Section 1.2.2 (Chapter 1), and (c) in airfield pavements, it is necessary to consider the stresses induced during aircraft landing and maneuvering.

2.4.1 Distress criteria

The following features can be helpful to distinguish other distress mechanisms.

1. Sub parallel cracking and cracking restricted to the near surface with scaling and spalling of the exposed surface and edges are primarily associated with freeze-thaw damage. A surface attacked by frost is rough and irregular.

2. Alkali-silica reactivity by itself does not usually cause disintegration of the surface, except for aggregate pop-outs.

3. D-cracking is primarily caused by freeze-thaw. This distress usually appears as a pattern of cracks running parallel and close to a joint. Depending on the severity of distress, loosening or displacement of concrete in the cracked region can occur. This D-cracking may eventually lead to disintegration of the concrete within 1 to 2 ft of the joint or crack (Figure 2-15).
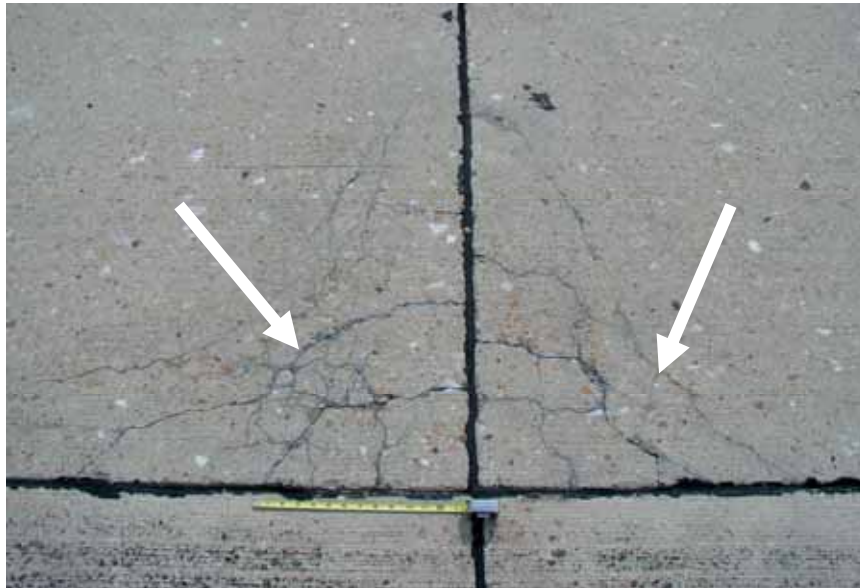
Figure 2-15. D-cracking ($\rightarrow$) in an airfield pavement.

If any of these distress criteria are present in an airfield pavement located in a region vulnerable to freeze-thaw, then one must exercise caution in identifying the primary cause of distress.

4. Severe exfoliation, that is, when layers of concrete are detached from the surface, generally caused by sulfate attack. However, chemical analysis, x-ray diffraction (XRD) or scanning electron microscope-energy dispersive spectroscopy (SEM-EDS) is essential for proper identification of reaction products, e.g., abundance of gypsum, ettringite, etc., to confirm sulfate attack.

5. Porous aggregates that undergo freeze-thaw attack can also cause pop-outs. In the case of ASR, the gel, if present, can be identified from visual inspection of the region of the crater created by pop-out. Typically, one or two additional symptoms of ASR, such as map cracking, laddering, misalignment of joints, etc. are associated with the pop-out.

6. Corner breaks (Figure 2-16), corner spall (Figure 2-17), joint spall (Figure 2-18), and transverse/longitudinal cracks (Figure 2-19) are caused by other distress mechanisms.

Figure 2-16. Corner break (→) in an airfield pavement.

Figure 2-17. Corner spall in another airfield pavement.

Figure 2-18. Longitudinal joint spall ($\rightarrow$).

Figure 2-19. Longitudinal cracks ($\rightarrow$) in an airfield pavement.

2.5 Application of dyes to detect ASR gel in the field

Use of the uranyl (uranium) acetate fluorescence method (UAFM) — Often it is not very easy to identify ASR gel in the field with the unaided eye. The surface of the pavement may be covered with dirt and grime deposited over many years. The dye method can be used on any concrete surface to identify ASR gel. The gel may be present in vary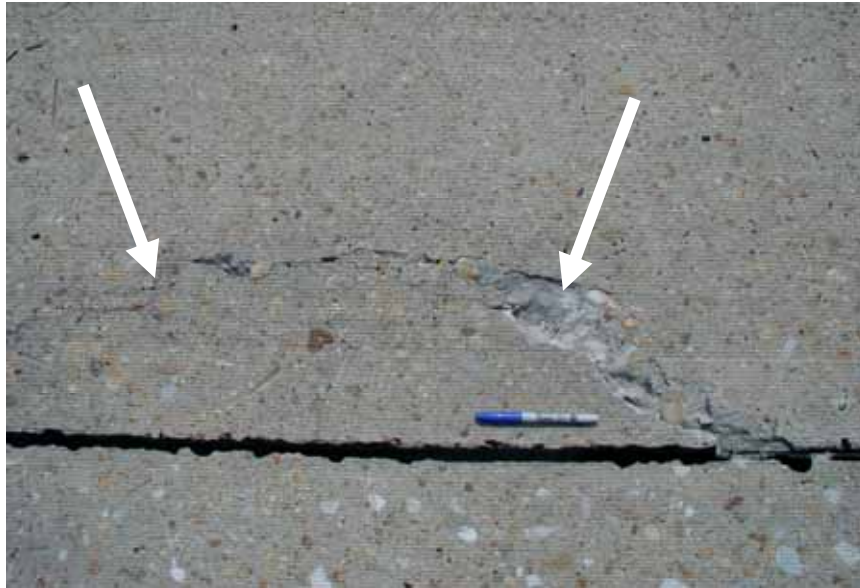ing proportions in aggregate rims and cracks, air voids, fractures, and on the exposed surface of concrete as exudation. By applying uranyl acetate solution to the surface, the gel, if present in an unaltered state, imparts a characteristic yellowish green glow in ultraviolet (UV) light (254 nm) because of uranyl ion substitution for alkali in the gel. The gel fluoresces much more brightly than cement paste due to the higher concentration of alkali. The following steps are recommended for use of this method. **All safety precautions must be followed while preparing and using this solution. Gloves must be worn when using some of these dyes. The Material Safety Data Sheet (MSDS) must be consulted before using dyes.**

Step 1: Uranyl acetate solution — Prepare a dilute acetic acid solution by adding 5 mL of glacial acetic acid to distilled water to make up 200 mL of solution. Add 5 g uranyl acetate powder to the dilute acetic acid solution. Warm but do not boil to dissolve the powder. The process will not work properly if the solution boils.

Step 2: A fresh concrete surface free of laitance and carbonation is required. This can be exposed at approximately ¼ inch depth using a rotary hammer, hammering by hand, or by sawing.

Step 3: Powder concrete must be rinsed off the surface with water.

Step 4: The uranyl acetate solution is sprayed on the fresh concrete surface, allowed to react for 5 minutes, and the surface is rinsed with water.

Step 5: A light-excluding viewing box (portable darkroom) containing ultra violet (UV) light is used because the fluorescence of the silica gel due to absorption of uranium ions is too faint to see in daylight.

Source:
Uranyl acetate is available from any chemical supplier.

Ultra violet light box – A viewing box that can be placed over the surface to be viewed. Provision must be made for a UV light lamp and for excluding ordinary light.

Use of other dyes such as cuprammonium sulfate solution does not provide very effective coloration to enable clear distinction of ASR.

2.6 Selection of coring locations for further laboratory investigation

If some definite indications of ASR are obtained from visual inspection of the pavement, then the next step is to collect cores from strategic locations for further laboratory investigation. Airfield pavements generally consist of a series of slabs. Very often these slabs were constructed at different times. So it is likely that different concrete mixture proportions were used. Background information about the different slabs in a concrete pavement, if available, can be useful for selecting coring locations. The location and number of cores should depend on the following:

1. ***Severity of distress*** — The severity of external cracking may not necessarily correlate with the severity of internal damage. So, collecting a full-depth core is always desirable. In general, it is recommended to collect one core per each distress feature. If the severity of a distress feature varies, e.g., from low to high then the engineer has the option to collect more than one core, for example, one from high-severity area and another from low severity area. Similarly, if the distribution pattern of a particular distress feature (such as map-cracking) is repetitive from one sample unit to another, then the engineer has the option to reduce the coring rating.

   In fact, cores from adjacent pavements without visual distress may be appropriate when attempting to determine the severity of distress. In some instances, ASR distress can be very localized and limited to small pockets where reactive aggregates were used (see Figure 2-3).

2. ***Age of concrete*** — If possible, cores from sections of different construction ages should be selected.

3. ***Concrete mixture proportions/Presence or absence of fly ash or slag*** — Cores from slabs/sections with different mixture proportions or at least whether fly ash/slag was used in the concrete should be included in the coring plan.

4. ***Variation in concentration of cracking within a slab*** — the concentration of cracking may vary from one section to another within the same slab as shown in Figures 2-20 and 2-21. If necessary, cores should be collected from different affected parts of the same slab to determine if ASR is localized or global distress.
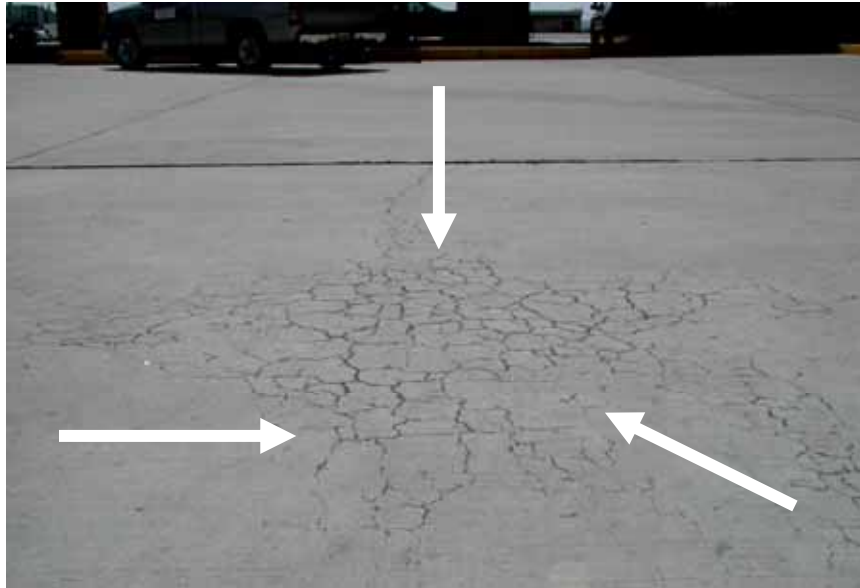
Figure 2-20. Cracks ($\rightarrow$) in the central part of a pavement section.
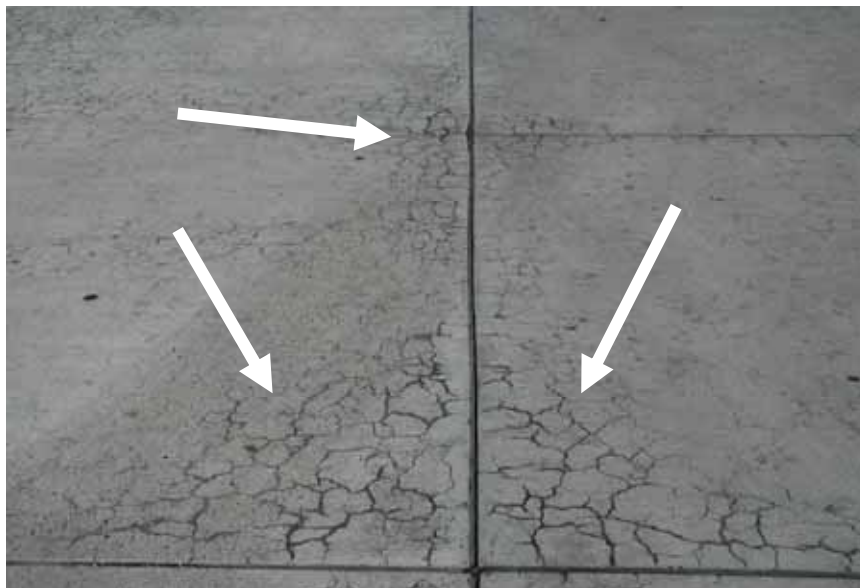
Figure 2-21. Different cracking pattern ($\rightarrow$) near the joint of the same pavement section.

Airfield pavement slabs may be as thick as 18 inches. Full-depth cores are recommended because there may be variation in cracking and distress pattern in the upper, intermediate, and bottom portions of the slab. This will also enable assessment of ASR-related distress as a function of depth.

The diameter of the cores should be at least 2 inches; otherwise, in situ recovery of core may be difficult.

2.6.1 Visual inspection of cores

Visual examination of the drilled cores with the unaided eye or a hand lens can often provide useful information about the type and extent of distress. The features to look for include the following:

1. Hairline cracks, originally due to drying shrinkage or some other distress mechanism,
2. Peripheral discoloration of aggregate, and
3. White gel around aggregate particles.
   An illustration is provided in Figure 2-22.

Figure 2-22. Full-depth cores from sections of an airfield pavement showing different distress features, such as short vertical cracks (A), horizontal cracks (B), peripheral discoloration of aggregate (C), and cracked aggregate (D).

2.7 Summary

A summary is presented in order to reinforce the steps involved in a performing a thorough field investigation.

- Visual signs to be considered: ***map-cracking, laddering, aggregate pop-out, reaction rim around aggregate particle, open or gel-filled cracks in aggregate particle, gel exudation.***
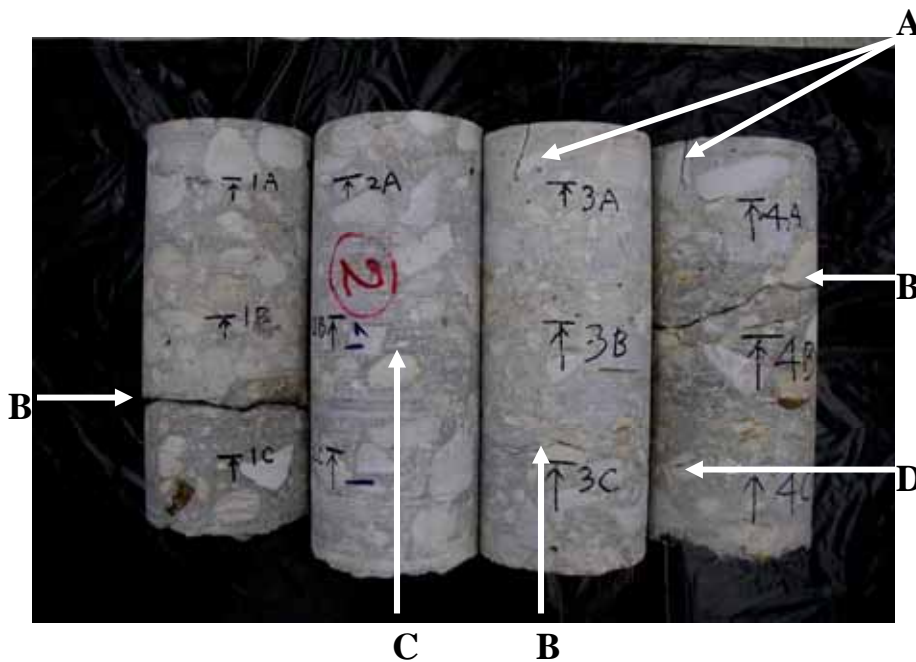- Structural evidence of expansion due to ASR to be considered – ***joint closure, joint seal damage, joint misalignment, blowup/heaving.***
- UAFM dye test method in field to detect ASR gel in visible cracks (applicable only if gel is present in an unaltered state). Unaltered gel if present, can be identified in cracks, and fractures on the exposed surface of pavement by its characteristic yellowish-green glow under UV light.

Coring for further laboratory investigation:

- In general, it is recommended to collect one core per distress feature.
- If the severity of a distress feature varies, e.g., from low to high then the engineer has the option to collect more than one core, for example, one from high-severity area and another from low severity area. Similarly, if the distribution pattern of a particular distress feature (such as map-cracking) is repetitive from one sample unit to another, then the engineer has the option to reduce the coring rating.
- Collect full-depth cores with diameter of at least 2 inch., but not larger than 4 inch.

Chapter 3: Laboratory Investigations

3.1 Use of dye

Slicing the full-depth drilled core at three or more different depths is desirable. All the sections must be properly identified and marked for orientation. Examination of these sections by the same dye method described in Chapter 2 can help to detect whether the gel is present throughout the core and, if so, the relative amount at different depths.

The dye test indicates the presence of unaltered ASR gel, but it is not a decision-making tool. Neither can the amount of gel be quantified by this method. Therefore, one must not rely solely on this test. Additional laboratory tests are strongly recommended. The advantage of using UAFM is demonstrated below in Figures 3-1 and 3-2.
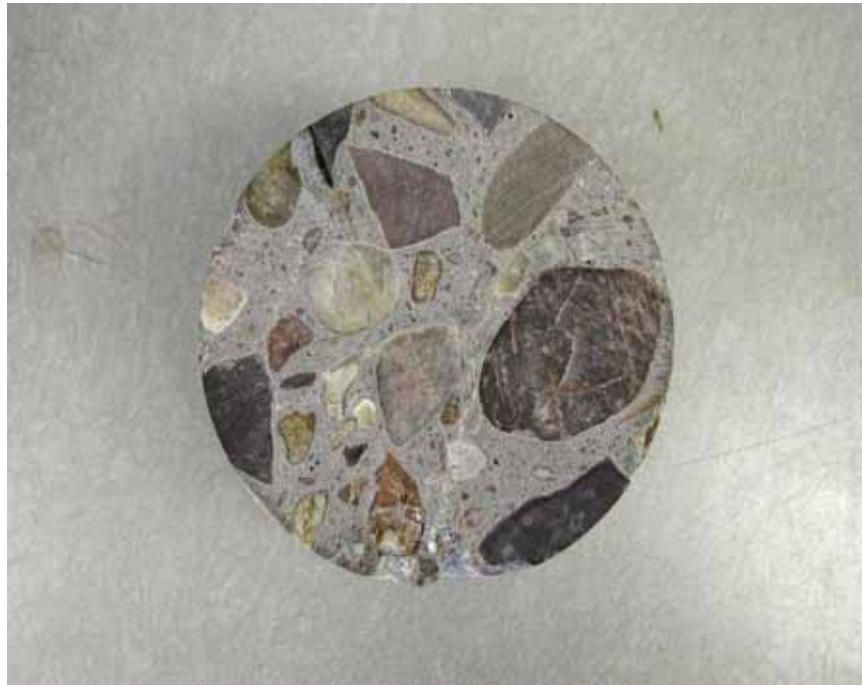

Figure 3-1. A slice of a concrete core collected from an airfield pavement under plain light (scale: 1= 1.75).
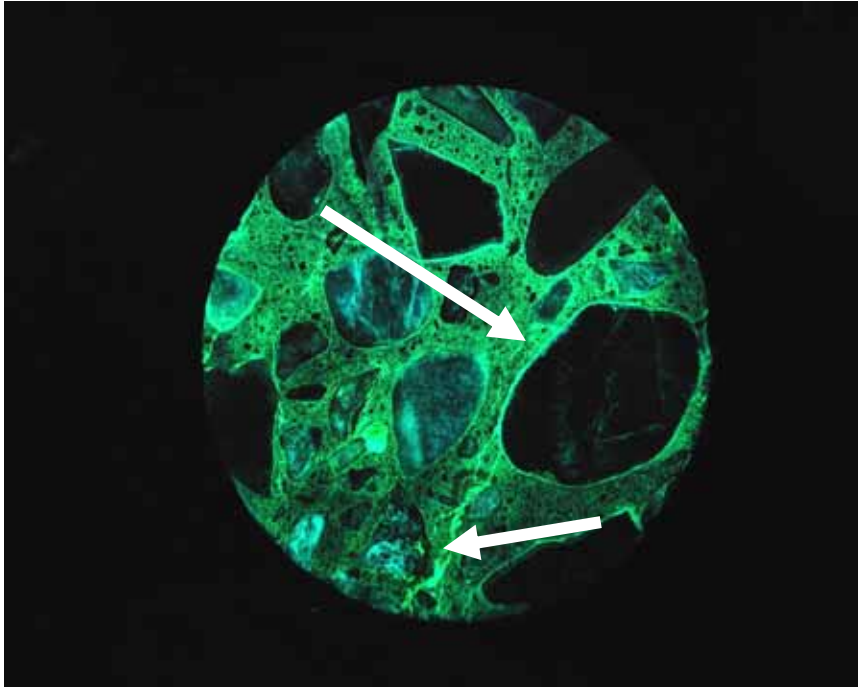
Figure 3-2. The same section after dye treatment when viewed under UV light shows ASR
gel along cracks and around aggregate periphery ($\rightarrow$). Scale: 1=1.75

3.2 Optical microscopic techniques to identify ASR

3.2.1 Optical microscopy

A polarizing light microscope, typically in the magnification range of ~32× – 800× is used
for petrographic analysis. The resolution of a petrographic microscope is between 5 and 10
μm. The polarizing light or petrographic microscope is designed to analyze light transmitted
through or reflected from a sample. Optical microscopy utilizes cross-polarization of light.
Qualitative data can be derived from microscopic examination. Thin concrete sections are
studied in the transmitted-light mode; the reflected-light mode is more suited for examination
of polished samples. Most modern petrographic microscopes are equipped with both light
sources. A camera attached to the microscope has become a standard accessory for
photographically recording important observations.

Optical microscopy is a highly useful, simple, and inexpensive tool for identifying ASR.
While optical microscopy offers a relatively rapid means of diagnosing ASR, sample
preparation is elaborate, time-consuming, and somewhat demanding. Nevertheless, optical
microscopy can reliably serve to identify the deterioration features of ASR. Although it can
provide some definite answers, additional testing, if available, is strongly recommended.

A resin-soluble blue dye can be vacuum impregnated during sample preparation. The use of
dye facilitates recognition of micro cracks and voids.

Commensurate with the cut sections of the core, petrographic examination of at least three thin or polished sections are recommended from a full-length core. The top 2 inches should be avoided because accumulation of dirt along cracks generally masks distress features.

3.2.2 Identification of ASR features under the microscope

Petrographic examination involves identifying the characteristic features of ASR, such as peripheral discoloration, reaction rims, polygonal cracking of aggregate, micro cracks in paste, presence of gel, etc. Microphotographs (Figures 3-3 through 3-4) are provided to illustrate these features. The blue areas in these photomicrographs represent vacant spaces, for examples, empty cracks and air voids.
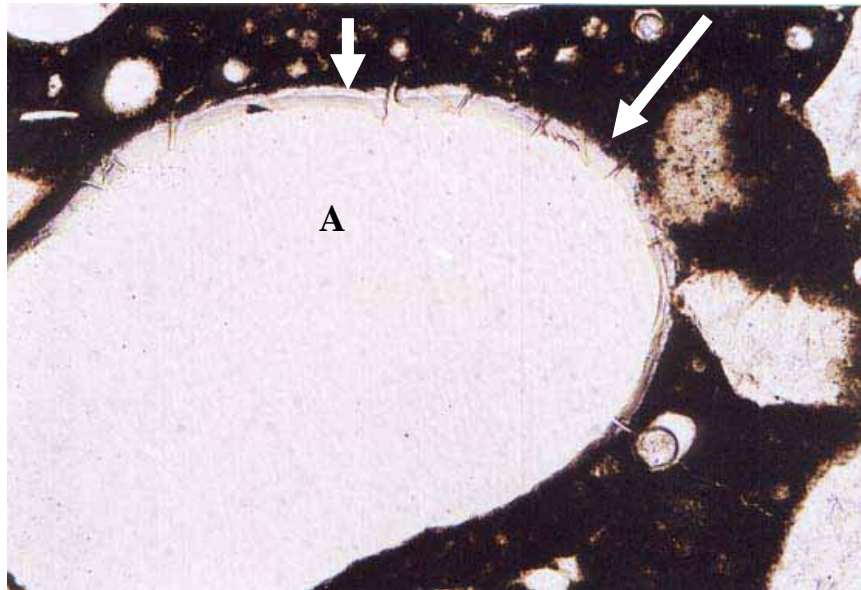
Figure 3-3. Reaction rim (→) around an aggregate (A) particle due to ASR. Magnification 100X.
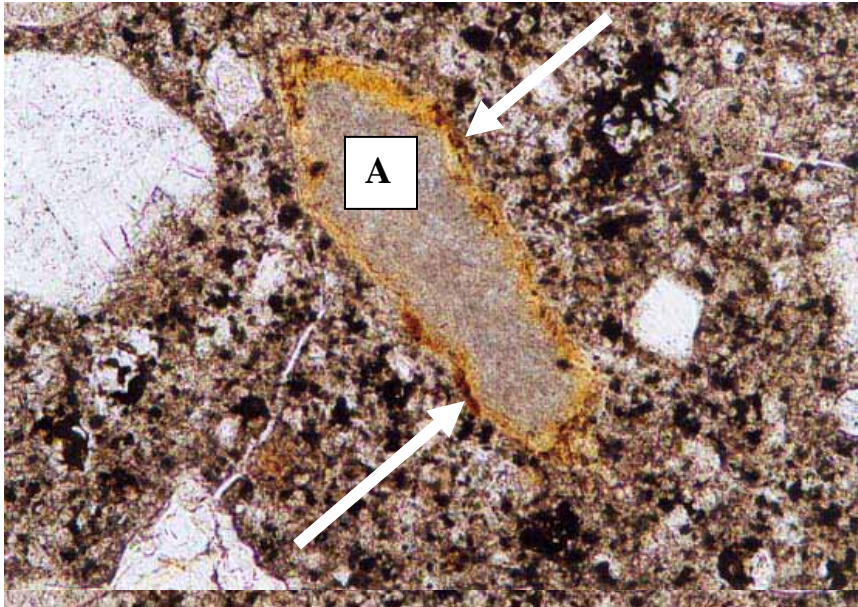
Figure 3-4. Peripheral discoloration ($\rightarrow$) of an opaline limestone aggregate (A) particle. Magnification 200X
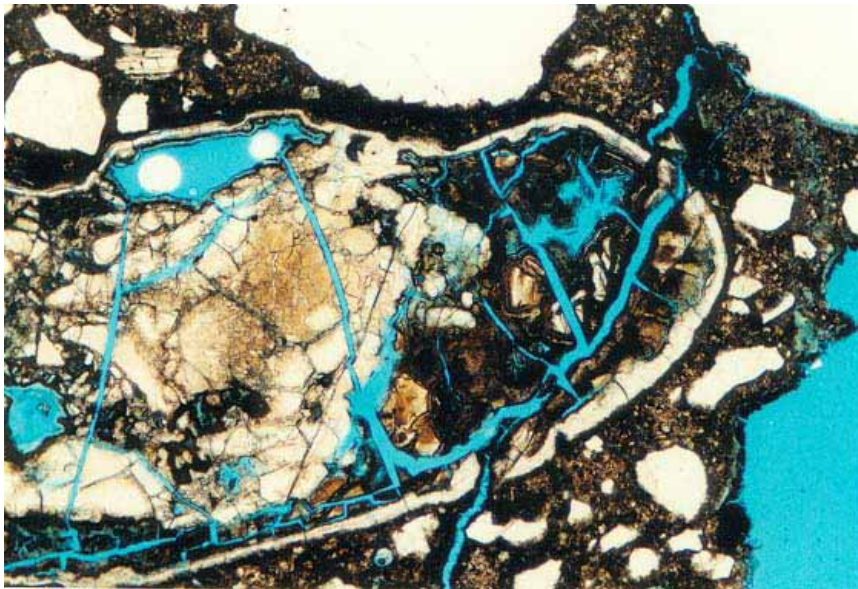
Figure 3-5. A severely cracked opaline siliceous fine aggregate due to ASR. Magnification 40X
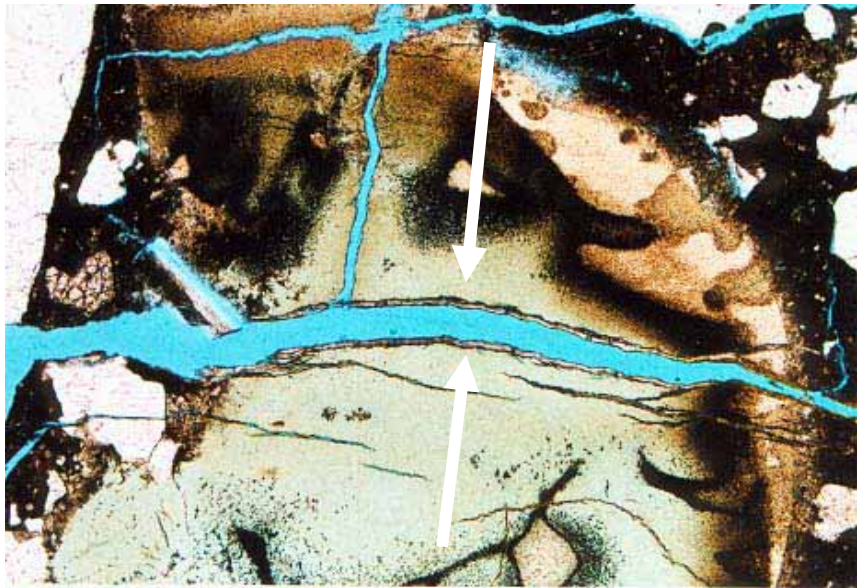
Figure 3-6. Transgranular cracks passing through paste and a reactive fine aggregate particle. Note the presence of gel (→) at the edges of cracks inside the aggregate. Magnification 40X.
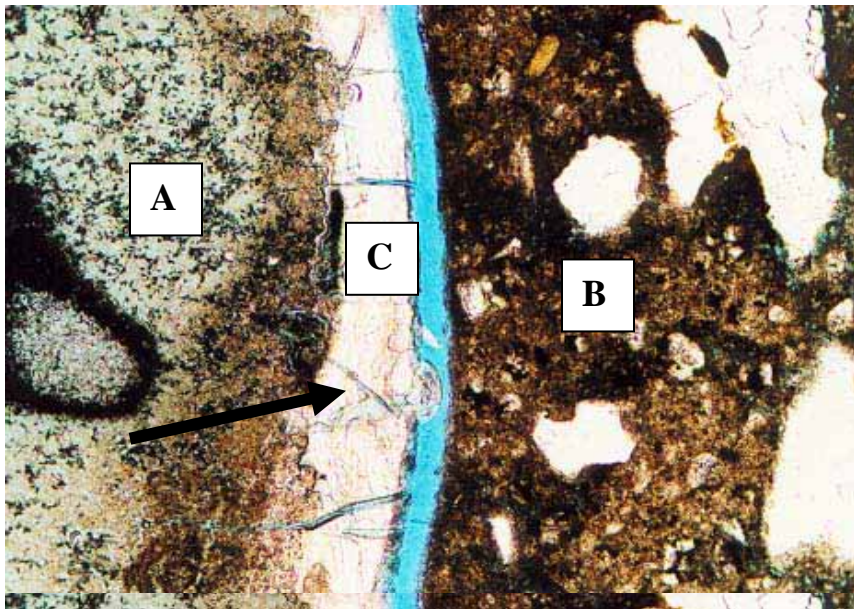
Figure 3-7. Presence of gel (C) with transverse cracks (→) at the interface between reactive aggregate (A) and cement paste (B). Magnification 100X.
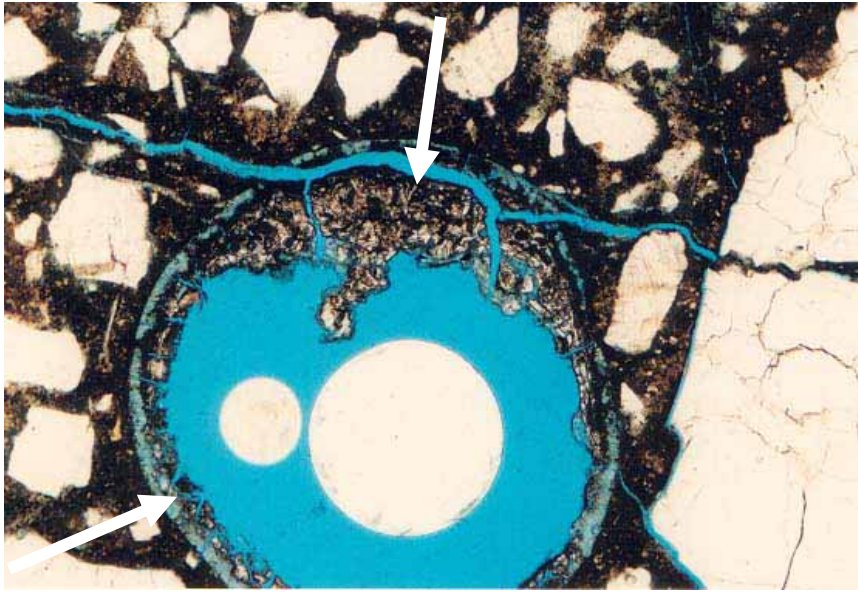
Figure 3-8. Accumulation of gel ($\rightarrow$) at the periphery of an air void. Magnification 40X.

Rapid identification of gel — The ASR gel is a clear transparent material with transverse cracks in plane-polarized light and is isotropic under cross-polarized light, i.e., it remains dark through a complete rotation of the microscope stage (Figure 3-9).
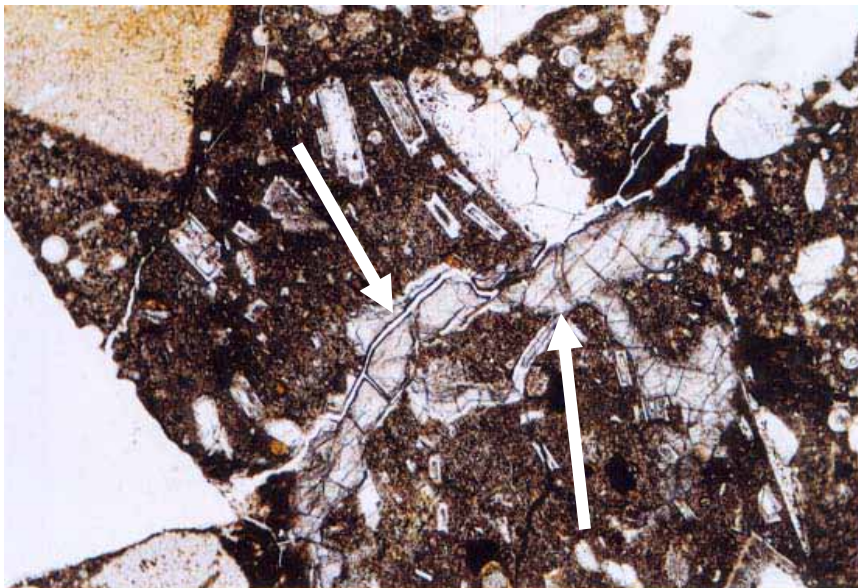
Figure 3-9. ASR gel with transverse cracks ($\rightarrow$) inside a reactive aggregate. Magnification 40X.

Identification of reactive aggregates — Both coarse and fine aggregates may be reactive. Therefore, both should be carefully examined petrographically. Figures 1-2 and 1-3 presented in Chapter 1 show a few examples of different forms of reactive silica.

3.3 Scanning electron microscopy/energy dispersive X-ray analysis

A scanning electron microscope (SEM) uses a primary electron beam to scan the specimen surface. SEM allows direct observation of surface topography. Very low (20×) to very high (50, 000×) magnification can be selected. SEM provides a much greater depth of field than optical microscopes, creating a three dimensional effect. In addition, SEM imagery is easy to interpret, especially in combination with energy dispersive X-ray analyzer (EDXA).

One of SEM's greatest advantages lies in the possibility of examining fractured concrete specimens, although flat polished specimens can also be observed with relative ease. Samples can be in any form, provided they can withstand the high vacuum required in the specimen chamber for the operation of the microscope. Concrete samples must be treated with a thin conductive coating of gold (Au), gold-palladium (Au-Pd), or carbon (C) prior to observation under the microscope to prevent charge build up on the surface.

EDXA is used in conjunction with SEM. EDXA determines the elemental analysis of the phases by analyzing the characteristic X-rays generated by an electron beam. Therefore, confirmation of the presence of ASR gel and its composition can be ascertained by SEM-EDXA. Crystalline and amorphous gel can be clearly distinguished by SEM. Since EDXA analysis cannot be restricted to an arbitrary small volume, spurious contributions as a result of the beam passing through the crystal being analyzed may jeopardize accurate analysis.

Scanning electron microscopy involves identifying ASR gel by its characteristic morphology. Typical morphologies of gel, namely rosette types (Figure 3-10), lamellar types (Figure 3-11) which are the crystalline variety, and massive cracked types (Figure 3-12) which is non-crystalline, can be used as diagnostic features to confirm ASR.

Figure 3-10. SEM image of rosette like crystalline ASR gel product.

Figure 3-11. Crystalline lamellar gel at the surface of aggregate.
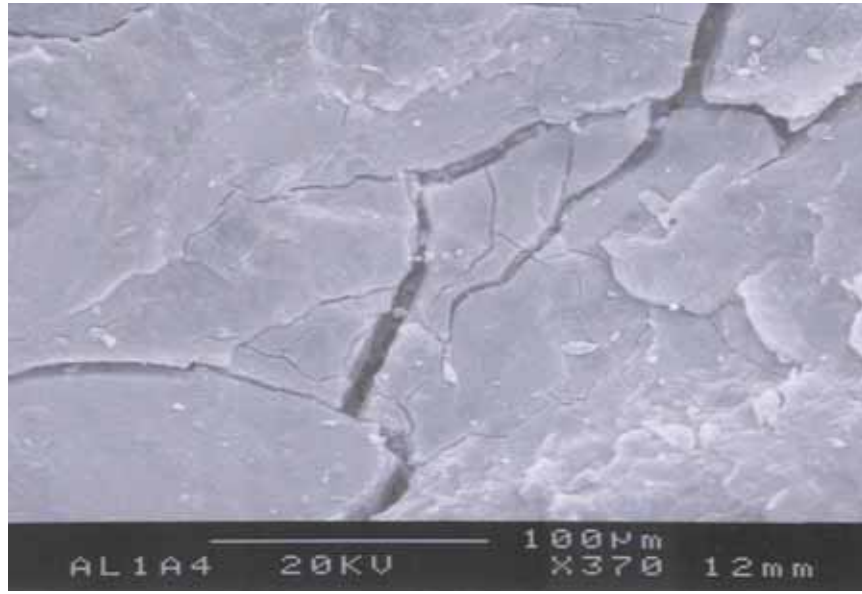
Figure 3-12. SEM image of massive type amorphous ASR gel.

Chapter 4: ASR Distress Analysis in Airfield Pavements

4.1 ASR condition survey

The condition survey of ASR in airfield pavements is based on identification of critical distress features from visual inspection, followed by laboratory investigation, if any symptoms of ASR are detected. The modified survey data sheet, which is based on the original condition survey of distress data sheet in ASTM 5340 *Airport Pavement Condition Index Surveys*, is presented in Table 1. Modifiers, that is, characteristic features related to ASR distress, have been in added to the original list of distress types in the survey sheet in order to provide a more authentic ASR distress rating.

Table 1: ASR condition survey data sheet for jointed airfield pavement

Jointed Rigid Pavement ASR Condition Survey Data Sheet for Sample Unit			

Facility	Sample unit		Date
Year of Construction		**Average RH**	
Average Annual Rainfall		**Slab Dimensions**	

Other Aggravating Factors

Score (A)

Fly ash/ Slag	Y	N
De-icing Salt	Y	N
Freeze-thaw+	Y	N
Average RH		
Average Rainfall	_____	

Sum   _____

+ **If "Y" then, on an average cycles per year**

Direction of Survey

Distress types

1 – Blow up, **2** – Corner break
5– Joint seal damage **8** – pop-outs
10 – Scaling / Map-cracks/crazing
11 – Settlement / Fault
13 – Shrinkage crack
14 - Spalling (joints) **15** – Spalling (corner)

Modifiers

(a) Laddering
(b) Aggregate cracking
(c) Gel exudation
(d) Joint closure
(e) Joint misalignment
(f) Heaving

Critical ASR Features	Visual inspection			Laboratory Investigation Score of ASR Features from Laboratory Investigation			
	Score of the ASR Features (B)	UAFM Test in Field	No. Core **	UAFM (C1)	Petrography/SEM-EDXA		
					Gel (C2)	Agg. Crack. (C3)	RR (C4)
10* (c)		Y					
13* (a)		Y					
10H		Y					
(c)		Y					
(b)		Y					
5* (d) (e)		N					
1* 5* (d) (e)		N					
11* (f)		N					
2 H		N					
15 H		N					
14 H		N					
Sum			Avg.				

Total Score: **Distress Rating:**

Residual Service Life:

Total score = Sum (A) + Sum (B) + Avg. (C1) + Avg. (C2) + Avg. (C3) + Avg. (C4)
* All levels of severity   ** One core/distress feature   RR – Reaction Rim
RH – Relative Humidity

4.2 Scoring of ASR distress

Visual inspection

- Based on **degree of severity** of critical ASR features

- High – **8**, Medium to high – **6**, Medium – **4**, Low to medium – **3**, low - **2**

Laboratory Investigation

From petrography

- **Reaction rim**

  12 – prominent and thick, **8** – intermediate, **4** – faint, **0** – absent

- **Presence of gel**

  12 – repetitive and frequently occurring in cracks, air-voids, aggregate - paste interface, inside cracked aggregate, **8** – localized, **4** - trace, **0** – absent

- **Aggregate cracking**

  12 – intense, **8 –** intermediate, **4** – trace, **0 –** absent

From UAFM test

- **12** – strongly affirmative (repetitive at different depths and frequently occurring either in cracks, air voids, or at aggregate – paste interface), **8** – affirmative (presence of gel is confirmed but not repetitive and frequently occurring and **4** – negative (gel not detected). It does not necessarily signify that gel is absent.

Effect of other aggravating factors on ASR

- **Average annual rainfall (inches)**

  5 – high ($>40^{//}$), **3** – moderate ($20\text{-}30^{//}$), **1** – low ($< 15^{//}$)

- **Average relative humidity (%)**

  3 – high ($> 80\%$), **2** – moderate ($70\text{–}40\%$), **1** – low ($<30\%$)

- **Freeze-thaw cycles**

  3 – high (20 cycles per year), **2** – moderate (10 cycles per year), **1** – low (5 cycles per year), **0** – absent

- **Use of de-icing salt**

  3 – used and alkali-bearing, **1** – used, but non alkali-bearing**, 0** – never used

- **Use of Fly ash**

  4 – not used, **3** – low fly ash proportion ($< 20\%$), **2** – moderate fly ash proportion (20-30%), **1** – high fly ash proportion ($> 30\%$).

- **Use of ground granulated blast furnace slag**

  4 – not used, **3** – low slag proportion (25-40%), **2** – moderate slag proportion (40-50%), **1** – high slag proportion ($> 50\%$).

Total Score = score of other aggravating factors (sum of "A") + score of visual inspection (sum of "B") + score of laboratory investigation (Avg. C1 + Avg. C2 + Avg. C3 + Avg. C4)

Distress rating from total score

High – when total score is > 75
Moderate – when total score is 75-45
Low – when total score is < 45

Example 1: ASR condition survey for an airfield pavement section (containing different sample units) with **high-severity ASR**

Jointed Rigid Pavement **ASR Condition Survey Data Sheet for Sample Unit**							
Facility RWY		**Sample Unit** 1				**Date** 3/15/02	
Year of Construction: 1957						**Average RH: >30%**	
Average Annual Rainfall: > 15 inch						**Slab Dimensions 25 x 25 FT**	

Other Aggravating Factors

			Score (A)
Fly ash/ Slag	Y	(N)	4
De-icing Salt	Y	(N)	0
Freeze-thaw	Y	(N)	0
Average RH			1
Average Rainfall			1
Sum			6

Distress types

1 – Blow up 2 – Corner break
5– Joint seal damage 8 – pop-outs
10 – Scaling / Map-cracks/crazing
11 – Settlement / Fault
13 – Shrinkage crack
14 - Spalling (joints) 15 – Spalling (corner)

Modifiers

(a) Laddering
(b) Aggregate cracking
(c) Gel exudation
(d) Joint closure
(e) Joint misalignment
(f) Heaving

Critical ASR Features	Score of the ASR Features (B)	UAFM Test in Field	No. Core	UAFM (C1)	Gel (C2)	Agg. Crack. (C3)	RR (C4)
				Visual inspection → **Laboratory Investigation** — Score of ASR Features from Laboratory Investigation / Petrography / SEM-EDXA			
10* (c)	6	Y	2***	8	12	12	8
13* (a)	4	Y	1	8	8	8	4
10H	8	Y	1	4	8	8	4
(c)	4	Y	0				
(b)	2	Y	0				
5* (d) (e)	4	N	1				
1* 5* (d) (e)	2	N	0				
11* (f)	4	N	1				
2 H	2	N	0				
15 H	2	N	0				
14 H	2	N	0				
Sum	40		Avg	7	9	9	5

Total Score: 76 **Distress Rating: High**

Residual Service Life: Less than 5 years

Total Score = Sum (A) + Sum (B) + Avg. (C1) + Avg. (C2) + Avg. (C3) + Avg. (C4)
*** 1 core in high severity area & 1 core in low severity area,
MH - Moderate to high

Direction of Survey

5	10(c)MH	5M 10 H		10 H 13(a)M
4	10(c) MH 13(a)M 5(d)(e)M		10H	5(d)(e) MH 13(a) M
3	11(f)M		(b)	5(d)(e) M
2		10H		10 (c)MH
1	(b)	(c)	10H	
	1	2	3	4

Example 2: ASR condition survey for an airfield pavement section (containing different sample units) with **low-severity ASR**

Jointed Rigid Pavement ASR Condition Survey Data Sheet for Sample Unit		
Facility RWY	**Sample unit** 2	**Date** 3/15/02
Year of Construction: 1957		**Average RH: >30%**
Average Annual Rainfall: > 15 inch		**Slab Dimensions 25 x 25 FT**

Other Aggravating Factors

		Score (A)
Fly ash/ Slag	(Y) N	**2**
De-icing	Y (N)	**0**
Salt		
Freeze-thaw	Y (N)	**0**
Average RH		**1**
Average Rainfall		**1**
Sum		**4**

Distress types

1 – Blow up 2 – Corner break
5 – Joint seal damage 8 – pop-outs
10 – Scaling / Map-cracks/crazing
11 – Settlement / Fault
13 – Shrinkage crack
14 - Spalling (joints) 15 – Spalling (corner)

Modifiers

(a) Laddering
(b) Aggregate cracking
(c) Gel exudation
(d) Joint closure
(e) Joint misalignment
(f) Heaving

Critical ASR Features	Visual inspection			Laboratory Investigation Score of ASR Features from Laboratory Investigation			
	Score of the ASR Features (B)	UAFM Test in Field	No. Core	UAFM (C1)	Petrography / SEM-EDXA		
					Gel (C2)	Agg. Crack. (C3)	RR (C4)
10* (c)	2	Y	1	8	8	4	4
13* (a)	4	Y	1	4	4	4	0
10H	2	Y	0				
(c)	2	Y	0				
(b)	0	Y	0				
5* (d) (e)	2	N	1	4	4	4	0
1* 5* (d) (e)	0	N	0				
11* (f)	0	N	0				
2 H	0	N	0				
15 H	0	N	0				
14 H	2	N	0				
Sum	14		Avg	5	5	4	1

Total Score: 33   **Distress Rating: Low**

Residual Service Life: 15-20 years

Total Score = Sum(A) + Sum (B) + Avg. (C1) + Avg. (C2) + Avg. (C3) + Avg. (C4)

Direction of Survey

5	10(c)L	10L 13(a)M		10L
4	10(c)L 13(a)M	10L		5(d)(e)L
3	13(a)L	5(d)(e)L		
2		10L		
1				
	1	2	3	4

Example 3: ASR condition survey for an airfield pavement section (containing different sample units) with **high-severity ASR.** Note that visual manifestation of ASR is comparatively low.

Jointed Rigid Pavement ASR Condition Survey Data Sheet for Sample Unit		
Facility RWY	**Sample Unit** 3	**Date** 4/15/02
Year of Construction: 1940		**Average RH: ~80%**
Average Annual Rainfall: ~30 inch		**Slab Dimensions 12 x 15 FT**

Other aggravating factors

		Score (A)
Fly ash/ Slag	Y (N)	4
De-icing	(Y) N	1
Salt		
Freeze-thaw+	(Y) N	3
Average RH		3
Average Rainfall		3
Sum		14

+ 20 cycles per year

Distress types

1 – Blow up 2 – Corner break
5 – Joint seal damage 8 – pop-outs
10 – Scaling / Map-cracks/crazing
11 – Settlement / Fault
13 – Shrinkage crack
14 - Spalling (joints) 15 – Spalling (corner)

Modifiers

(a) Laddering
(b) Aggregate cracking
(c) Gel exudation
(d) Joint closure
(e) Joint misalignment
(f) Heaving

	Visual inspection			Laboratory Investigation			
Critical ASR Features	Score of the ASR Features (B)	UAFM Test in Field	No. Core	Score of ASR Features from Laboratory Investigation			
				UAFM (C1)	Petrography / SEM-EDXA		
					Gel (C2)	Agg. Crack. (C3)	RR (C4)
10* (c)	2	Y	1	8	8	8	4
13* (a)	2	Y	1	8	12	12	8
10H	2	Y	0				
(c)	4	Y	1	4	8	12	4
(b)	4	Y	0				
5* (d) (e)	4	N	1				
1* 5* (d) (e)	2	N	0				
11* (f)	2	N	1				
2 H	6	N	0				
15 H	4	N	0				
14 H	4	N	0				
Sum	36	Avg	7	9	10	5	

Total Score: 81	**Distress Rating: High**
Residual Service Life: ~10 years	

Total Score = Sum (A) + Sum (B) + Avg. (C1) + Avg. (C2) + Avg. (C3) + Avg. (C4)

Direction of Survey

	1	2	3	4
5		2H 15H	10L	15H 14H
4	10(c) L 13(a)M 5(d)(e)M		10(c)L	
3	(c)			5(d)(e) M
2		10L		10 (c)M
1	11L		13(a)L 10L	

Example 4: ASR condition survey for an airfield pavement section (containing different sample units) with **medium-severity ASR.** Note that visual manifestation of ASR is very low but laboratory investigation reveals ASR with relatively high intensity inside.

<table>
<tr><td colspan="9" align="center">**Jointed Rigid Pavement**
ASR Condition Survey Data Sheet for Sample Unit</td></tr>
<tr><td colspan="4">**Facility** RWY</td><td colspan="3" align="center">**Sample Unit** 4</td><td colspan="2">**Date** 4/15/02</td></tr>
<tr><td colspan="5">**Year of Construction: 1940**</td><td colspan="4">**Average RH: ~80%**</td></tr>
<tr><td colspan="5">**Average Annual Rainfall: ~30 inch**</td><td colspan="4">**Slab Dimensions 12 x 15 FT**</td></tr>
</table>

Other Aggravating Factors

		Score (A)
Fly ash/ Slag	Y (N)	4
De-icing Salt	(Y) N	1
Freeze-thaw+	(Y) N	3
Average RH		3
Average Rainfall		3
Sum		14

+ 20 cycles per year

Distress types

1 – Blow up 2 – Corner break
5– Joint seal damage 8 – pop-outs
10 – Scaling / Map-cracks/crazing
11 – Settlement / Fault
13 – Shrinkage crack
14 - Spalling (joints) 15 – Spalling (corner)

Modifiers

(a) Laddering
(b) Aggregate cracking
(c) Gel exudation
(d) Joint closure
(e) Joint misalignment
(f) Heaving

Critical ASR Features	Visual inspection			Laboratory Investigation			
	Score of the ASR Features (B)	UAFM Test in Field	No. Core	Score of ASR Features from Laboratory Investigation			
				UAFM (C1)	Petrography / SEM-EDXA		
					Gel (C2)	Agg. Crack. (C3)	RR (C4)
10* (c)	2	Y	1	8	12	4	4
13* (a)	2	Y	1	8	8	4	8
10H	2	Y	0				
(c)	0	Y	0				
(b)	0	Y	0				
5* (d) (e)	2	N	1	4	8	8	4
1* 5* (d) (e)	0	N	0				
11* (f)	0	N	0				
2 H	0	N	0				
15 H	0	N	0				
14 H	2	N	0				
Sum	10		Avg	7	9	5	5

Total Score: 50   **Distress Rating: Medium**

Residual Service Life: 10-15 years

Total Score = Sum (A) + Sum (B) + Avg. (C1) + Avg. (C2) + Avg. (C3) + Avg. (C4)

Direction of Survey

5		10(c)L
13(a)L 5(d)(e)L 4		
3		13(a)L
2 10L		10L
1		

1   2   3   4

4.3 Detailed explanation of the survey sheet

4.3.1 Other aggravating factors: Data collection and scoring

Although high moisture, sufficient alkali, reactive aggregate are the essential parameters for ASR to occur, other factors related to climate and materials can aggravate ASR. For example, supplementary cementitious materials such as fly ash, slag or combination thereof in concrete when used in appropriate proportions, have been demonstrated to control expansion due to ASR. On the other hand, the use of de-icing salt, or repeated occurrence of freeze-thaw cycles can aggravate ASR. Alkali-bearing de-icing salt that was used in the past, can act as a source of additional alkali. The frequency of cracks can increase as a result of regular freeze-thaw cycles. This in turn can act as passage for moisture to penetrate the concrete. Similarly, high relative humidity (RH) condition and heavy rainfall can also aggravate ASR.

4.3.2 Visual inspection

Identification of critical ASR features and scoring based on degree of severity

- Visual signs to be considered: ***map-cracking, laddering, aggregate pop-out, reaction rim around aggregate particle, open or gel-filled cracks in aggregate particle, gel exudation***
- Structural evidence of expansion due to ASR to be considered: ***joint closure, joint seal damage, joint misalignment, blowup/heaving***

UAFM dye test method in field to detect ASR gel in visible cracks (applicable only if gel is present in an unaltered state)

- Unaltered gel if present, can be identified in cracks, and fractures on the exposed surface of pavement by its characteristic yellowish-green glow under UV light.

Coring for further laboratory investigation

- In general, it is recommended to collect one core per distress feature.
- If the severity of a distress feature varies, e.g., from low to high then the engineer has the option to collect more than one core, for example, one from high-severity area and another from low severity area. Similarly, if the distribution pattern of a particular distress feature (such as map-cracking) is repetitive from one sample unit to another, then the engineer has the option to reduce the coring rating.
- Collect full-depth cores with diameter of at least 2 inch., but not larger than 4 inch.

4.3.3 Laboratory Investigation of critical ASR features

Visual inspection of cores

- Inspect type of cracks, whether they are due to shrinkage or due to other causes, peripheral discoloration of aggregate, white gel around aggregate particle, internal cracks in aggregate particles.

Repeat UAFM dye test method on core samples and scoring based on test result

- Slice the full-depth drilled core at three or more different depths, example, top, middle, and bottom.
- Examine these sections by the UAFM dye method to detect presence of unaltered ASR gel at different depths.

Gel can be identified (if present) in aggregate rims, cracks, and fractures by its characteristic yellowish-green glow under UV light. If the glow is observed then ASR is affirmative.

Application of optical microscopic techniques for confirmation of ASR as indicated from visual inspection and scoring

Identification of critical ASR features
- Presence of gel inside aggregate, at the cement paste – aggregate interface, in air voids and along cracks
- Cracking of aggregate and micro-cracks in paste
- Reaction rim around aggregate

Scanning electron microscopy / energy dispersive X-ray analysis
- Involves identifying ASR gel by its characteristic morphology, namely rosette structure, massive or lamellar type etc. at higher magnification SEM
- Confirmation of the elemental composition of ASR gel from EDXA

Complete survey sheet, and **assign ASR distress rating** in survey sheet. The distress rating, e.g., low, medium and high will be based on the combined results of visual inspection, laboratory investigation and other aggravating factors related to materials and climate.

Chapter 5: Mitigation and Prevention of ASR

5.1 Common preventive measures for ASR

1. Use **non-reactive aggregate**, if possible. According to ASTM C1260 test (Chapter 7) expansion less than 0.10% at 14 days is indicative of innocuous behavior of most aggregates and can be considered as diagnostic feature of non-reactive aggregate. Furthermore, petrographic examination according to ASTM C 295 method is desirable to confirm this (Chapter 1, Section 1.2.1).
2. Use **low-alkali cement** – typically but not always, less than 0.6% sodium oxide (Na_2O) cement controls ASR.
3. Limiting the **alkali content** of the concrete mixture – 3 kg/m^3 alkalis in concrete can be a limit for potentially reactive aggregate where aggregate reactivity is defined as (i) reactive when expansion is greater than 0.20% at 14 days, and potentially reactive when it is between 0.10% and 0.20% at 14 days according to ASTM C 1260 test method.
4. Use **supplementary cementing materials.**

(a) **Fly ash replacement**: 30% to 35% fly ash replacement by mass of cement is an effective way to reduce expansion due to ASR. The reaction can be slowed down to the point where it will prevent ASR for the design life of a concrete pavement. However, reduction in expansion due to fly ash incorporation varies with aggregate type, class and chemical composition of fly ash, especially the alkali content, and amount of fly ash replacement. In general higher the amount of fly ash replacement, the better the effect of controlling expansion. Higher the pozzolanic activity of fly ash, the higher the preventive effect on ASR provided fly ash does not contribute any extra alkali. Reduction in expansion incorporating class F fly ash, regardless of the replacement percentage, is higher than that of class C fly ash. Increasing the level of replacement of fly ash or slag can produce greater reduction in expansion, but may lead to poor resistance to deicer salt scaling. The use of an appropriately proportioned ternary mix results in a marked reduction in expansion equal to, or greater than influences of a single supplementary cementing material. Pessimum effect of fly ash to control ASR possibly does not exist.

(b) **Silica fume:** The addition of 10% silica fume by mass of cement can completely suppress ASR, possibly because of reduction in OH$^-$ concentration.

(c) **Ternary blend** cement with appropriate proportions of fly ash, slag or silica fume in combination causes a marked reduction in expansion due to ASR that exceeds the influence of a single supplementary cementing material.

(d) **Use lithium nitrate:** Lithium is the lightest metal in the elemental periodic table, with an atomic number of 3, atomic weight of 6.94, and density of 0.53 g/cm^3 (about half that of water). It is a naturally occurring substance and is a silvery-white metal, slightly harder than sodium, but softer than lead. Lithium nitrate ($LiNO_3$) is the most effective form of Li used in mitigation of ASR. When lithium is used, although silica

gel is still formed, the gel remains innocuous, i.e., it does not cause cracking. There are two aspects of mitigating ASR with the use of lithium compounds in concrete, i.e., (a) prevent expansion by adding lithium compound in new concrete and (b) mitigate further expansion in concrete that has already been affected by ASR.

5.2 Lithium use in new concrete

When a concrete is designed to last 50-75 years or more, incorporation of lithium in the mixture to prevent the future occurrence of ASR can be beneficial. The alkali content of cement in a concrete mixture determines the dosage of lithium nitrate that needs to be incorporated. The standard dose is 0.55 gallons of lithium per pound of alkali per unit of concrete. The minimum dosage of lithium should be based on aggregate reactivity tested according to the modified ASTM C 1260 method. The effect of lithium in reducing ASR expansion cannot be tested by the standard ASTM C 1260 method by adding lithium in the mortar mix, because lithium leaches out in the 1N NaOH solution. The sodium in the soak solution swamps the amount of lithium necessary. To overcome this problem, lithium is added to the soak solution at levels to match the alkali equivalent (Na_2O_{eq}).

Standard dose of lithium present in most commonly used lithium-bearing compounds are (1) $LiNO_3$ - 30% $LiNO_3$ in solution, and (2) lithia glass –the dose is based on Li/Na molar ratio. 100% lithia glass dose represents the amount of glass that supplies 0.74 Li/Na molar ratio. The lithium content is calculated from lithia or LiO_2 concentration in glass, and sodium from the Na_2O_{eq} of the cement.

Lithia glass is a new type of solid admixture now commercially available. It is basically glass made from a mixture of recycled soda-lime glass and lithium. Lithium is added to the glass, and the mixture is re-melted. The resulting glass is then ground to a fine powder suitable for use as a supplementary cementing material. The glass is formulated to react in the concrete over a period of time, that is, slowly release lithium into the cementitious system. Typically, the dosage of lithia glass is 1.85 kg per cubic yard of concrete.

Lithia glass in combination with other supplementary cementing materials (especially fly ash) has demonstrated expansion lower than either lithia glass or fly ash alone in the laboratory. These combinations have suppressed ASR expansion to a very low level. The combined use of lithium and supplementary cementing materials is recommended for economic reasons and for improving concrete quality.

5.3 Mitigation of ASR in existing concrete

Lithium is effective in controlling further expansion in concrete structures with existing ASR and, therefore, can extend the service life of the ASR affected concrete. The effectiveness of lithium treatment depends on the depth of penetration. The following are the common application methods for treating ASR affected concrete.

1. Electrochemical chloride extraction,
2. Topical application, such as ponding and spraying

3. Vacuum impregnation, and
4. Pressure injection

However, the dosage and application technique may vary according to conditions such as extent of damage and type of structure. In case of airfield pavements, the most practical methods of application are (a) topical application, such as ponding and spraying, (b) vacuum permeation, and (c) pressure injection. These methods are briefly described below.

Spray Application. This is most common for flatwork such as pavements, and bridge decks. Tests will have to be performed on the spray rate, which can be varied from 3.0 to 4.5 gal/1,000ft^2, and the soak time required. Additionally, the effect of multiple passes needs to be evaluated. This of course can increase the total amount of lithium nitrate required from 3.0 to 9.0 gal/1,000ft^2.

Ponding. The pavement structure needs to be ponded with lithium nitrate solution so as to maintain contact with the structure for at least 24 hours to get sufficient penetration into the surface.

Vacuum Permeation. This is a fairly recent and distinctive technology, which was originally developed in Europe. The basic process has been used in North America since 1985. Unlike pressure injection, the vacuum permeation process withdraws air and moisture from cracks and pores prior to impregnation of the repair solution or resin, which in this case will be lithium nitrate. The tendency for the damaged structure to burst, so characteristic of conventional pressure injection methods, can be eliminated by the vacuum permeation process. Some of the possible advantages of this process include the removal of residual moisture, and stress concentrations at the ends of cracks. The process can be expected to eliminate the internal damages caused by induced high pressures that normally arise when using pressure injection techniques.

Pressure injection – The principle of this method is the same as that for injecting grout or slurry through cracks. This method is not recommended if structural integrity has been severely compromised due to advanced ASR, as the pressure applied to inject the lithium solution is likely to cause the structure to burst open.

Another method in existence is ***electrochemical chloride extraction***. This method was originally developed to remove chloride and thus reduce corrosion. However, the process can trigger ASR by introducing alkalis if the aggregate is reactive. The use of lithium in the electrolyte prevents ASR and therefore, the method is applicable to ASR remediation. Lithium ions can prevent ASR, regardless of the pH, at high dosages. However, this method may not very economical for airfield pavements.

Chapter 6: References and Further Reading

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Chapter 7: Test Methods for ASR

ASTM C 289: *Standard test method for potential alkali-silica reactivity of aggregates (chemical method).*

This method is a quick chemical test to estimate potential reactivity of siliceous aggregate. This test identifies highly reactive aggregates fairly rapidly and is useful for initial screening of aggregate.

Drawbacks: This test fails to identify slowly reactive aggregates. Certain aggregates produce a high amount of soluble silica in this test but do not necessarily produce expansion in service. The test does not always give reliable results and cannot be used to test carbonate rocks.

ASTM C 227: *Standard test method for potential alkali reactivity of cement-aggregate combinations (mortar-bar method).*

This is a useful method for testing ASR susceptibility of cement-aggregate combinations. It measures expansion of mortars made with the test aggregate. Aggregate should conform to standard grading. Longer testing periods are preferred for differentiating reactivity of aggregate.

Drawbacks: Unless highly reactive aggregates are tested, meaningful results require one year or more. Even after a long testing period, not all deleterious aggregates exhibit expansive behavior. Sometimes this method fails to distinguish between slowly reacting and innocuous aggregates.

ASTM C 295: *Standard guide for petrographic examination of aggregates for concrete.*

This method is a comparatively quick way to predict aggregate reactivity based on microscopic examination of aggregate samples. Mineral properties in aggregate determine aggregate reactivity. This method is used as a screening method for aggregates. Correlating petrographic analysis of aggregate with service record in concrete can derive useful information.

Drawbacks: This method does not give any quantitative information about aggregate's actual behavior in concrete and is time consuming. Results will not reveal if an aggregate will cause deleterious expansion in concrete.

ASTM C 441: *Standard test method for effectiveness of mineral admixtures or slag in preventing excessive expansion of concrete due to alkali-silica reaction.*

This method is based on expansion developed in mortar bars and uses a combination of cement, mineral admixtures, and a reactive crushed Pyrex glass. The method can be used for preliminary screening to evaluate the relative effectiveness of different materials used to prevent excessive expansion due to ASR.

Drawbacks: This method is considered unsatisfactory because Pyrex is highly reactive and may contain significant levels of alkalis. Moreover, it is not adaptable for testing aggregates from different sources, since it is mainly a test for cement ASR reactivity.

ASTM C 1260: *Standard test method for potential alkali reactivity of aggregates (mortar-bar method).*

This is one of the most commonly used test methods for assessing the potential reactivity of aggregates. Expansion data of mortar can be obtained within as little as 16 days. The test method was developed because of the shortcomings of ASTM C 227 and ASTM C 289. This method, however, does not replace lengthier test methods.

Drawbacks: Severe test conditions are applied which do not conform to field conditions. Aggregates with good field track records and no history of ASR can sometimes be classified as reactive when tested according to this method.

ASTM C 1293: *Standard test method for concrete aggregates by determination of length change of concrete due to alkali silica reaction.*

This method measures expansion of concrete prisms made with the coarse and fine aggregates in question. Total alkali content of concrete should be 5.25 kg/m^3.

Drawbacks: This method involves cement-aggregate combinations and requires up to one year to complete.

Chapter 8 is deleted, no superceding reference

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