RILEM State-of-the-Art Reports

Bruno Godart
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Guide to Diagnosis and Appraisal of AAR Damage to Concrete in Structures

Part 1 Diagnosis (AAR 6.1)

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RILEM State-of-the-Art Reports

Volume 12

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Dedication

This RILEM Report is dedicated to the memory of the two Technical Committee colleagues who worked together to establish, formulate and draft its original contents:

Dr Joe Larbi & Dr Sylva Modry.

Joe Larbi was born in Ghana, where he graduated in geological engineering, before gaining an MSc in Canada, studying alkali-aggregate reactivity. Joe then moved to Delft University of Technology in the Netherlands, where he obtained a PhD in 1991: *'The cement paste aggregate interfacial zone in concrete'*. Afterwards, Joe remained in the Netherlands, working first for Intron and finally for TNO, during which time he took an active part in the RILEM work on alkali-aggregate reaction. Sadly, after many years of poor health, Joe died in 2009.

Sylva Modry was from the Czech Republic, where he graduated in chemical technology in 1959 and initially worked at the Raw Materials Institute. From 1962, Sylva was at the Klokner Institute (Czech Technical University) in Prague, where he was awarded a CSc in 1974 and a DrSc in 2001. Sylva gave courses on building chemistry (in English) and on durability and alkali-aggregate reaction for the Ministry of Education. Sylva was created an Honorary Fellow of RILEM in 2000, but sadly died before the formation of the current TC 219-ACS.

Foreword

This document was drafted by the Working Group Diagnosis and Appraisal of AAR Damage to Concrete in Structures under the direction of RILEM TC 191-ARP Technical Committee: Alkali-Reactivity and Prevention - Assessment, Specification and Diagnosis. The Working Group consisted of the following members:

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It was later decided to split the draft into two parts. The present Part I on Diagnosis was revised in spring 2006, and subsequently in 2007 and 2008 to improve the material scientist to structural engineer coordination. Modifications and additions to the original draft were supplied by:

Bruno Godart	France
Viggo Jensen	Norway
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Prognosis, appraisal, management and the influence of AAR on structural behaviour will be dealt with in AAR-6.2, but amendments to improve the interface with AAR 6.2 have been incorporated in AAR-6.1 Diagnosis (see Appendix 2).

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1 Introduction

1.1 Why the Need for a Diagnosis Document

Diagnosis of damage to concrete in structures caused by Alkali-Aggregate Reaction (AAR) often involves complex processes because of the resemblance of the external characteristics of the damage with those caused by other actions, such as e.g. frost attack or shrinkage. The wide variety of aggregate types used in concrete worldwide, the different reactivity and proportions of the reactive constituents in the aggregates involved and the wide range factors that influence the reaction result in wide variability found in site samples. This makes diagnosis difficult and has sometimes led to subjective or even erroneous interpretations and conclusions.

Furthermore, there has frequently been a lack of agreement amongst experts on how to approach the issues of diagnosis and prognosis of AAR damage in structures. The reasons for the differences in opinion include:

1. The wide range and often inconclusive methods used for performing the assessment.
2. The limited number of reliable internationally applicable standard procedures or methodologies for performing the diagnosis and prognosis.
3. The inherent variability of aggregate sources and of concrete which make AAR diagnosis from limited sampling dependant on the local composition of samples selected.
4. The not uncommon occurrences of localised patches of AAR cracking in site concretes, which leads to diagnosis of AAR as a problem, even though the magnitude of the reaction is not sufficient to produce significant problems of serviceability or structural function.
5. The assessment that is often carried out from core samples without reference to the structure itself.
6. Difficulties in simulating the long term AAR damage in a structure with short term laboratory tests and the translation of the test results to the actual structures.
7. Several national laboratories, private companies and even individuals using their own procedures, which are very often ‘tailored’ to solve only specific local types of AAR damage, thus limiting their flexibility in use.

Over the past few decades, experts in several countries with AAR problems have pooled their resources and expertise to prepare national guidance documents for assessing damage of concrete caused by AAR. The current document presents an international procedure for the diagnosis of AAR damage to concrete in structures.

B. Godart et al. (Eds.): *Guide to Diagnosis & Appraisal of AAR Damage*, RILEM 12, pp. 1–12.
DOI: 10.1007/978-94-007-6567-2_1

The guidance outlined in this document is based on experiences, recommendations or national guidance of several countries throughout the world where the AAR problem is well understood and documented [1-10]. Experience in Austria, Australia, Belgium, Canada, Czech Republic, China, Denmark, France, Iceland, Japan, The Netherlands, New Zealand, Norway, United Kingdom, United States of America and several other countries has been documented in the proceedings of the thirteen ICAAR (International Conferences on AAR) since 1974 in Denmark (see Appendix 1).

Like many other causes of damage in concrete, diagnosis and prognosis of AAR in structures relies to a large extent on the judgement and the level of expertise of the personnel involved. A reliable analysis to identify, evaluate and establish the extent of the damage and to make prognosis of its effect on the structure requires a clear and thorough understanding of the mechanisms and processes of damage resulting from AAR. To do so, the effects of AAR need to be considered as part of a complex of structural and 'non-structural' actions and deterioration which lead to cracking and damage in the concrete. Complete diagnosis of distress caused by ASR usually involves a series of steps involving multi-disciplinary tests and investigations, performed in a systematic manner. Figure 1 shows an outline flowchart of these interactions relative to the main diagnostic procedures; the complete flowchart showing the place of the diagnosis within an overall investigation and making the links between AAR-6.1 and AAR-6.2, is presented in appendix 2.

1.2 Scope

This document describes procedures and methodologies used predominantly to obtain a diagnosis of damaged concrete possibly caused by Alkali-Aggregate Reaction (AAR). The document has two primary objectives, namely to:

1. Identify the presence of AAR reaction, and whether or not the reaction is the primary or contributory cause of damage in the concrete.
2. Establish its intensity (severity) in various members of a structure.

The guidance includes aspects such as field inspection of the structure, sampling, petrographic examination of core samples, and supplementary tests and analyses on cores, such as mechanical tests and chemical analysis. Evaluation of test data for prognosis, consequences and appraisal will be more fully set out in AAR-6.2.

The document begins with a brief overview of the alkali-aggregate reaction, the various types involved and conditions under which it causes damage to concrete. Next, routine inspection and visible effects of damage is picked up. If these inspections results contain observations or symptoms that may be due to an expansive reaction of concrete, chapter four helps to determine whether or not it could be AAR. A detailed outline of the various systematic methodologies for diagnosing, establishing and assessing AAR damage to concrete in a structure is presented, illustrated where appropriate with diagrams and photographs.

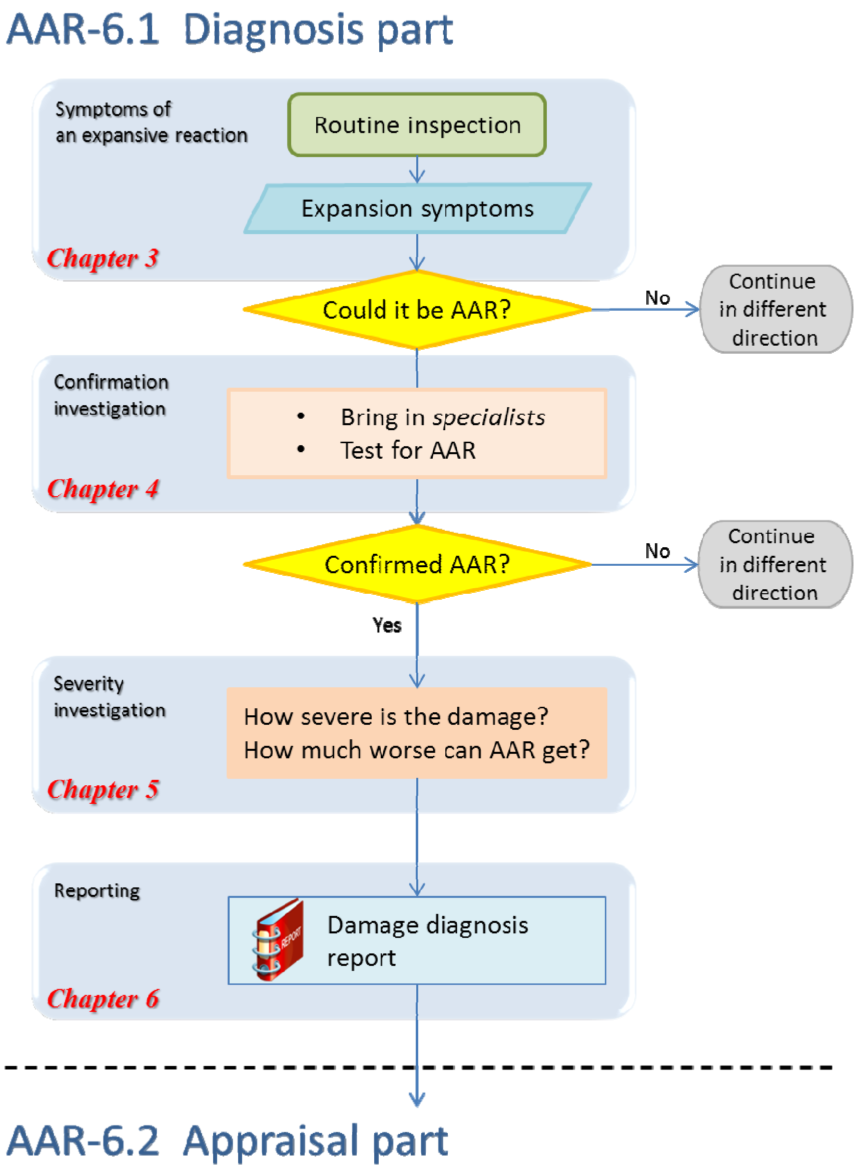

Fig. 1 Flow chart with different stages from diagnosis to appraisal of AAR damaged structures. Only part AAR-6.1 is described in the current document.

When AAR has been confirmed the severity of the situation is described in chapter five to provide documented input to the reporting in chapter six. This is where AAR-6.1 ends. Following this initial diagnosis the next part will be document AAR-6.2, which is currently still under review.

1.3 Definitions

The following definitions apply in this Guidance:

Acid Rock (“Silicic Rock” is Preferred): a conventional term denoting igneous rocks with more than 66% or 70% SiO_2, corresponding rhyolite (granite) plus some dacite (granodiorite). When it is defined by the content of free quartz, it may be at least 20% free quartz. To avoid confusion with chemical term “acid”, it is recommend to use “silicic” or “felsic”.

Aggregate: granular material used as a filling material, such as sand, gravel or crushed stone or crushed concrete, which together with a hydraulic cementing medium produce either concrete or mortar.

Air-void: a space in cement paste, mortar, or concrete filled with air. *Entrapped* air-voids are characteristically more than 1 mm in size and irregular in shape. *Entrained* air-voids are typically between 10 µm and 1 mm in diameter and spherical.

Alkali: Part of the alkali metals of the period system (Li, Na, K, Rb and Cs). In cement chemistry normally only sodium (Na) and/or potassium (K) are considered, mainly contributed by the cement, but in minor amount also by the aggregates, deicing salt and sea water. It is usually expressed as the sodium oxide equivalent: Na_2O equivalent = $Na_2O + 0.658\ K_2O$.

Alkali-Aggregate Reaction (AAR): a chemical reaction in either mortar or concrete involving hydroxyl (OH^-) ions associated with the alkalis sodium and potassium from Portland cement or other sources, with certain mineral phases that may be present in the coarse or fine aggregates. Under certain conditions, deleterious expansion of the concrete or mortar may result. There are two main types of alkali-aggregate reaction: alkali-silica reaction and alkali-carbonate reaction. The so-called alkali-silicate reaction is now recognized as a slow/late type of alkali-silica reaction.

Alkali-Carbonate Reaction (ACR): the reaction between alkali hydroxides (from Portland cement or other sources) and certain argillaceous dolomitic limestone aggregates accompanying dedolomitization. Under certain conditions, deleterious expansion of the concrete or mortar may result. The reaction of carbonate aggregates that produce only dedolomitization rims without deleterious expansion is not called ACR.

Alkali-Silica Gel: the reaction product that forms in some concretes when certain susceptible silica/silicate minerals or rocks react with the alkalis in the pore solution to form a gelatinous sodium, potassium and calcium silicate. The composition and swelling characteristics of the hygroscopic gel varies depending on the composition of the alkaline pore solution and the age of the gel.

Alkali-Silica Reaction (ASR): the reaction between the alkali hydroxide from Portland cement and/or other sources and certain siliceous rocks or minerals, such as opaline silica, chert, microcrystalline quartz, and acidic volcanic glass, recycled glass, etc. present in some aggregates. The products of the reaction, the alkali-silica gel, may cause abnormal expansion and cracking of concrete in service.

Andesite: a fine-grained 'intermediate' volcanic rock with 52-65% SiO_2, composed mainly of plagioclase feldspar (oligoclase-andes**ine**) and mafic minerals pyroxene and/oramphibole. In well-crystallized andesite of younger geologic ages, free-silica appears as cristobalite, tridymite and/or quartz, while in rapidly cooled lava, volcanic glass is formed. Some andesites are potentially reactive.

Argillaceous Rocks: a group of very fine grained detrital sedimentary rocks, commonly clays, shales, mudstones, siltstones and marls. Two grades of particle size are recognised: silt grade, in which the particles range in size from 0.0625 to 0.004 mm, and clay grade with particles of less than 0.004 mm.

Basalt: a fine-grained 'basic' volcanic igneous rock with less than 52% SiO_2, dominated by plagioclase feldspars, the rest consisting essentially of mafic (iron-magnesium) minerals pyroxene, olivine and/or magnetite.

Basic Rocks: a conventional term denoting mafic igneous rocks, mostly quartz-free and containing feldspars that are generally more calcic than sodic. Rocks in this group (for example basalt), defined in terms of silica percentage, contain less than 52%silica. Basic rocks grade into intermediate rocks by increases in the silica content and the sodium content of the feldspar.

Calcite: a common rock-forming carbonate mineral composed of calcium carbonate ($CaCO_3$). Calcite is the principal constituent of limestone, chalk and marble, and is a major raw material in the manufacture of Portland cement, but may also occur as a carbonation product of the cement paste near the concrete surface. A rock with a significant amount of calcite is said to be calcareous.

Calcium Hydroxide: hydrated or 'slaked' lime obtained by treating quicklime with water, $Ca(OH)_2$. It is called portlandite**,** also one of the products of the hydration of calcium silicate hydrates (C_2S and C_3S) in the Portland cement.

Carbonate Rock: a rock comprised mainly of carbonate minerals, for example**,** limestone, dolomitic limestone, or dolostone.

Carbonation: a reaction between carbon dioxide (CO_2) in the atmosphere and the pore solution of the cement paste fraction of concrete or mortar. In the reaction, calcium hydroxide is converted to calcium carbonate ($CaCO_3$). When calcium hydroxide diminishes in solution calcium from the calcium silicate hydrate (C-S-H) can leach out and take over the reaction to continue carbonation.

Cement: Portland cement or blended hydraulic cement.

Cement Paste: mixture of water and cement found in concrete, mortar, or grout. It can be fresh or hardened.

Chalcedony: a general name applied to fibrous cryptocrystalline silica, and sometimes specifically to the brown translucent variety with a waxy lustre. It is deposited from aqueous solutions and is frequently found in lining or filling cavities in rocks.

Chert: a siliceous sedimentary rock occurring as a bed or layer, comprising extremely fine-grained quartz, e.g. cryptocrystalline, microcrystalline and/or chalcedonic quartz. Flint is a variety found in the form of nodular or concretional masses in the chalk beds, which was re-deposited as distinct beds in gravel deposits. Chert and flint are classified as potentially alkali-silica reactive in concrete. They often produce a strong pessimum effect with a low percentage in the aggregate causing more expansion than a higher amount.

Coarse Aggregate: aggregate particles larger than 4 mm (see aggregate or size of aggregate particles).

Compressive Strength: the measured maximum resistance of a concrete or mortar specimen to axial compressive loading expressed as force per unit cross-sectional area. Uniaxial compressive strength, which is more realistic and more sensitive to AAR damage than tests on short specimens, is obtained with special platens or long cores with (length /diameter) >2.

Concrete: a composite material consisting essentially of a mixture of cementing material and water, within which are embedded particles of fine and coarse aggregate.

Crack: a complete or incomplete separation, of either concrete or masonry, into two or more parts, produced by breaking or fracturing.

Cracking Index: Index representing the development and severity of cracking from AAR on a part of a structure, see also Expansion Index. Methodology and definition are described further in part AAR-6.2.

Creep: time-dependent deformation in response to sustained load.

Cristobalite: a high-temperature form of crystalline silica, occurring as imbrecated aggregation of minute octahedra or cubes in certain lavas such as andesite, or as small spherulites in acid lavas and glasses of younger geologic ages. It also occurs in some opaline sedimentary rocks as a metastable product during diagenesis.

Cryptocrystalline: a rock or a mineral consisting of crystals that are too small to be recognized and separately distinguished under the optical microscope. The dimension of the crystals is generally less than 0.001 to 0.004 mm. Cryptocrystalline quartz is an example of this size.

Crystalline Rock: a term used loosely to imply an igneous or metamorphic rock, as opposed to a sedimentary rock, for example, in this sense crystalline limestone is equivalent to marble.

Curing: the maintenance of a satisfactory moisture content and temperature in concrete during its early stages so that desired properties may develop and the adverse effects of premature drying may be avoided.

Dedolomitisation: a process occurring in nature whereby a dolomite-bearing rock (eg. dolomitic limestone) is converted to calcite-bearing rock. In concrete, dedolomitisation can occur under the influence of alkali hydroxides, whereby dolomite is converted to calcite and the excess magnesium is converted to brucite (magnesium hydroxide), forming reaction rims surrounding the dolomitic limestone aggregate particles in concrete or mortar. There is no direct evidence that dedolomitization produces a volume increase or expansion in concrete without the presence of reactive silica.

Deformation: a change in dimension or shape (see also creep, expansion and shrinkage).

Delamination: a separation along a plane parallel to a surface, as in the separation of a coating from a substrate or the layers of a coating from each other or, in the case of a concrete slab, a horizontal splitting, cracking, or separation near a surface. It can be a feature of severe AAR damage developing from sub-parallel cracking in the plane of reinforcement. Delamination also occurs frequently in bridge decks and can be caused by factors such as the corrosion of reinforcement steel and/or freezing and thawing. It is similar to spalling, scaling or peeling, except that delamination affects large areas and can often only be detected by tapping or chain dragging.

Delayed Ettringite Formation (DEF): delayed formation of ettringite can occur in concrete that has been subject to heat curing at excessive temperatures (greater than approximately 65°C). It can also develop when the temperature rise from initial hydration raises the temperature above about 65°C. The delayed formation of ettringite can cause swelling of the hardened concrete. DEF should not be confused with secondary ettringite, which forms in cracks or air-voids in concrete by solution and re-precipitation of primary ettringite. This secondary ettringite reaction may occur in concretes cured at normal temperatures.

Deleterious: mineral or rock minerals that are considered to be physically harmful to concrete in terms of strength reduction (eg. fissile shales), pop-out formation, or porosity, or that are chemically harmful and expansively alkali-aggregate reactive.

Deterioration: (a) physical manifestation of failure of a material, e.g. cracking, delamination, flaking, pitting, scaling, spalling and staining, caused by environmental or internal autogenous influences on rock and hardened concrete as well as other materials; (b) decomposition of material during either testing or exposure to in-service conditions.

Dolomite (mineral): a calcium-magnesium carbonate mineral ($CaMg(CO_3)_2$).

Dolomite (rock): a sedimentary carbonate rock composed dominantly of the mineral dolomite.

Dolostone: an alternative term to Dolomite (rock), which is preferred by some, in order to avoid the ambiguity in using the same term for both a mineral and a rock.

Durability: the ability of concrete to resist weathering action, chemical attack, abrasion and other conditions of service.

Efflorescence: a deposit of salts, usually white, formed on a surface, having emerged in solution from within concrete or masonry and been deposited by evaporation.

Ettringite: a mineral, hydrated high-sulfate calcium sufoaluminate ($3CaO.Al_2O_3.3CaSO_4.32H_2O$), which occurs in nature, is one product of the hydration of Portland cement and/or is formed by sulfate attack on mortar and concrete. It is the product of the principal expansion-producing reaction in 'expansive' (or 'shrinkage-compensated') cements.

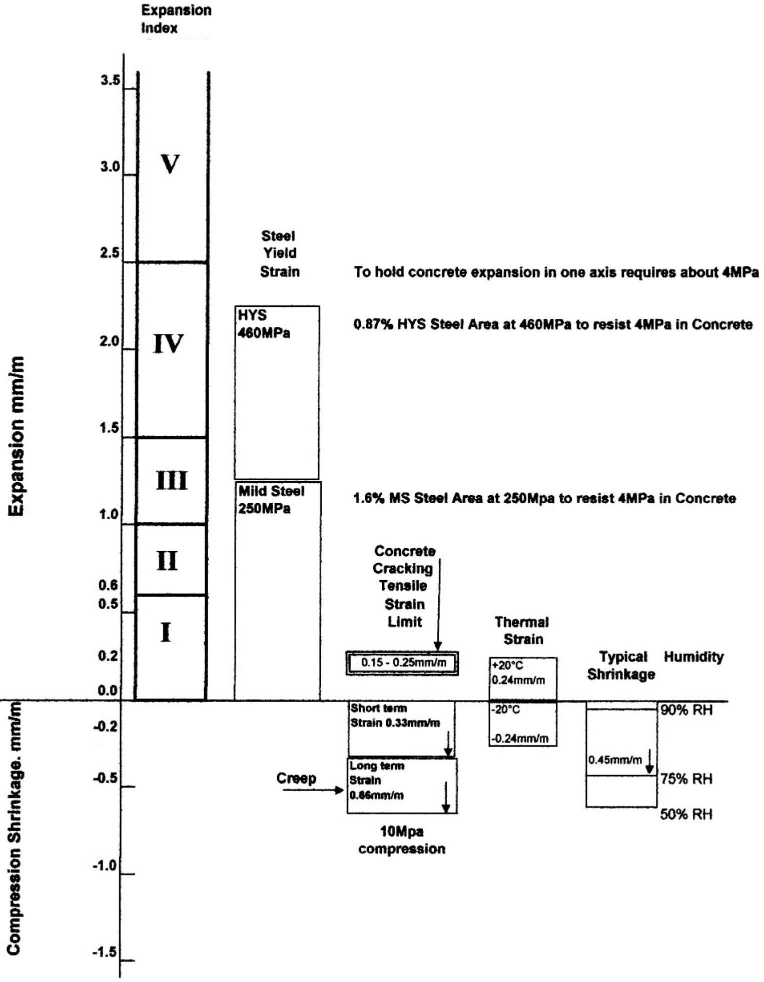

Fig. 2 Expansion index (derived from IStructE [3])

Expansion: increase in the volume of the material, resulting in increased dimensions. When particles of the aggregate expand generating forces exceeding the tensile strength of the concrete, cracks are formed. Expansion from AAR is anisotropic when the expansion is constrained. AAR expansions are usually characterised by high variability.

Expansion Index: a broad classification for the severity of AAR as free expansion to date or potential total free expansion in IStructE [3]. It ranges from ‘I’ less than 0.6 mm/m to ‘V’ greater than 2.5 mm/m, see Figure 2. It differs from the ‘Cracking Index’ in that adjustments are made for the effects of restraint on free expansion and non-AAR cracking is discounted.

Exudation: a liquid, often viscous gel-like material discharged through a pore or crack.

Felsic Rock: term denoting igneous rocks with more than 66% or 70% SiO_2, corresponding rhyolite (granite) plus some dacite (granodiorite). When it is defined by the content of free quartz, it may be at least 20% free quartz. To avoid confusion with chemical term “acid”, it is recommend to use “silicic” or “felsic”.

Fine Aggregate: aggregate particles with a maximum particle size of 4 mm (see aggregate or size of aggregate particles).

Freeze-Thaw: a cycle of freezing and thawing of concrete. In the absence of de-icing chemicals, freezing starts to occur when the temperature drops below $-2^{o}C$ and thawing occurs when the temperature rises above $0^{o}C$.

Glass: Glass intentionally added to aggregate as a decorative feature or unintentionally included in recycled aggregates, which can produce damaging AAR.

Hydrated Lime: calcium hydroxide or 'slaked' lime, a dry powder obtained by treating quicklime with water.

In Situ: a Latin term frequently used to distinguish material (e.g. rocks, minerals, concrete, mortar) found in its original position of formation, deposition, placement or structure.

Insoluble Impurities: the substances found in the interstices of a carbonate rock material that cannot be dissolved by warm, dilute hydrochloric acid. These substances may include clay, quartz, micas, feldspars and pyrite.

Limestone: a sedimentary rock composed largely of calcite, $CaCO_3$, formed by either organic or inorganic processes.

Macrocrack: a crack in a sample readily visible without the aid of a microscope.

Map-Cracking: a closely spaced network of cracks on the surface of concrete that may be caused by a decrease in volume of the material near the surface, through processes such as plastic shrinkage, or an increase in volume of the material below the surface, through expansion processes such as alkali-aggregate reaction (see Figure 3), sulphate attack, and freeze-thaw cycles.

a = overview b = details

Fig. 3 Pattern of cracking in concrete of a non-reinforced structure affected by AAR

Microcracks: microscopic cracks within concrete, not readily visible to normal or corrected-to-normal vision, but visible using an optical microscope.

Microcrystalline: texture of a rock or a mineral phase (like microcrystalline quartz) consisting of crystals that are too small to be visible to normal or corrected-to-normal vision, but visible using an optical microscope.

Microscopy: study of objects by means of a microscope.

Modulus of Elasticity: Young's Modulus, E. The measure of stiffness of a material defined as E = (change in stress)/(change in strain). For true elastic materials E is a constant and stress/strain curve is straight to close to failure stress. Concrete is more complex, and its stress-strain curve is non linear. AAR microcracking softens the concrete reducing E and developing a hysteresis in the stress/strain curve. Reduction in E is a sensitive indicator of developing microcracking from any cause. Restrained AAR expansions produce anisotropy of E.

Opal: amorphous silica with varying amounts of water ($SiO_2.nH_2O$). Some opal exhibit crystallites of crisobalite and/or tridymite in the XRD analysis. Opal is highly reactive with hydroxyl and alkali ions tending to form ASR sol/gel in concrete. The presence of a few percent in the aggregate can cause more expansion than a higher amount. This is known as a "pessimum phenomenon". Opal is generally found in sedimentary and volcaniclastic rocks of younger geologic ages.

Pessimum: The percentage of a reactive mineral in the aggregate, the other constituents of which are non-reactive, which produces maximum expansion.

Petrology: the science of rocks, involving their origin, structure and composition from all aspects and in all relations. Petrography is a descriptive part of the petrology.

Polarizing Microscope: a microscope equipped with elements permitting observations and determinations to be made using polarised and cross-polarised light. Thin-sections or mineral powders are used for observation. In cement chemistry, polarizing microscope equipped with a reflecting light apparatus is used for observing polished thin sections.

Pop-out: a term used to denote the breaking away of small portions of a surface due to localised internal pressure, which leaves a shallow, typically conical, depression. In concrete, small pop-outs leave pits up to 10 mm in diameter, medium pop-outs leave pits 10 to 50 mm in diameter, and large pop-outs leave pits greater than 50 mm in diameter. Pop-outs are usually caused by the presence of frost-susceptible aggregate particles, but may also be caused by alkali-silica reaction in aggregate particles.

Portland Cement Constituents: principal phases of the Portland cement clinker include, with the cement chemist's notation, alite (solid solution of C_3S or $3CaO.SiO_2$), belite (solid solution of C_2S or $2CaO.SiO_2$), aluminate (solid solution of C_3A or $3CaO.Al_2O_3$), and ferrite (solid solution typically C_4AF or $4CaO.Al_2O_3.Fe_2O_3$). Appreciable amounts of alkalis can be incorporated into an alkali-aluminate variety when the cement clinker is rich in alkali.

Portlandite: ($Ca(OH)_2$), a typical product of cement hydration, see calcium hydroxide.

Quartz: mineral SiO_2. One of the most common rock-forming minerals, composing approximately 12% of the earth's crust.

Reaction Rim: a perimeter staining surrounding some types of alkali-silica reacted aggregate particle not resulting from wetting of the aggregate prior to its use in concrete, but caused by interaction of aggregate and cement paste.

Reinforced Concrete: concrete containing reinforcement and designed on the assumption that the two materials act together in resisting normal structural forces.

Restraint: Expansions are restrained by compressive force from structural stresses (e.g. compression along column axis) and/or generated by resistance to AAR expansions from adjacent elements or anchored reinforcement. Restrain needs to be separately considered for the three axes of a member. Restraint in one direction reduces expansions and cracking transverse to that axis, while increasing it in less restrained directions perpendicular to that axis.

Silicic Rock: term denoting igneous rocks with more than 66% or 70% SiO_2, corresponding rhyolite (granite) plus some dacite (granodiorite). When it is defined by the content of free quartz, it may be at least 20% free quartz. To avoid confusion with chemical term "acid", it is recommend to use "silicic" or "felsic".

Shrinkage: decrease in volume. Shrinkage may be restricted to effects of moisture content or chemical changes.

Spall: a surface fragment, usually in the shape of a flake, detached from a larger mass by a blow, by the action of freezing and thawing, weathering, reinforcement corrosion, by pressure, or by expansion within the larger concrete mass.

Spalling: the development of spalls.

Strain: The ratio of the change in a dimension to its original length. Normally expressed as microstrain where 1000 µstrain = 1mm/m. Expansions from AAR produce strains that are developed by internal gel pressures.

Supplementary Cementitious Material or Addition: a material (for example, fly ash, silica fume, ground granulated blastfurnace slag) that, when used in conjunction with Portland cement, contributes to the properties of the hardened concrete through hydraulic or pozzolanic activity or both.

Sub-clinical AAR: Concrete where a few signs of gel or reaction are present, but are not sufficient to cause significant expansion or cracking.

Swelling: an increase in volume with consequent increases in strains which are anisotropic where concrete is restrained in one or more directions.

Tensile Strength: the maximum stress that a material is capable of resisting under uni-axial tensile loading. It is based on the cross-sectional area of the specimen before loading.

Tensile Strain Limit: the strain at which rupture or cracking occurs and is typically in the range 150 to 250 µstrain for concrete. Cracking in a structure indicates that this limit has been locally exceeded.

Thermal Cracking: Cracking of concrete caused by restrained contraction during dissipation of the heat of hydration (example, cooling) at early stages, or cracks formed due to excessive thermal gradient within a concrete.

Tridimite (SiO_2): a polymorph of silica (quartz) that is stable at temperatures above 870°C. It is metastable at ambient temperatures. Tridimite is found in some felsic volcanic rocks such as andesite, dacite and rhyolite of younger geologic ages, but may occur in some opaline sedimentary rocks as a metastable product during diagenesis.

Tuff: a rock consolidated from volcanic ash.

Volcanic Glass: an amorphous natural glass produced by cooling of molten lava, or liquid fraction of it, too rapidly to permit crystallization.

Volcanic Rocks: fine-grained igneous rocks that have resulted from rapid cooling of molten material that has extruded on to or very near the Earth's surface. Common volcanic rocks are rhyolite, andesite, dacite and basalt.

Weathering: the disintegration or alteration of natural or artificial materials such as rocks and concrete in response to exposure to water, air or living matter. Weathering is accompanied by changes in colour, texture, strength, chemical composition or other properties of the materials.

2 Alkali-Aggregate Reaction

2.1 Introduction

Alkali-aggregate reaction in concrete is the name given to a group of reactions leading to expansion caused by a chemical reaction between the alkalis contained in the cement paste and certain reactive forms of (usually silica containing) minerals in the aggregates, see Figure 4.The alkalis in the pore solution are derived from the hydration of the cement but may be augmented by alkalis in some aggregates or alkaline salts from the environment [5]. One characteristic consequence of AAR, in the presence of sufficient moisture, is variable expansions. The expansion may cause extensive cracking of the concrete, especially if it is not restrained, leading to various forms of structural damage and durability problems. Maintenance costs of the structure tend to increase and the service life can become reduced.

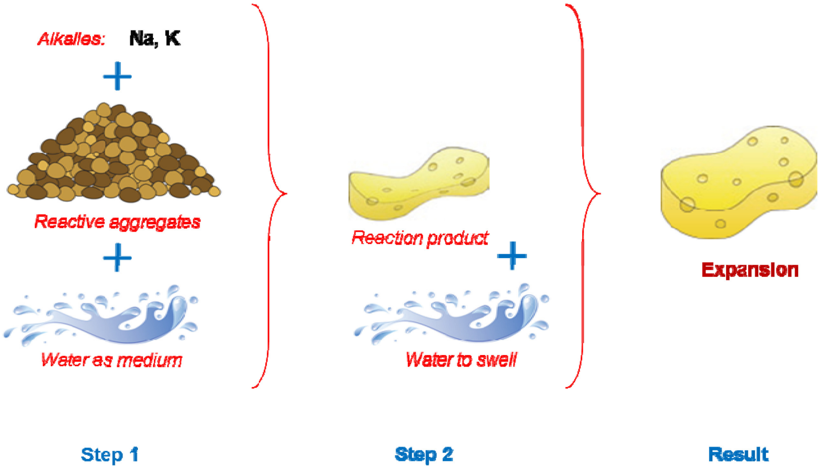

Fig. 4 Schematic steps involved in AAR

It was first described in the classic research by Stanton [11] in the early 1940s. Since documentation of the first case, many other cases have been documented worldwide of various structures affected by AAR. They include several hundreds of major structures, including dams, foundation blocks of electricity sub-stations,

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bridges, locks, car parks, reservoirs, jetties, viaducts, multi-storey buildings, sewage treatment works and highway pavements and structures. Research has progressively led to an understanding of the fundamental characteristics of the reaction with major early contributions by Mather [12], Diamond [13], Idorn[14], St John [15], and Oberholster[16].

This chapter provides a very brief overview of the main chemical and physical processes involved in AAR in order to better understand the changes of the material properties they induce and the structural consequences that can follow from these material property changes. The different components as outlined in Figure 1 will be briefly discussed in the next section.

2.2 Alkalis

The presence of alkalis is required for reactive aggregates to actually react by AAR. The chemical elements lithium (Li), sodium (Na), potassium, (K), rubidium (Rb) and caesium (Cs) are called the alkali metals. The oxides of the alkali metals react with water to form soluble hydroxides which are known as alkalis.

The main source for alkalis acting in AAR is usually the cement itself. Cement contains the alkali metals sodium and potassium. In the cement industry it is customary to combine these together. However, to do this it is not possible to simply add the sodium oxide (Na_2O) content and the potassium oxide (K_2O) content together because of the different molecular masses of the two oxides (Na_2O = 62.0 and K_2O = 94.2)). Instead, a concept known as Na_2O equivalent is used calculated through the following equation:

$$\begin{aligned} Na_2O\ equivalent(\%) &= Na_2O(\%) + \left(\frac{62.0}{94.2}\right) K_2O(\%) \\ &= Na_2O(\%) + 0.658\, K_2O(\%) \end{aligned} \tag{1}$$

The alkali content of concrete can be expressed in the same way as that of cement. However, for concrete the alkali from all sources need to be taken into account. This includes the contribution from any cement replacement materials, additions, admixtures or the release through aggregates like feldspar, some micas, glassy rocks and glass. Further sources of alkalis can be de-icing salts applied to concrete, seawater or even poorly washed sea-dredged aggregates.

2.3 Aggregates

Traditionally two types of AAR are distinguished: Alkali-Silica Reaction (ASR) and Alkali-Carbonate Reaction (ACR), of which ACR is extremely rare. A third type of reaction has been described as 'alkali-silic*ate* reaction', but this is now recognised as a particular (slow/late) form of ASR.

ASR is by far the more common reaction in comparison with ACR. ASR in concrete occurs between the alkalis in the pore solution of the (hardened) cement paste and certain forms of siliceous constituents in the aggregate. First alkalis in the pore solution react with reactive silica to form an alkali-silica gel. Second, the gel absorbs water and expands as a result thereof. This expansion exerts internal forces on its components, which can subsequently lead to cracking and damage of the concrete [17-19].The reactivity of the silica depends largely upon the degree of atomic disorder and internal surface area. Also a high dislocation density in the quartz atomic structure can be an important factor [20]. Reactive silica constituents which may be present in aggregates include opal, cristobalite, tridymite, siliceous and intermediate volcanic glass, chert, glassy crypto-crystalline volcanic rock, artificial glasses, some argillites, phyllites, schists, gneisses, gneissic granites, vein quartz, quartzite, impure sandstone and chalcedony. The most reactive in general are opal, chalcedony, porous flint stone and impure sandstones.

For ACR these are carbonate based rock types, more specifically dolomite limestones [$CaMg(CO_3)_2$] containing some clay. Alkali-carbonate reaction, ACR, in concrete is the chemical reaction between certain fine-grained, argillaceous dolomitic limestone aggregates in concrete and the alkalis in the pore solution of the cement paste. However, not all reactive rocks in this category cause deleterious expansion, which is what makes AAR so difficult to predict with certainty based on aggregate type selection alone. It has been established that problems involving ACR increases when the rock shows the following features: (1) very fine grained dolomite (small crystals), (2) considerable amounts of fine grained calcite, (3) abundant interstitial clay, and (4) the dolomite and calcite crystals evenly dispersed in a clay matrix [21].

The reaction is not properly understood but can be generalised as follows. Alkalis react with the mineral dolomite, causing it to break down into brucite and calcite in a reaction that is called ‘dedolomitization’. The reaction can be represented as follows (in which potassium can take the place of sodium) [22]:

$$\underset{\textit{Dolomite}}{CaMg(CO_3)_2} + \underset{\textit{alkali}}{2NaOH} \rightarrow \underset{\textit{Brucite}}{Mg(OH)_2} + \underset{\textit{Calcite}}{CaCO_3} + Na_2CO_3 \tag{2}$$

This reaction is expansive. The alkali carbonate is hygroscopic. In the presence of portlandite, the alkali carbonate can transform to calcite thereby regenerating the alkalis. According to Gillott [19], the dedolomitization reaction opens up the rock allowing water to enter the unsaturated clay, which in turn swells and disrupts the aggregate even further, finally cracking the concrete.

ACR differs from ASR in that with ACR no gel was detected by the classical optical microscopy. However, modern techniques (SEM and EPMA) revealed that cryptocrystalline quartz and ASR gel are present in the typical ACR aggregate in both field and laboratory concretes, and that ASR occurs in open spaces created by dedolomitization [23]. Since expansion is basically caused by ASR, it is appropriate to avoid the conventional use of the term ACR.

Finding alkali-reactive constituents in an aggregate does not provide a simple prediction of that type of aggregate being harmful through AAR for concrete. To do this a judgement needs to be based on field performance or a laboratory expansion test.

2.4 Water

Presence of water is generally necessary for the actual swelling to induce the necessary stresses for cracking. Krogh [24] showed that the water uptake in gels at equilibrium is a function of relative humidity, see Figure 5. Swamy [25] went one step further based on experiments and case study evidence, and published Figure 6 to illustrate the type of relationship between relative humidity and expansion.

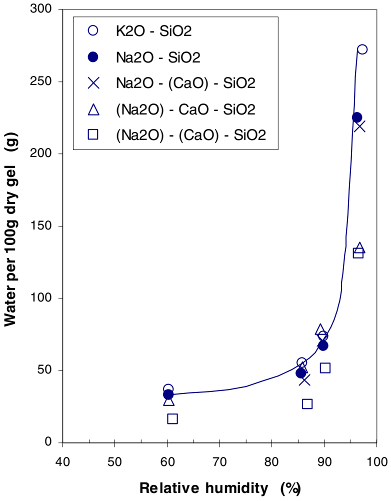

Fig. 5 Relationship between water content in gels at equilibrium and relative humidity [24]

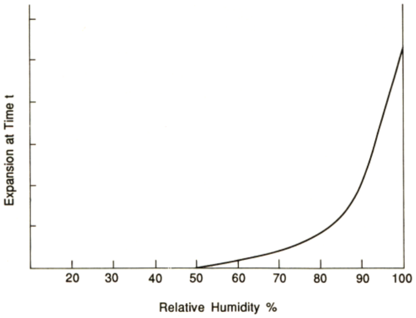

Fig. 6 The effect of relative humidity on the expansion of concrete due to alkali-silica reaction [25]

2.5 Pessimum Behaviour

With the fastest reacting forms of reactive siliceous aggregates, it has been found that the AAR-related expansion is not necessarily proportional to the content of reactive minerals in aggregates. Some silica-rich aggregates containing large amounts of very reactive forms of siliceous minerals lead to very low or even no expansion at all. At low proportions, the expansion increases with the increasing amount of siliceous minerals but beyond a certain amount of these minerals the expansion diminishes and can even disappear. The proportion of reactive aggregate corresponding to the peak expansion is called the **pessimum content** [26, 27]. With aggregates containing flint, for example, this particular situation occurs with a flint content of around 20% to 30%. When the flint proportion reaches and exceeds 60% in aggregates, no expansion occurs any more. For pure opal, which is one of the most reactive silica, this pessimum content is far lower, commonly between 2 and 5%. Figure 7 gives an example of such behaviour.

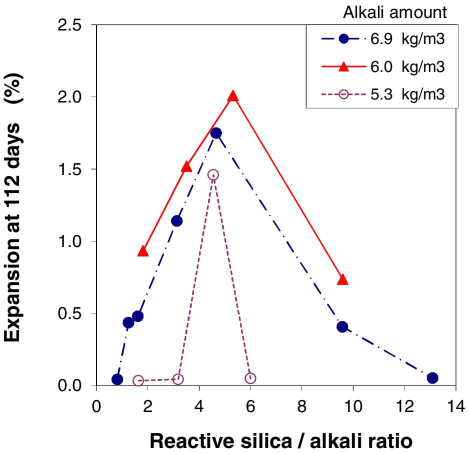

Fig. 7 Dependence of expansion of mortars on the ratio of reactive opaline silica/alkali. The mortars have w/c = 0.41; aggregate/cement = 2, silica particle size = 150-300 µm, and are immersed in water at 20°C [28].

The expansion curve of such materials can be divided into four main regions as function of the reactive aggregate content (see figure 8):

- In the first region, **region A,** the reactive silica content is still low and gel formation is too small to give any expansion and to induce cracking.
- In the second region, **region B**, the amount of expansive gel is such that it can induce expansion and cracking. Expansion increases with increasing the amount of reactive silica. The expansion ceases with time when either the reactive silica or soluble alkalis are depleted by the AAR.
- In **region C**, the amount of reactive silica is high but the gel formation begins to be limited by the alkali content, cracking occurs and expansion ceases only when the alkalis in the pore solution are reduced to a threshold level or are depleted. In this region there is an excess of reactive silica in contrast to the available alkalis. The reactive sites are present in large proportion and well dispersed. However, because of the lack of soluble alkali, the formation of AAR-gel in each reactive site is limited and therefore the expansion of each of them is limited too.
- In the last region, **region D**, the reactive silica content is very high, consequently reactive sites are numerous and well dispersed. The reaction is very fast, soluble alkalis are quickly consumed, but little gel formation occurs in each reactive site and at the end no damage and expansion happen.

In the B region, the reactive silica content is the limiting factor, while in the C and the D regions the limiting factor is the alkali content. In region C, the total amount of gel is not less important than in the two previous regions, but this gel is widely dispersed in small quantities in numerous reactive sites and cannot generate trouble. This situation is true as soon as the concrete alkali content is limited.

The pessimum content depends not only on the reactive silica content but also on the aggregate size (**pessimum size**). It has been demonstrated by Meyer and Co [29] that, for a given alkali content, a decrease of particle size leads to a sharper but higher pessimum peak. Also, the peak moves to the left hand side of the diagram, that is to say towards the smallest reactive silica contents.

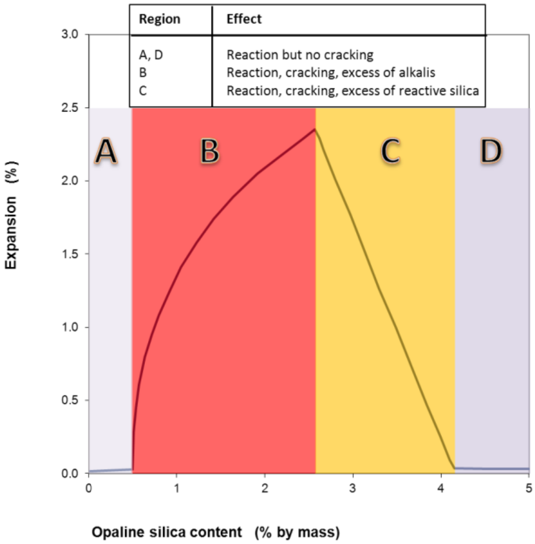

Fig. 8 Pessimum behavior here shown by an aggregate with opaline silica (after [28]).

2.6 Summary

To summarize the most important parameters for AAR the following sequence is important. The effects of AAR are generally judged by determining the amount of expansion. This expansion is caused by the formation of a gel that generally uptakes water. The amount of water that can be taken up depends on the amount of gel present as well as the type of gel. The amount, type and rate of gel produced depend on the alkali amount present as well as the amount and type of reactive aggregates.

Hence, the conditions for damage of concrete caused by AAR can occur if all the following four requirements are fulfilled:

- A critical amount of reactive constituent in the aggregate combination
- A Sufficiently high alkalinity of the concrete pore water
- A Sufficient moisture in the concrete and its environment
- A Sufficient concentration of portlandite. If any one of the above requirements is absent, damage to the concrete from AAR may not occur.

3 Symptoms of an Expansive Reaction during Routine Inspection

3.1 General Inspection Remarks

For any existing structure, a routine inspection is ordinarily a starting point of a cyclic process to maintain the safety and reliability of the structure (Figure 9). It is part of an inspection process where detailed inspection and in depth investigation are important actions. This chapter covers review of existing records, field equipment and materials, personnel and expertise and so on. Also some general field symptoms of AAR are given to recognize first signs of AAR.

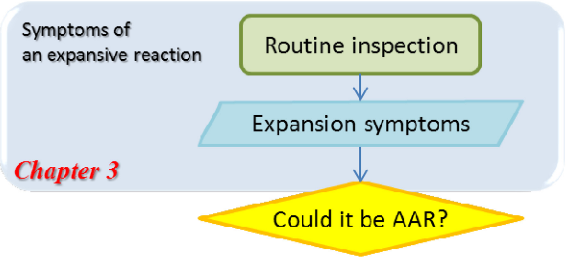

Fig. 9 Starting point for the cyclic process to maintain a structure's safety and reliability is ordinarily a routine inspection

3.2 Review of Existing Records

This aspect involves a review with the engineer of available documents relating to the structure prior to the inspection. Many of these documents will have been consulted prior to the current inspection. Details, preferably obtained in advance, should include:

- Name of the structure, type, location and the conditions to which it is or has been exposed because of its location or function;
- Age, including date of completion, and details of any major or minor remedial works;
- Details of concrete construction procedures and, including mix designs, sources of materials (if available). The early thermal and curing procedures may be significant for other possible causes of cracking [30].

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- Design loading (if available) and construction details, including foundations, drainage system, joints, and the position and arrangement of reinforcement or prestressing;
- Reports of previous inspections or testing, either routine or detailed, and particularly the dates on which signs of damage or deterioration were first noticed;
- Changes to environmental conditions (temperature, exposure to water, humid air or de-icing salt) from drainage, waterproofing, cladding etc.
- Details of any other structures in the area known to be exhibiting signs of possible AAR.
- Available access and requirements for access equipment
- Any other information that may be relevant for the field inspection and the investigation.

Original as built and/or revised scale drawings, including plans, elevations and sections, may be available at this stage. Copies of such drawings showing underlying reinforcement are useful for making an accurate recording of observations during the site inspection.

Changes made to the structure should be checked during the fieldwork. The validity of documentary evidence, particularly earlier test results, needs to be assessed carefully and, where possible, checked against site observations of locations of sampling.

The engineer's preliminary view on the potential sensitivity of structural elements to AAR, based on consideration of details shown on the reinforcement drawings, should be obtained before and during the site visit (see AAR-6.2).

3.3 Planning of a Comprehensive On-Site Inspection

The routine investigation deals primarily with the case where the cause of damage has not yet been established. There are many well written up case studies of the inspection, testing, and petrographic evaluation of specific types of structures which provide examples of good practice. These include Pavements [31], Bridges [32, 33] Dams [35] Railway sleepers [36], Swimming Pools [37].

Prior to the full site investigation, the history and condition of the structure should be discussed with the management and engineering team responsible for its operation and maintenance. The management strategy and priorities for the structure need to be understood and set out in the client's brief for the investigation. There may well be particular requirements for access and for avoiding disruption to users to be considered. Discussions with those responsible for routine maintenance and previous assessments can be helpful.

The site inspection needs to be planned to give extra attention to sensitive areas so that their condition can be reliably assessed (see AAR-6.2).

3.3.1 Field Equipment and Materials

The required equipment and materials for the field inspection should include the usual materials and equipment that are used for routine field inspections, such as:

- Hand lens or strong magnifying glass
- Crack width gauge or crack width microscope
- Metric steel tape, say 4m long, a 1m straight-edge,
- Binoculars
- Mirror
- Powerful electric torch
- Flexible endoscopes (to obtain information from areas inside the structure, which are not readily accessible, such as those hidden by cladding) and,
- Good quality camera (digital or loaded with colour film) equipped with a flashgun. Digital cameras must be set for high resolution images.

A comprehensive photographic record should be made and a description of each photograph should be recorded in a notebook. Every photograph should include a scale. A video camera may be additionally useful, but should not be relied upon to produce records where high definition is required.

Other equipment for general site inspection, not all of which may be relevant to the diagnosis of AAR, might include a spirit level, a plumb line, a crack-width microscope, a small hammer, and a penknife. Non-destructive testing equipment may be useful, such as a Schmidt rebound hammer and an electromagnetic covermeter. The covermeter will be essential to check reinforcement locations prior to coring

Detailed records of the inspection should be written into a notebook or on forms held on a waterproof clipboard. Portable dictation machines are useful, especially in wet or windy weather, but care must be taken at the outset to ensure that the recording is taking place satisfactorily, and that background noise is not excessive. Wherever possible, visible signs of deterioration should be recorded on copies of scale drawings. In some cases, the field inspection and sampling may both be carried out at the same time, when it will be necessary to consider what equipment will be needed for sampling. In any event, the inspector should carry a small selection of sample bags and indelible marking pens.

3.3.2 Personnel and Expertise

A reliable field inspection of structures must be performed by experienced personnel, who have been trained to identify, make careful observations of the external characteristics of damage and to record their findings in a systematic manner. Because the findings of this phase of the investigation are vital to the interpretations and conclusions that will be made, the personnel involved should preferably consist of qualified civil, structural, geological or material engineers or scientists with a good understanding of AAR and other concrete deterioration mechanisms. Because of the breadth of expertise required this usually involves a multi-disciplinary team. It is of prime importance that such personnel be not only familiar with the sampling and various laboratory tests but also should be able to discriminate between cracks and damage caused by AAR and those caused by other effects. Because of the strong interaction between AAR cracking and the stress fields and underlying reinforcement, the assessment of the structural integrity must be done by a qualified structural engineer, experienced in AAR assessments.

A successful routine inspection will enable a detailed site inspection to be planned to suit the significance of the structure and the resources available when necessary.

3.4 The Routine On-Site Inspection

The on-site or field inspection of the structure affected should be designed on the basis of the type of structure concerned. For example, site investigation of a block or a concrete road will be rather different from that of a viaduct or a major bridge, where structural aspects are more important.

In the case of a routine inspection, both the cause of the damage and its extent and distribution in the individual members of a structure are not yet fully established. On the basis of this preliminary work, a full-scale investigation, involving analysis and tests on core samples may or may not become necessary. At the start of an investigation, every mechanism, which could contribute to concrete cracking or deterioration, should be considered as a possibility, such as for example attack by sulphate and frost. No single possible cause should be eliminated until the investigation has shown clearly that it could not have contributed to the deterioration.

The aim of the site inspection carried out by the materials specialist with the engineer is to acquire information on the structure, in order

- To formulate a first idea about the range of possible structural effects and deterioration mechanisms,
- To locate representative areas for sampling.
- To remove some first (core) samples for laboratory studies [6, 38, 39].

One of the objectives of the field inspection is to establish whether or not the structure exhibits any features which are consistent with damage caused by ASR, and to identify those features which possibly indicate other mechanisms. The inspection should be thorough and systematic, and disproportionate attention should not be paid to those areas exhibiting the most obvious deterioration or damage [1-3, 40, 41].

The buried parts of structure often have large concrete elements with limited reinforcement in consistently damp conditions and are often the most structurally sensitive to AAR. They need to be considered in the preliminary inspection and if necessary be exposed in more detailed further studies.

During the field inspection, determination with the engineer of the severity and extent of cracking related to stress fields and underlying reinforcement configuration and assessment of the deformations in specific members of the structure are important. These features will be used to decide how further to proceed with the diagnosis and monitoring.

The environmental conditions to which the structural elements are exposed should be clearly described and related to the recording of cracking. In the case of a viaduct or bridge (in cold temperate climate regions), clear distinctions should be made between those areas that are more prone to de-icing salts, such as the top portions, joints etc. Areas of ponding, seepage and steady moist conditions, including buried elements, usually develop signs of AAR cracking first

Particular attention should be given to areas where such effects as run-offs, leakages, standing water, groundwater (buried portions of concrete foundations), seawater or condensation can be experienced. In addition, an overview or record should be made of all the surfaces, which may have come into contact with salt solutions, such as seawater, de-icing salts, salt spray and some industrial environments. Any possibly affected areas should be defined clearly and care taken to record variations in the degree of damage in those areas.

If the cause of damage to the structure has not yet been established, then this phase of inspection should be considered as preliminary. The information obtained from the inspection should be evaluated and should be used as the basis for selecting areas for sampling for the preliminary laboratory investigation. The first step in the interpretation of the results is by examining the cracks, because cracking in structural concrete rarely has a single cause. Cracks can be induced by a variety of mechanisms, including plastic shrinkage, drying shrinkage, early-age thermal contraction, frost attack, corrosion of reinforcement [30], and loading. Less common causes of cracking are sulphate attack and alkali-silica reaction.

In special cases, reinforcement and prestress reinforcement drawings can be shaded to illustrate the extent and severity of certain important features. These drawings will assist in correlating the observed features with the environmental variations, in locating areas for detailed inspection, and in deciding, with the engineer, a safe and representative set of sampling locations [1-3, 6, 8]. After the end of the field inspection, information obtained on the cracks should be correlated with the existing reinforcement and the location of prestress: normally the initial cracks tend to be oriented in the direction of compressive stress induced by loading or restraint from the main reinforcement or the prestressing tendons. As the reaction develops more varied cracking evolves.

Finally, it should be pointed that the field inspection alone can neither confirm nor discount ASR as a contributory cause of damage with any certainty. Early hasty deductions and conclusions should not be made from the field work. Detailed laboratory investigation on samples, coupled with various other tests are essential before any definitive interpretation can be made.

3.5 Concrete Surface Features Suggestive of AAR

AAR is only one of many possible mechanisms that may be responsible for damage to concrete in a structure. As such, when making an assessment of the cause of damage to concrete in a structure, it is necessary to consider all possible mechanisms that may have contributed to the deterioration or damage. AAR should be assumed or ruled out only when adequate investigation, consisting of site inspection and laboratory investigation, have taken place, so that a reliable judgement concerning the type of damage can be made. All concrete structures exhibit cracking to a greater or lesser degree. The cracking to be expected from structural actions and from the wide range of other 'Non-Structural Cracking' [30] need to be considered as precursors to any AAR cracking.

Damage to concrete caused by AAR may be manifested at the external surface in several forms. In the early stages, slow developing AAR tends to increase the magnitude of pre-existing cracking before its magnitude reaches a level (0.4 mm/m to 0.6 mm/m free expansion) at which the strains from AAR exceed those from other causes of cracking. As further AAR develops over time the distinctive characteristics of AAR cracking and damage observable in petrography become progressively more apparent. The most commonly reported ones are:

- Development of extensive cracking, often in the pattern of 'map-cracking' where concrete is unrestrained by adjacent structures or by internal reinforcement.
- Cracking tending to develop longitudinally parallel to the direction of dominant restraint, as the transverse cracking is suppressed where compression stresses develop from restraint or loading (e.g. axially loaded columns).
- Variable expansions, causing relative movements, displacements and deformations at different scales between parts of a structure and/or out-of plane displacement of crack lips, etc.

There are secondary features which tend to relate to specific aggregate types:

- Cracks are occasionally filled with the reaction products (ASR-gels, in the case of ASR as exudations, see Figure 10 and Figure 11).
- Surface discoloration, particularly along cracks.
- Scaling or spalling of portions of the surface.
- Surface pop-outs, often caused by reaction of coarse aggregate particles close to the surface, but may be simply due to frost.

In extreme cases with free expansions over 2.5 mm/m:

- Delamination developing in the plane of the reinforcement which can fracture lap connections of reinforcement and cause de-bonding of reinforcement layers in flat slabs or foundations.
- Failure of brittle steel reinforcement on bends.

a = concrete pavement

b = part of a concrete wall

c = part of the wall of a lock

d = part of the wall of a lock

Fig. 10 Map-cracking of concrete shown in the surface of various members of non-reinforced concrete structures damaged by AAR. Some of the cracks are filled with carbonated ASR-gel.

The guidance and recommendations given in this document, deal with the diagnosis of damage to concrete in structures caused by AAR. Part AAR-6.2 will deal with prognosis and assessment of structural effects.

A record should be made of the external features that are suggestive of damage resulting from AAR. In particular examples of the pattern of cracking and its intensity in the various members should be carefully mapped and described, with the view that after the site inspection a reliable assessment can be made of the extent and severity of each feature in each of the elements inspected. On larger structures, or where only a few pours of concrete are showing signs of cracking, recording in the diagnostic phase should focus resources on the rigorous inspection of selected representative areas, ideally in readily accessible locations.

a = part of a retaining wall

b = part of the abutment of a lock

Fig. 11 Cracking and deterioration of concrete shown in the surface of two structures damaged by AAR. Both structures are exposed to long periods of wet conditions. Some of the cracks are filled with carbonated ASR-gel.

Examples of other distinct external features suggestive of damage caused by AAR should be noted and recorded, including surface discoloration in particular along cracks, efflorescence and exudations, and pop-outs [42]. Differential movements between parts of structure, and global deformations of the structure (deflection, bulging,…) [7] should be recorded. Examples of the extent of surface discoloration are most easily recorded by colour photography. Staining may be caused by reinforcement corrosion ('rust') or pyrites but this should be readily distinguishable.

Expansion of individual aggregate particles and/or exudation by AAR-gel close to an exposed concrete surface can sometimes cause detachment of a conical portion of the surface, leaving a small pit or 'pop-out'. The number, size and distribution of examples of pop-outs should be recorded and the nature of the aggregate exposed in the base of the pit should be identified. Pop-outs can also be produced by the frost action on porous aggregate particles, and should not be mistaken with pop-outs created by AAR. The ratio of the diameter of the detached concrete fragment to its depth is characteristic of the type of the material, and according to experience this ratio for the frost action is nearly 1.0 [42]. To avoid confusion with pop-outs caused by frost-susceptible aggregates, any exudation associated with pop-outs should be recorded and photographed and, if possible, samples removed for laboratory examination.

The presence of algal or moss growth along with seepage stains and carbonate deposits indicate damper areas of concrete. Local AAR cracking in these areas is a helpful indicator of more extensive damage likely to develop in the long term.

3.5.1 Crack Pattern

All concrete structures have cracking due to a range of 'Structural' and 'Non-Structural' [30] causes. For example the use of high cement contents can produce substantial cracking from early thermal and longer term shrinkage effects. These can interact with the slower developing AAR cracking. Visually , all one sees in the end are cracks, without a description of what mechanisms caused the cracks.

Therefore, the range of crack forming phenomenon need to be considered and recorded by the engineer and material scientist during the site inspection. Comparisons with previous inspection reports, when available, should be carried out to study if there is an evolution of the cracking. The recording of crack occurrences and patterns should be supported with photographs. Major cracks, especially those in critical areas of the structure, should be drawn to the attention of the assessing engineer. He may require them to be drawn to scale onto the reinforcement drawings or the prestressing drawings to help interpretation. Examples of cracks traversing through coarse aggregates, particularly those cracks that are filled, possibly with AAR-gel, should be noted and, where possible, photographed. Large cracks around aggregates (if apparent on the surface) should also be noted and recorded.

a = overview

b = details

Fig. 12 'Map' pattern of cracking in non-reinforced concrete affected by AAR

At the construction level, the main external evidence of deterioration caused by AAR is usually abnormal cracking. In unrestrained concrete, such as pavements, the cracks usually have a characteristic random distribution, which is often referred to as 'map-cracking' (see Figure 12). In that case, the cracks consist of a network of initially fine cracks, some of which may have been filled with AAR-gel. These fine cracks can be made more visible by brushing the concrete surface with a wire brush to remove any dirt or debris. Then a fine spray of water, allowed to dry, will reveal the cracks which retain the moisture a little longer.

This type of cracking should not be mixed with similar looking drying or plastic shrinkage, which also can appear as map cracking. The distinguishing difference in this case is the time period in which cracks appear. AAR cracking takes longer to develop (years) than the relatively early signs of drying or plastic shrinkage (days to months).

The expansive forces arising from AAR may be restrained, for example by steel reinforcement, pre-stressing or external loads. In that case, the cracks are preferentially oriented in the direction of the main reinforcement (see Figure 13) or parallel to the main compressive stresses.

a=part of a viaduct

b=part of the wall of a lock

Fig. 13 Preferred 'reinforcement-controlled' pattern of cracking in the concrete of two reinforced structures affected by AAR

The following general aspects should be noted in recording cracks: crack width, continuity, surface displacement, path (whether around or across aggregate particles) and any other association with features such as underlying reinforcement, stress orientation or surface discoloration. The range of moisture conditions in the cracked area should be noted.

A standard method should be adopted for describing the width of cracks. A suitable scheme is shown in Table 1. Fine cracks less than 0.1 mm can usually be ignored, as they are endemic on most concrete. Where they are unusual for the type of construction examples may merit recording. Cracks from 0.1 to 0.3 mm can be found in most reinforced concrete and the type and orientation of cracks needs careful consideration relative to the range of possible interacting causes. Cracks from 0.3 to 0.5 mm are large, but not immediately structurally alarming in reinforced concrete structures. They do, however, deserve attention from a durability point of view. Cracks over 0.5 mm need careful recording and should be referred to the engineer to consider if they indicate a structural risk.

Table 1 Classification of crack widths on site

Crack width (mm)	Description		Abbreviation
< 0.1	Fine	Usually present	F
0.1 – 0.3	Normal	To normal limit for RC	N
0.3 – 0.5	Large	Over limit	L
0.5 – 1.0	Moderately wide	Record all	MW
2.0 – 5.0	Wide	Refer to Engineer	W
>5.0 – 10.0	Very wide	Refer to Engineer	VW

Note: for a prestressed concrete structure, the scale has to be adapted towards lower values of crack width.

Fine cracking due to surface drying and shrinkage etc., is present on most concretes and little is to be gained by recording it unless it is unusual for the type of construction, e.g. with prestressed concrete structures. Re-cracking of cracks, filled with epoxy some years before could give a measure of expansion rate [43].

3.5.2 Displacements and Deformations

The process of AAR is a potentially expansive mechanism, so that significant movements in the structure can sometimes occur. A record should be made of any differential movement, such as closing of joints, relative displacement of adjacent concrete sections, excessive deflection, and twisting or bulging of originally flat surfaces. The correspondence of this movement with other features, such as concrete of different composition, unusually wet or exposed locations, or less restrained parts of the structure, should be noted and recorded [44]. Simple markers and gauges may be fitted at the time of the routine inspection so that further movements will be measurable in the future. Long term monitoring using more rigorous and precise methods will be covered in AAR-6.2.

3.6 First Assessment of Field Observations

An assessment of the probability that damaging AAR has occurred can be made by considering the apparent damage to the structure and determining whether the nature of the damage is consistent with AAR. Table 2 and Table 3 list a number of features that may indicate AAR and classifies their occurrence as indicating a low, medium or high probability of AAR [1]. This assessment relies on individual interpretation and should only be carried out by a concrete inspector experienced in examination of AAR-affected concrete in structures.

Table 2 Classifications system for probability of AAR based on first site or field observations (developed from [1])

Feature	**Probability of AAR**		
	Low	***Medium***	***High***
Cracking and crack pattern	None	Some cracking patterns typical of AAR (i.e., map-cracking or cracks aligned with major reinforcement or stress)	Extensive map-cracking or cracking aligned with major reinforcement or stress; Misalignment of facings (differential expansion, on each side of the crack…)
Deformation and / or displacement of elements	None	Some	Structure shows symptoms of increase in concrete volume leading to displacement and misalignment of elements

Table 3 Specific features which are sometimes associated with AAR. Their absence does not rule out AAR (developed from [1]).

Feature	**Probability of AAR**		
	Low	***Medium***	***High***
Surface discoloration. *(This is variable)*	None	Slight surface discoloration associated with some cracks	Line of crack having dark discoloration with an adjacent zone of light-coloured concrete
Pop-outs with ASR gel deposit	None	Some	Many
Exudations	None	White exudations around some cracks	Colourless, jelly-like exudations readily identifiable as AAR gel associated with some cracks
Environment	Dry and sheltered	Outdoor exposure but sheltered from wetting	Parts of component frequently exposed to moisture, for example, rain, groundwater, water due to natural function of the structure (hydraulic dam)

4 Confirmation Investigation

4.1 Introduction

When routine inspection results, like examples given in the previous chapter, show indications which could point in the direction of AAR, it is a wise decision to bring in the specialists. As these specialists are normally brought in when something odd has been observed, the first step to be taken is to establish what the cause of the "strange" results is. At this point AAR is still only one of the options, and therefore, other alternative causes of damage should also be considered, see Figure 14.

To eliminate or confirm the presence of AAR, some simple tests can be performed. This part is described in the current chapter. Depending on the severity of the damage and the likelihood of the damage being caused by AAR, a judgment call can be made to confirm AAR and investigate the severity of the AAR damage in parallel. In this report the severity investigation is described in Chapter 5, while the confirmation methods and tests are described in the current chapter.

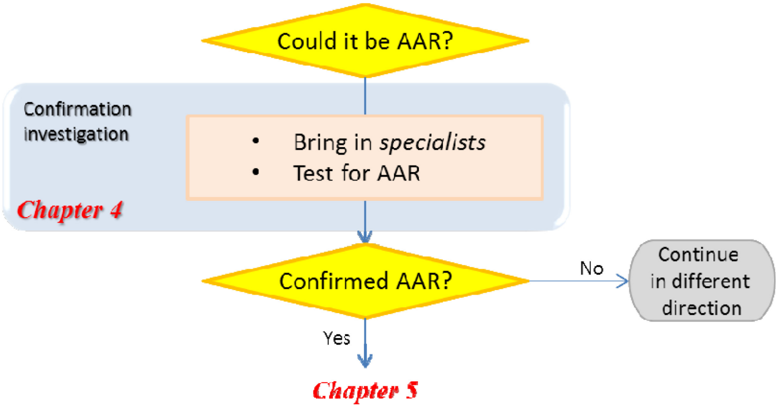

Fig. 14 In this chapter the confirmation or elimination of AAR as cause of damage is described

4.2 Available Methods, Personnel and Expertise

Alkali-aggregate reaction in concrete can be reliably diagnosed by one or a combination of several methods. These include core-scanning (taking an image of the cylindrical outer surface of a core, see [45]), visual and stereomicroscopic

B. Godart et al. (Eds.): *Guide to Diagnosis & Appraisal of AAR Damage*, RILEM 12, pp. 31–63.
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examinations, point-counting, thin- section petrography based on polarizing, reflecting and fluorescence microscopy of the polished thin-sections, XRD (X-Ray Diffraction) analysis, SEM (Scanning Electron Microscope) observation, mapping of elements using EPMA (Electron Probe Micro Analysis) and quantitative EPMA analysis.

To establish the cause of damage, an integrated analytical procedure involving concrete petrography, which consists primarily of stereomicroscopy and examination of thin section of concrete is used, with or without impregnation of fluorescent-dye. To confirm the presence of AAR, sometimes SEM applied on a fractured concrete may provide sufficient information. Where reactive rock types are complex (such as those consisting of siliceous, argillaceous and dolomitic limestone) a combined investigation of SEM and EPMA analysis on polished thin sections without a cover glass, is recommended [23].

The investigation should be performed by skilled personnel. In particular, the petrographic examination should be performed by a concrete petrographer with experience of AAR and access to reference samples of known cases. This is imperative for the reliable identification and assessment of any AAR damage in the concrete samples collected. The concrete materials team should have extensive knowledge covering cement chemistry, mineralogy, petrology, geology, stereology and concrete engineering, which enable identification of concrete materials, interpretation of test results and assessment of concrete durability. They should also have a strong background in basic science, especially X-ray diffraction analysis and other analytical methods.

Petrography reveals many characteristics of concrete which will be helpful in understanding other ‘Non- Structural’ forms of cracking and this should be considered in planning the overall testing scheme. To avoid a misleading diagnosis of concrete deterioration, petrographers are recommended to visit the concrete structures in question, to examine the mode of deterioration and the context from which the samples were taken, or, otherwise, to study site information, including at least photographs that show the damage of the structures and of the surroundings of the locations from which each of the cores have been taken.

4.3 Approach for Diagnosis of AAR in Structures

Diagnosis in the context used in this document deals with assessment of suspected AAR damage to concrete in a structure in order to determine whether or not the damage is primarily caused by AAR (this chapter), and the severity and extent of damage and its distribution in the structure (following chapter). The effects of AAR on the structure as a whole and the prospect of future damage and possible maintenance implications during service life will be dealt with in AAR-6.2.

There are several types of diagnostic investigations possible depending on the overall objective. There are investigations that cover a large area, for example a whole region and others that are related to a specific structure or group of structures. Each type of investigation has a specific purpose. In the former case, the investigation may be conducted to gain information about the frequency of

AAR and the type and nature of reactive aggregates used to assist in refining specifications. In the latter case it may be conducted to gain information for making judgements about the future maintenance and repair of the structure(s). The maintenance case can be broadly divided into two phases:

- The cause of damage is not yet known or AAR damage has not yet been established: *new or unknown situation*. A confirmation investigation is needed.
- The cause of damage has been established as AAR: *severity investigation and/or monitoring* are the next steps (see next chapter).

Each phase of the investigation has a specific purpose, which is controlled by the budget and the time available. Usually, the first step of diagnosis, after a potential problem has been identified from unusual cracking or movements during routine inspection, is to plan and adopt a strategy. This will depend on the location and severity of cracking and the structural assessment of the sensitivity of the structure to deterioration. The level of the investigation will also depend on whether or not the structure is one of a group with a known history of damage caused by AAR, or the structure is made with a concrete composition known to have reacted in another structure.

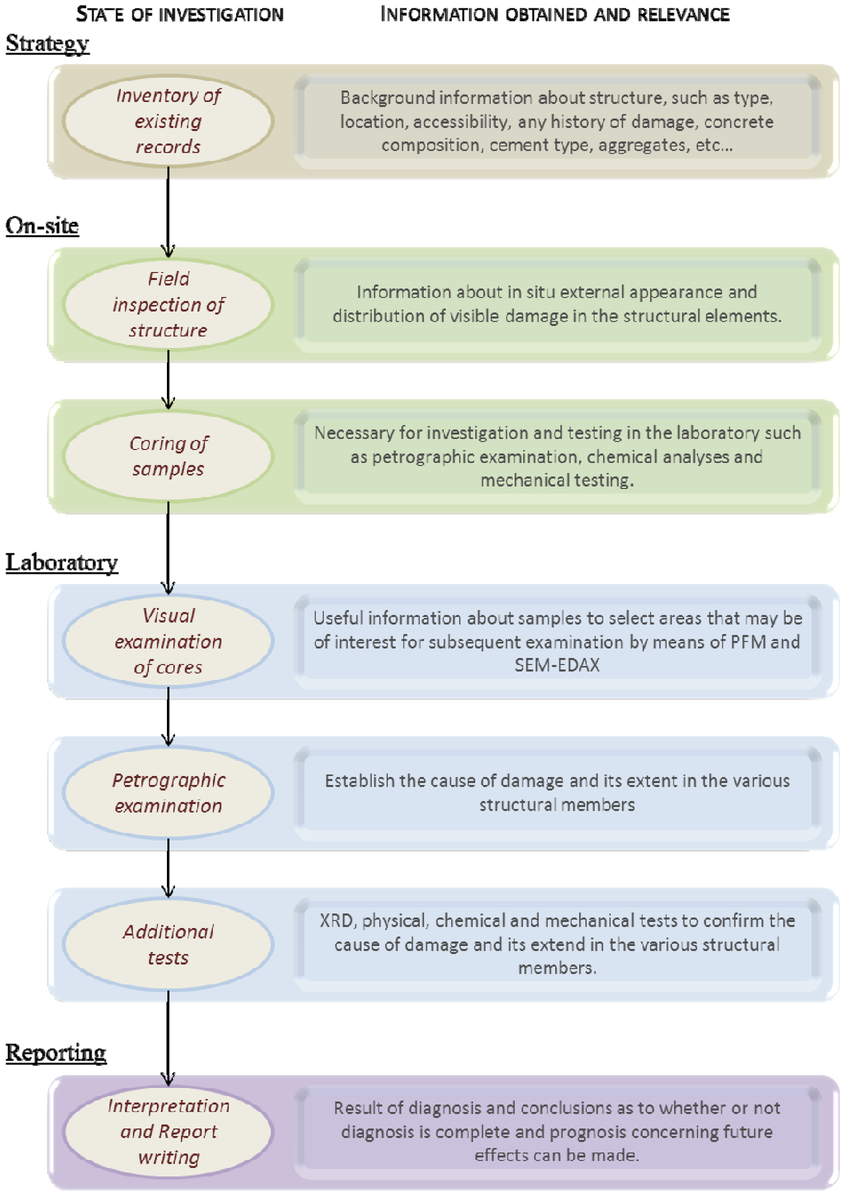
Figure 15 shows a generic flow chart for the diagnostic materials related studies within an overall investigation of a structure to determine or eliminate the presence of AAR. As before, the strategy starts by making an **inventory of existing records** and information. Next, the **field inspection** of the structure needs to cover the whole potential range of structural and materials deterioration related factors which may be contributing to the cracking which could have triggered the investigation.

This field inspection must be carried out with the engineer responsible for the structure and severity and types of cracking must be related to the underlying reinforcement configuration and its sensitivity to deterioration.

Part of the inspection is **coring of samples**. The sampling needs to be carried out guided by the engineer to ensure that coring does not damage the reinforcement or highly stressed areas of concrete structure. Sampling needs to include both samples for the diagnosis of AAR and other potential contributory materials phenomenon. If appropriate also sampling for the testing for prognosis and appraisal of the structure should be performed.

The diagnostic laboratory investigation follows and usually consists of **visual examination of the samples** with the aid of a stereo-microscope, **petrographic examination**, **SEM observation**, EPMA analysis and **additional tests** and analyses on the representative groups of core samples.

The final stage consists of **interpretation and report writing**.



Background information about structure, such as type, location, accessibility, any history of damage, concrete composition, cement type, aggregates, etc...

Information about in situ external appearance and distribution of visible damage in the structural elements.

Necessary for investigation and testing in the laboratory such as petrographic examination, chemical analyses and mechanical testing.

Useful information about samples to select areas that may be of interest for subsequent examination by means of PFM and SEM-EDAX

Establish the cause of damage and its extent in the various structural members

XRD, physical, chemical and mechanical tests to confirm the cause of damage and its extend in the various structural members.

Result of diagnosis and conclusions as to whether or not diagnosis is complete and prognosis concerning future effects can be made.

Fig. 15 Various stages of confirmation investigation and their relevance to the diagnosis of AAR in a concrete structure

4.4 On-Site Sampling for AAR Confirmation

Sampling is one of the most important stages of the investigation. Its purpose is to remove representative cores or suitable materials from specific locations of the structure for further examination and testing in the laboratory. For small structures, an ad hoc sampling programme may be planned and executed in the light of the overall investigation. If the investigation is a preliminary one, the test programme must be tailored specifically to diagnose those factors which may contribute to the observed cracking and damage. If on the other hand, the investigation is a detailed one, then the test programme should be planned as a subsidiary part of an overall investigation to include structural testing for assessment and modelling and the investigation of factors other than AAR, such as carbonation and chloride penetration.

Many structures contain a range of mix types from various aggregate sources. Construction records and recollections may help with this and it needs to be considered when planning sampling. Local surface grinding to reveal aggregate can help preliminary identification of mix types easier. Because of the wider implications of cases of AAR on specification for new construction it may be necessary to identify the sources of reactive aggregates and cementitious materials.

4.4.1 Cores

Core samples should be drilled with a diamond bit from safe locations that represent the state of deterioration of a concrete structure. Before coring, any adjacent reinforcement buried in the concrete must be located using information from the drawings checked with a covermeter. Coring locations must avoid structurally critical areas and should be directed by the engineer. Any reinforcement found in cores must be recorded and reported to the engineer so structural damage can be assessed. Cores should be taken from damaged areas, but also from undamaged areas; the latter ones as reference and determination of potential future damage.

To avoid excessive damage or fracturing of the cores, the equipment used for coring should be very well fixed to the structure during coring. After coring, the hole created should be filled or sealed with a suitable cement-based material acceptable to the engineer. To minimise shrinkage, this must have a sufficient aggregate content with moderate cement content with a low water/cement ratio to match the concrete and be well rammed home.

Percolation of water into core holes through deck surfacing as a consequence of failure to properly fill and seal can lead to severe local acceleration of AAR. If a waterproofing layer exists on the top surface of the structure (e.g. a bridge), it is advised to core from below and upwards (and to stop well before the waterproofing membrane).

It is desirable to take cores with a diameter three times or at least two and a half times the maximum size of coarse aggregate contained. That is 50 mm in diameter minimum when 20 mm aggregate is used. To be able to remove the cores from the structure, the drilling depth should be more than the diameter of the core.

Particular care is needed with the I-shape or T-shape girders in which PC cables are densely installed along with reinforcing steel bars. However, wherever possible 75 mm (preferred) or 100 mm should be used as these cores generally will also be better suited for residual expansion testing and for mechanical tests (see chapter 5).

4.4.2 Fragments

Lumps or block samples of concrete (fragments) can be obtained either from the concrete surface by hitting, or from a waste pile originated from previous repairs of the structure. Because cracking caused by hammering is misleading, and old surfaces of concrete are more or less weathered, evidence of any AAR can be masked by carbonation of both the cement paste and gel. Besides, gel and alkali may have been leached out from surface near concrete. Thick and large blocks allow extraction of unweathered portions of concrete by cutting in the laboratory, but small concrete fragments are usually not recommended for use in chemical analysis and detailed petrographic examination. Hence, fragments are not recommended as samples to confirm AAR.

4.4.3 Drilled Powdered Material

Drilled powered samples of the type used for determining chloride profiles are of little value in investigating AAR, other than as an indication of Na^+ ingress associated with the Cl^-. Drilled powders should not be used for petrographic examination.

It is also not recommended to use powdered drilling to determine the alkali content of the bulk concrete. Where cement alkali contents need to be determined, the most rigorous procedures are required to ensure the results are not confused by alkali from aggregates or powder coal fly ash (PFA) or ground granulated blast furnace slag (ggbfs) or other alkali sources. Furthermore, the alkali content needs to be related to the cement content. It has been found [46] that there are large spatial variations in alkali content particularly near the surface. The analysis of a number of sub-samples taken from cores is necessary to understand this variability, before an average value for the bulk of the concrete is determined. The variability of alkali levels contributes to the variability of expansions which create the micro-cracking and macro-cracking. In major structures comprehensive analysis of the spatial variability of alkali levels along with variability of reactive aggregates may be useful.

4.4.4 Efflorescence and Exudations

Examples of efflorescence materials should be collected for identification, for example using X-ray diffraction (XRD) analysis. Soft whisker substances forming on the humid surfaces of concrete, should be collected with a brush and stored in a small glass bottle with a tight cap, otherwise, they can be dehydrated or carbonated into a different form during transportation before analysis. Hard encrusting types of efflorescence, resembling stalactites, can be collected by scratching with a needle or by chiselling the concrete surface with the efflorescence attached.

In some AAR-damaged structures repaired with a sealant material, a local inflammation of the sealant caused by an entrapped liquid can be seen on the concrete surface. This can be an indication of either exuding AAR sol from the interior of concrete or entrapped water that has migrated though cracks and voids from the rear of the structure (originated from rain or ground water). To check this, it is necessary to collect solution using an injection tube for chemical analysis [45].

4.4.5 Number of Samples

The number of samples that will be required is dependent on the type and complexity of structure and the range of mix types and environments. The sampling scheme should provide a series of samples representative of the elements of the structure under investigation. Owing to the heterogeneity of most concrete within a large structure, and depending on the type of structure and phase of investigation, three or more areas can be chosen from representative examples of each member type (slab, beam, foundation or abutment), variously representing *sound*, *typical or moderately damaged* and *severely damaged concrete*. It is suggested that core samples should be taken from each of the three areas, as deemed appropriate. Almost inevitably, the limitations of access and economics will be deciding factors in the selection of the sampling locations, and of the number of samples to be taken. Once the variability of characteristics between cores is established, statistical tests can be applied to judge if the number of samples is sufficient for determining the full range in the structure.

A more representative assessment is obtained from selected tests carried out on many samples taken from different parts of the structure, as distinct from concentrating a wide range of testing on a few samples [2]. The locations on the structural elements from which the cores are to be removed should be defined by:

- indelible marking
- numbering the cores according to the sample locations in a systematic way
- defining the top and the bottom parts of the cores, including broken ones
- showing any other aspects on the cores that may be relevant for the investigation, such as orientation.

Irregular samples, consisting for example, of powder, lumps or any other forms should be treated in the same way with suitable codes and location numbers.

4.4.6 Preservation of Samples

Concrete cores and fragments should be surface dried if wet cored and sealed tightly immediately after sampling to prevent desiccation and secondary carbonation. This can be done by wrapping these samples with commercial cling-film in several layers, after which they should be sealed in polyethylene or vinyl bags for protection. If the cores are long and fragmented, it is recommended to use core boxes for transportation.

Drilled powders should be sealed in a small polyethylene bag, expelling the air. Small glass bottles with a tight cap should be used for preservation of efflorescence materials. Large bottles are not recommended because moisture from the sample cannot be maintained in the sample in a large space.

4.5 Visual Examination of Cores

4.5.1 Receipt of Cores and Documentation

Cores should arrive at the laboratory, being wrapped with a cling-film to retain moisture. They should be unwrapped, then immediately examined and photographed in the 'as-received' condition. Core samples are sometimes fragmented during coring, and cannot always be recovered as one continuous length. Upon receipt, they should be re-assembled and arranged in logical order, to enable a log to be created and check if any pieces are missing. If core boxes with timber V-sections are available for placing cores, this procedure becomes easier. Each piece of a core should be marked with an identification number using waterproof ink, in successive order from the structure surface.

Once unwrapped, concrete cores dry out rapidly, but it is necessary to take time to reconstruct broken cores and prepare logs, check and label reference numbers, and describe apparent information of cores (diameter, length, aggregate type and degree of deterioration). If some cores have dried out in transit, this should be recorded, because drying may influence the extent of carbonation and subsequent expansion of gel. Keeping a record of the weight of samples at all stages is essential for checking for any drying and for subsequent water uptake during testing.

Photographs of the cores as-received and of the reconstructed portions of broken cores should be taken, if necessary using a series of overlapping views, using a reflex camera at a constant distance with the same lighting. The logged cores are photographed with a scale bar to display any reacted particles, visible reaction products, distribution and gradation of coarse aggregate, as well as discoloration of cement paste along any cracks, cold joints and/or areas of honeycombing, and the location of any embedded steel. Any embedded steel found must be reported to the engineer as soon as possible.

Information about the cores should be stored in the project file, including the location and name of the structure from which the cores were taken, date of construction (if known), name of the supplier, and any tests already or to be performed on the samples. A preliminary allocation of parts of cores for different tests can be made at this stage. Full petrographic testing is usually only carried out on selected sub-samples of material from the cores.

4.5.2 First Visual Description of Cores

As a first step to diagnosing alkali-aggregate reaction in the laboratory, visual examination should be made of core samples. Visual examination is the first step not only for gathering information about the AAR damage features, but it is also used to guide in the selecting of specimens for more detailed examination. The following are of primary importance during visual examination of the cores:

a. Aggregate

The types of coarse aggregate should be identified, including whether it is polymictic gravel or monomictic crushed stone, or a mix of either of these. Maximum size and the size range of the aggregate, e.g. 5-20 mm, should be determined. Where possible, the maximum size and grading, plus the presence of any segregation or preferred orientation should also be recorded for fine aggregate, along with distinction between natural sand, manufactured sand (crushed rock or crushedslag) or a blended material.

Many large structures were constructed using ready-mix concrete and/or precast units from a variety of sources. Classifying the aggregates into ‘reactive’ ‘slightly reactive’ and ‘non-reactive’ types and relating this to their distribution on the structure is important. Site comparisons of slices of cores from the laboratory with surface ground areas on different pours enables the aggregate type distribution of a structure to be mapped during later more detailed investigations.

b. Pop-outs

If aggregate is very active, a pop-out may occur within one week after sampling around a reacting particle on the cylindrical core surface, which is a result of liberation of strain caused by expansive AAR gel that had accumulated around the particle. In this case, a flat-conical shaped concrete fragment, attached with a reacting particle on its top, can be removed from the host concrete. The close-up view of this fragment should be recorded either by a reflex camera or by a stereomicroscope, before subjected to thin-sectioning for polarizing microscopy and XRD analysis**.**

c. Matrix

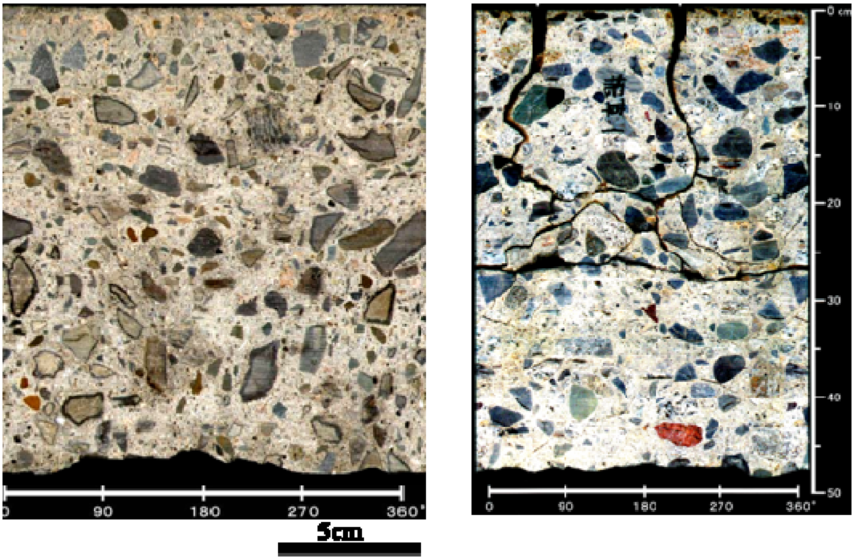
The colour of cement paste should be recorded, especially any gradation, mottling or abrupt changes in the sequence of core samples, which could suggest the secondary alteration of cement paste. The air-voids in concrete may be filled with AAR gel, other deposits or cement hydrates. It is advisable to assess whether concrete is likely to have been air-entrained (AE), containing more than 3% of air composed mainly of spherical voids. Well compacted non-AE concrete should contain less than 3% (normally 1 – 2%) of air-voids, mostly being irregular in shape.

When the preliminary examination is over, the core should be re-wetted and re-sealed by a wrapping film tightly and then stored overnight. On the next morning, 'sweaty patches' looking dark may be found on the core surfaces around any reacted aggregate particles, which is suggestive of on-going AAR in concrete. It is desirable to select these active portions of AAR for the preparation of polished thin-sections and other specimens for further study, including polarizing microscopy, XRD analysis, SEM observation and EPMA analysis.

4.5.3 Photography and Core-Scanning

Any visible sites of alkali-aggregate reaction found on the concrete surface (cracks, reaction rims, pop-outs, exudations of gelatinous gel and deposits) should be recorded at low magnifications (up to about 5 times), using a reflex camera attached with a suitable macrolens or a digital camera with a macrofocusing capacity.

Before cutting the core, the texture of its cylindrical surface may be recorded by the core-scanner (slit camera, or panorama camera), if available. This type of camera takes a photograph of the continuous outer surface (360 degrees) of the core, either on film or as digital electronic data [45]. This has merit for petrographic examination, because, when a small core (say, 50 mm diameter x 100 mm long) is taken, the core-scanner provides wide area of the concrete surface (150 mm x 100 mm), as large as three times that of the narrow longitudinal section (50 mm x 100 mm) of the same core, which can be used for the point-counting of constituents. Core-scanning is useful in characterizing internal macrocrack patterns in concrete, see Figure 16.



a: reaction rims of andesite.

b: crack propagation from concrete surface.

Fig. 16 Example of core-scanning of concrete affected by ASR

Core-scanning is suitable for depicting the macroscopic textures in concrete, such as:

- cracking possibly caused by AAR, which is widening toward the concrete surface;
- ‘sub-parallel’ cracking developing parallel to the surface usually close to the plane of the reinforcement which is a precursor of structural delamination.
- distribution of rimmed aggregate particles, gel pockets and gel exudations that occurred before or after coring;
- indication of carbonated area as shown by spraying a phenolphthalein solution;
- defects attributable to poor workmanship and abnormal workability of fresh concrete during casting, e.g. honeycombing, cold joints, segregation and preferred orientation of coarse aggregate;
- lamination of concrete caused by frost attack and repeated fatigue;
- opened interface between any repairing material and underlying concrete, perhaps induced by AAR or the corrosion of embedded steel bars.

4.5.4 Visual Examination and Stereomicroscopy Aid

Visual examination aided with stereomicroscopy is one of the first steps of diagnosis of concrete deterioration caused by AAR. Stereomicroscopy is usually a cursory method, which is used to aid visual examination of the samples. A stereomicroscope, by virtue of its name, is a microscope with a low resolution (typically magnification up to about 60 times) that is capable of magnification while still providing a 3-dimensional view of the sample. Usually, it is used to examine areas of the samples that may be of interest for subsequent examination by means of polarising and fluorescent microscopy (PFM) or scanning electron microscopy (SEM). For examples, see Figure 17.

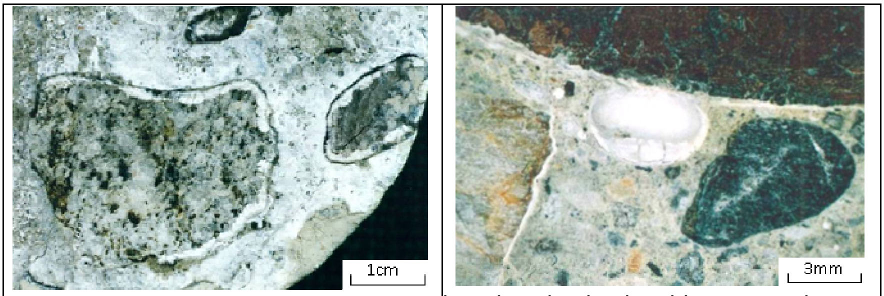
Of particular importance here are:

- the pattern of cracking and location, that is, at the surface, around or through aggregate particles, associated gel exudations (material filling the cracks), width and depth;
- presence of any gel in pores, cracks, around aggregate particles, or exuding from the core;
- damp or 'sweaty' patches on the concrete surface; reaction rims around aggregate particles, but these are only found with certain aggregate types.

During examination of the samples and treated specimens with the aid of stereomicroscopy, special attention should be given to the following aspects and features:

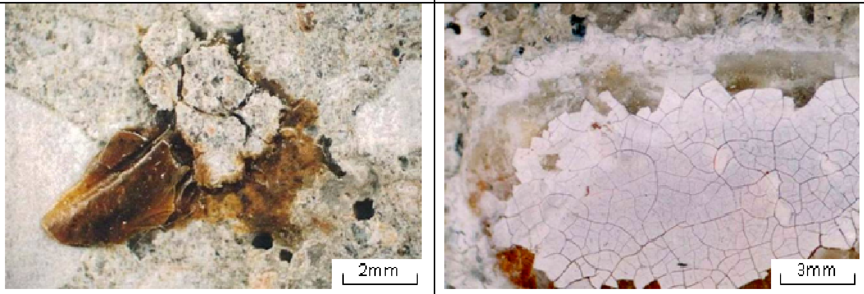
a. Aggregate

When the core has been kept damp prior to examination, by wrapping with a protective film, exudation of wet AAR sol may be found as darkening around reacting aggregate particles on the core surface. Where concrete exhibits cracks that transect aggregate particles, it is essential to check if there are any reaction rims (dark outer and white inner rims), exudations of AAR gel or carbonation products on the reacted aggregate. It is also necessary to check whether or not the aggregate particle is gelatinised and bound well with the cement paste. Some aggregate particles from gravel have a weathering rim before introduction into concrete. However, the formation of a rim on crushed stone in concrete can indicate that alkali-aggregate reaction has taken place.



a: reaction rims on gneiss.

b: gel pocket in air void on reacted mudstone.



c: pop-out formation with gel-exudation after coring.

d: ASR gel on the fracture surface of reacted chert.

Fig. 17 Close-up photographs through macro lens and binocular microscope. Fracture surface (a), (d), and core surface of concrete (b), (c), affected by ASR. ASR gel is generally conspicuous on the fracture surface.

In concrete where carbonate aggregate exhibits some rim features, it is essential to check the nature of this rim on the sawn surface, to assess whether or not it is caused by reaction. Some classical literature on carbonate rock reactions recommends etching of carbonate aggregate particles in concrete with hydrochloric acid to discriminate the rim (positive, neutral or negative relief), but this is a destructive method and hence not recommended at this stage. For the carbonate aggregate, combined tests of SEM observation, element mapping and EPMA analysis of reaction products (sections 4.7.1 and 4.7.2) is recommended using polished thin-section. The presence of reaction rims in the dolomitic aggregates indicates that ASR gel may be difficult to detect and detailed examinations may be required.

b. Cement paste

Random-oriented cracks develop in the cement paste in concrete affected by AAR, interconnecting reacted aggregate particles. The freshly broken surface of concrete exposes ASR gel that was filling cracks. In sound concrete, freshly exposed cement paste has a greyish lustre due to CSH gel and integral moisture. In contrast, poor-quality concrete, which has suffered early frost damage or was made using higher water/cement ratios, typically presents a less vitreous, light chalky appearance owing to carbonation of cement paste around abundant voids. In concrete made with blastfurnace slag cement, freshly exposed cement paste has a characteristic dark greenish-grey colour, which turns to grey after exposure to the atmosphere.

Where dolomitic aggregate is present, any discoloured carbonate halo in the cement paste adjoining reacted dolomitic aggregate particles should be examined, because this may be suggestive of dedolomitization. ASR has been known to be associated in this rim-forming dolomitic aggregate in concrete, represented by the Canadian Pittsburg aggregate [23], but it is not possible to identify the nature of the carbonate rock reactions only by the visual examinations. Careful examination should be made to avoid confusion with secondary deposition of either calcite or portlandite at the interface between the coarse aggregate and the cement paste.

c. Cracking

Cracks in concrete are formed by excessive expansion, contraction, strains and fatigues. Cracking caused by AAR in concrete is often intermixed with cracks from various deteriorating factors. Examples can be drying shrinkage of the concrete surface, local cracking induced by shrinking/expanding aggregate, lamination of surface concrete due to frost action, fragmentation due to cumulated fatigue, expansion cracks and disintegration due to sulphate attack, cracking resulting from corrosion of steel bars, and penetrating cracks due to thermal stress. Some of the cracks found in the concrete specimens may be an artefact of coring and cutting.

When alkali-silica reaction occurs in concrete, the interior of concrete expands more than the outer surface of the concrete structure, resulting in the formation of large tension cracks perpendicular to the exposed surface. Therefore, if some of the cracks in the concrete section are filled with ASR gel, and the internal cracks system is typical of that of ASR, then AAR is thought to be a probable cause of the deterioration at this preliminary stage of investigation. Some forms of AAR (e.g. UK cherts in fine aggregate in South West England) produce expansion and cracking of aggregate particles extending out into the concrete, but with little apparent gel even when severe cracking occurs.

d. Voids

A wide variety of pore structures occurs in the hardened cement paste of concrete, among which stereomicroscopic examination concerns only the air-voids (entrained and entrapped air). The petrographer should confirm the abundance of any ASR gel in concrete, including whether that ASR gel fills voids forming gel-pockets, or lines the inner walls of voids, or is apparently absent in these voids whereas reaction rims are visible around aggregate particles.

Also, recording the presence of hydrates (tufts, tablets and granular precipitations) along with their colour (milky white or colourless) is useful preliminary examination of AAR-affected concrete. It is advisable to check whether the hardened concrete is air-entrained (AE) or not (non-AE), paying attention to the total volume, size and shape of voids (irregular, spherical, ellipsoidal or meniscus). The occurrence of flocculated bubbles near formed concrete surfaces, sheets of voids under coarse aggregate particles, and bleeding channels skirting the coarse aggregate, can suggest unusual workability of concrete during casting and vibration.

e. Sawn or polished surfaces

On the sawn or polished surfaces of concrete, it is important to record the size, shape and lithological type of any aggregate that has associated reaction rims and/or ASR sol or gel. Impregnating the concrete section with an epoxy resin containing a fluorescent dye can enhance visualisation of the crack pattern. When the surfaces are adequately polished, they can be readily examined using the unaided eye or low-power optical microscopes, under an ultraviolet (UV) light system. Under UV illumination, the dye mixed with the epoxy resin fluoresces and highlights crack patterns and reaction products in the cracks.

Other features that can be examined or identified on the polished slab are:

- crack patterns and fillings;
- internal cracking of aggregates and cracking of cement paste;
- presence of any ASR-gel in relation to cracking;
- any poor quality of the cement paste: weak, fractured, poorly bonded to particles
- any other irregularities in the concrete.

If necessary (e.g. to show that the air-void system is consistent with the requirements for frost resistant concrete), point counting or linear traverse under the stereomicroscope (using e.g. the method given in [47]), applied to the polished slab of concrete section with sufficiently large areas (preferably > 75 x 100 mm), reveals the bulk proportions of coarse aggregate, fine aggregate, cement paste and air-voids (air content).

As AAR microcracking develops concrete becomes increasingly vulnerable to frost damage. There are indications that gels can fill the air-voids, so they become ineffective. This should be checked in petrographic examination.

4.5.5 Selection of Specimens for Further Testing

Concretes undergoing alkali-aggregate reaction are often badly cracked and fragile, like those suffering from freezing and thawing, steel corrosion and sulphate attack, and may disintegrate during cutting or coring in a small size. In this case, before cutting, core samples should be reinforced by epoxy resin or plaster filled within a framework, or hardened either by vacuum impregnation with resin or by immersing more permeable samples in cyanoacrylate. Such cores should be dried at temperatures below 50^{o}C by slow heating, or in the vacuum at ambient temperature in advance using a cold trap. It should be noted that overheating during preparation can produce various misleading artefacts, such as map-cracking within the cement paste and ASR gels, thermally-induced cracks and openings along cement-aggregate boundaries, and alteration of the optical properties of cement hydrates, particularly ettringite (elongation and refractive index).

Prior to the selection of the specimens, special attention should be given to the fracture surfaces. In most cases, the development of cracks in concrete structures can be viewed as a multiple initiation site failure mode [48]. The fracture path in a specimen failing in tension attains a maximum width on the concrete surface. Propagation of cracks through the cement paste and around or through aggregate particles provides some measure of the strength of the paste-aggregate interface. The nature of any reaction products inside the aggregate and at the aggregate-paste interface helps to identify the cause.

The specimens that are required for preparing polished and thin-sections should be selected from areas where the features of the AAR damage are more pronounced. These features can easily be identified with the aid of a hand lens or stereomicroscope. On the fractured surface of the cores, for example, the reacted aggregate particles are often cracked or fractured, some with remnants of AAR-gel filling the cracks in the particle and streaming into the adjoining cement paste or at the interface of the particle (see Figure 16). AAR-gel can also fill voids and cracks in the cement paste and exuded gels can often easily be identified with the aid of the stereomicroscope (see Figure 17).

An example of the documentation of selected areas for further testing is given in Table 4.

Table 4 Example table of documentation – Areas of cores where specimens were removed for preparing polished or thin-sections

Sample code	Location in structure*	Characteristics of damage possibly caused by AAR
1A	Inner lane right deck	Top portion of core over two cracked coarse aggregate particles, each containing colourless to white exudations, possibly ASR-gel
2B	Outer lane left deck	Middle portion of core over a large void (at the interface of a cracked coarse aggregate particle) filled with white exudation, possibly AAR-gel
3C	Abutment North side	Across two large cracks at the bottom portion of the core completely filled with a gel-like material
4D	Abutment Southside	Central portion of core over a cracked coarse aggregate particle, containing colourless to white exudations, possibly AAR-gel

*The structure concerned in this case is a viaduct with a dual carriageway. The field inspection was performed on the entire structure. Cores were drilled from the deck, from the abutment and from columns.

4.5.6 Cutting and Grinding

In the laboratory, concrete cores should be cut by a diamond saw in a direction, either normal to the main crack or the structure surface, or parallel to the direction of emplacement of concrete. Cutting with oil is recommended, but if wet chemical analysis is additionally planned to determine the content of chloride and alkali ions, dry cutting is necessary using coolant air. Where a multiple examination is planned using the same core, the design of cutting depends on the intentions.

If the core is to be used only for visual or stereomicroscopic examination, water can be used for cutting and grinding as a lubricant and cooling medium. However, if detailed examinations are planned thereafter, oil should be used instead of water. This is because water reacts with unhydrated cement particles and dissolves some part of cement hydrates, AAR gel and efflorescence materials (mainly Na, K, Ca, S and Cl), which can lead to spurious observations in the microscopical examinations and chemical analyses of concrete. However, oil is viscous and specimens need sufficient cleaning using an ultrasonic vibrator to remove abrasive powders and dusts that fill voids in concrete.

If several kinds of testing are to be made within one core, including thin-section microscopy, wet chemical analysis for chloride and alkali ions, and large-area element mapping by EPMA, the core should be cut longitudinally into three pieces without using oil. Then, the central slab is ground and polished for mapping, and a half-cylindrical portion (left side) of the cores is selected to include a reacting coarse aggregate particle for thin-sectioning, SEM observation and XRD analysis, while the other half-cylinder (right side) is further cut into five or more 20 mm long slices, ranging from the surface to the depth of the structure, for chemical analysis.

4.6 Petrographic Examination

4.6.1 Introduction

For the detailed petrographic examination of concrete, polarizing microscopy coupled with reflectance microscopy is recommended. Reflectance microscopy on the polished thin-section is suitable to identify objects that are smaller than the thickness of the thin-section and opaque substances. This gives a sharp image with clear-cut grain boundaries within fine textures (even up to 1000× in a dry system), including details of cement clinker phases (alite, belite, aluminate, ferrite, periclase, etc.) and their partial hydration processes; corrosion textures of reacted minerals and/or reaction rims on the aggregate periphery formed through AAR; and opaque minerals in the aggregate (pyrite, pyrrhotite, magnetite, hematite, ilmenite, goethite, etc.); all of which can be readily distinguished based on their colourand reflectance. Reflecting microscopy is necessary to check the surface roughness in selecting the target area for EPMA analysis (see section 4.7.2).

Thin-sections should be prepared from various positions on the cores, where there is apparent evidence of AAR (see Table 4), including, where possible, the surface. To be able to identify the various components in the thin-sections and adequately characterise the microstructure, especially the effects of any AAR, the petrographic examination should be performed using polarising and fluorescent microscopy. This is a two-fold method, which is based on examination of thin-sections using polarised-light microscopy and fluorescent light microscopy [1, 6, 38]. By means of transmitted light microscopy with magnifications up to 400 times, the various components of concrete and any damage caused by AAR can be established.

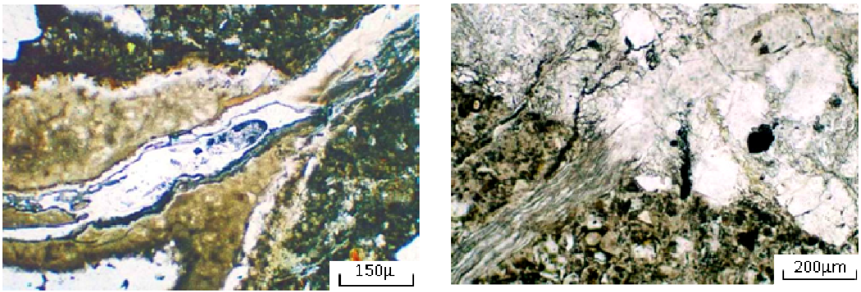
If thin sections are also to be examined using SEM and EPMA it is necessary to prepare polished thin-sections with a mirror-surface, finished by the diamond paste (grain size 1-2 μm) without mounting a cover glass. Thus they can be used first for observations under the polarizing/reflecting microscope, before subjected to SEM and EPMA analysis. Common thin sections with a cover glass may be finished by grinding with coarser abrasives (up to #3000, or 6μm). Polished thin sections without a cover glass should be stored in a vacuum desiccator to avoid secondary hydration and carbonation of cement particles exposed on to the surface.

Using polarising and fluorescence microscopy, the following information may be obtained from the thin-section analysis:

- types of aggregates used to prepare the concrete, their distribution in the concrete (better seen in large thin-sections: 150 mm x 100 mm), and any that have possibly been affected by AAR;
- type of cement used, degree of hydration, concentration of calcium hydroxide in the cement paste and homogeneity of the cement paste;
- general characterisation of any microcracking, including intensity, size range of cracks, apparent association with a particular aggregate type, cracking in and around aggregate particles, the nature of the aggregate-paste interface and the presence of any ASR-gel or other deposits in cracks;
- presence of any ASR-gel streaming from reacted particles into adjoining cement paste and in voids (see Figure 18 and Figure 19), including other deposits such as ettringite in voids;
- degree of the cement paste-aggregate bond;
- any other irregularities.

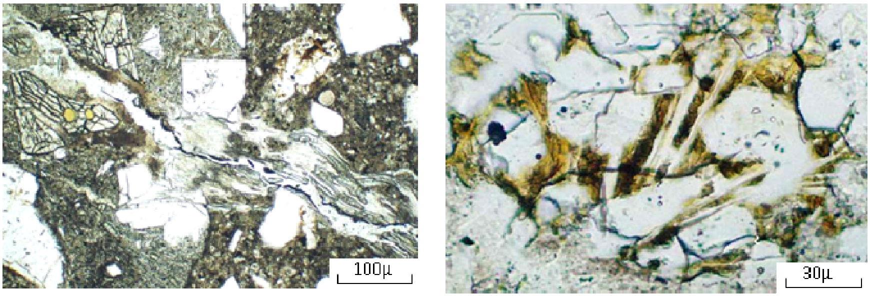
The thin-sections used are usually prepared by first sawing portions of the samples that are of interest to the analysis. The sawn specimens are vacuum-dried and impregnated under vacuum at normal temperatures with an epoxy resin containing, where deemed appropriate, a fluorescent dye.

The most popular dye has a strong yellowish colour, which on excitation by an ultra violet light presents a greenish fluorescence (wave length 530 nm). Younger laboratory concretes rich in capillary pores tend to present uniform fluorescence, resulting in little difference between cracked and uncracked areas. The strong colour of the dye may hinder details of the optical property of minerals and gel in concrete under the polarizing microscope. It should be noted that fluorescence readily fades at the area on which ultraviolet light is focused, so that photographs in low magnifications should be taken first. Ultraviolet light is hazardous to the naked eyes and protection is required.



a: reacted flint.

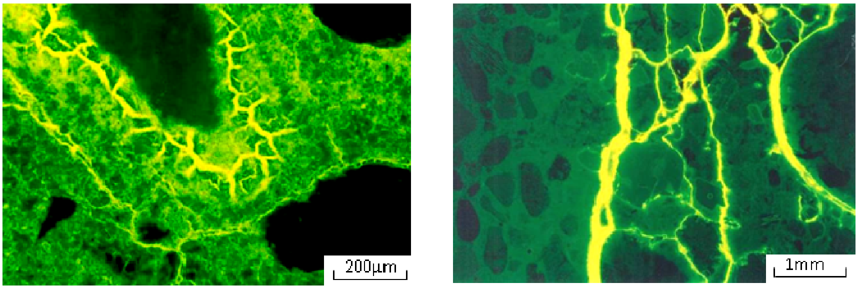
b: reacted sandstone.



c:reacted andesite.

d: alkali-aluminate in a cement particle.

Fig. 18 Polarizing microscopy. Thin sections of concrete showing ASR gel (a), (b), (c), streaming from a reacted aggregate particle into adjoining cement paste and inducing cracks, partially filled with ASR gel. Elongated crystals of alkali-aluminate in unhydrated cement particle in concrete affected by ASR (d).



a: reaction rim of flint with desiccated ASR gel.

b: delamination cracks due to freezing and thawing.

Fig. 19 Fluorescent microscopy. Thin sections of concrete as viewed under UV light in (a) transmitted light and in (b) reflected light. Fluorescent dye is impregnated within cracks and capillary pores in concrete.

Impregnation of the specimens with a fluorescent resin makes it easier to study crack distribution and aspects of micro-porosity in old field concretes. Thin-section observations under ultraviolet light are used effectively in characterizing delamination of freeze/thaw damage, developed parallel to the concrete surface. Furthermore, information can be obtained regarding microstructural aspects like changes in the capillary porosity of the cement paste, content of air-voids and their fillings, depth of carbonation and other changes in the microstructure of the cement paste arising from other chemical deterioration of the concrete.

After hardening, the required thin-sections of about 20-25 μm thickness are prepared from the specimens. Traditionally, geological thin-sections are 30 μm in thickness; however, if possible, it is useful to make the polished thin-section thinner (say, thickness 20 μm or less), with a mirror-surface finished with the diamond paste without mounting a cover glass. This is because the average size of cement and fly ash particles before hydration is 6 μm and 15 μm, respectively, and that of the granulated blast-furnace slag and of the interstitial phases of cement clinker is far smaller. In transmitted light, thick sections (> 25 μm) make it more difficult to see every detail of these constituents in concrete, along with fine textures of carbonated cement paste dominate by calcite, and are therefore less suitable for detailed petrographic examination of concrete.

Detailed aspects of the polarizing/reflecting microscopy will be described hereafter.

4.6.2 Detailed Aspects from Optical Microscopy

a. Aggregates

Coarse Aggregate
In the early stages of some types of AAR, reaction rims may appear around reacting aggregate particles. However, it is generally difficult to distinguish this petrographically from a reaction rim that may have been caused by a pozzolanic reaction under a low alkali condition in concrete. Reaction rims are usually distinct to the unaided eye on the fracture surfaces of concrete, but, paradoxically, may not be visible when observed in thin-section in the transmitting light. In this case, examination of the polished thin-section under reflected light can provide details of the rim-forming texture.

Since concrete has a very coarse-grained texture, broadly analogous to a natural conglomerate or breccia, the volumetric ratio of each rock type that constitutes the coarse aggregate in concrete cannot be determined by the thin-section petrography. This can be achieved by the point-counting of wider areas of the cylindrical outer surface of a core sample, which is obtainable either by the manual tracing, or by core scanning with the panorama camera (see section 4.5.3).

Petrographic examination of concrete thin-sections under the polarizing microscope is particularly useful for identifying the rock type(s) of the aggregate particles, especially those that have actually reacted to crack and produce ASR gel, or have shown another type of unsound behaviour in concrete. It is also important to determine whether potentially reactive minerals (such as opal, chalcedony, cristobalite, tridymite, cryptocrystalline quartz, microcrystalline quartz and rhyolitic glass) are contained or reacting within the damaged concrete. A highly reactive constituent can have a marked pessimum behaviour, which may cause locally excessive expansion when they are contained in a small proportion in concrete.

Where the coarse aggregate is a carbonate rock, particularly dolomitic in composition, it is important to investigate whether there is a combined presence of a reaction rim within the dolomitic aggregate and a carbonate halo within the surrounding cement paste. This provides evidence of a carbonate rock reaction, but not necessarily proof of deleterious expansion. Some literature recommends etching with hydrochloric acid to characterize the rim on the polished sample, but this is not recommended here since it destroys the concrete texture as well as the reaction products contained in it. To confirm the nature of the rim formation on the carbonate aggregate, a combined study of SEM observation and element mapping by EPMA is recommended using the polished thin-section.

Fine Aggregate

Point-counting can be made using thin-sections to establish the volumetric composition of individual rock and mineral types comprising the fine aggregate in concrete. In some cases, only the fine aggregate may be responsible for any AAR, while the coarse aggregate is non-reactive (e.g. a chert-bearing sand or a volcanic rock-bearing sand with a pure limestone coarse aggregate). It is necessary to compare whether any reacted rock types were the same as those of the coarse aggregate, as well as to check whether any reactive silica minerals are contained possibly in a pessimum proportion (for example, perhaps only a few percent for opal, or less than 10 % for cristobalite and tridymite) that may cause an excessive expansion of concrete.

Other deleterious minerals that can cause unsound effects in concrete include smectite, laumontite, iron-bearing brucite, and pyrite. Likewise, some artificial compounds can behave deleteriously in concrete, for example when contaminated by periclase, free lime, anhydrite**,** and Ca-hauyne ($3CaO.3Al_2O_3.CaSO_4$) that comprises an expansive cement (see reference [42])**.** All these deleterious materials can produce pop-outs on the concrete surface, and should be distinguished from any pop-outs caused by AAR associated with highly reactive opal or hydrated glass.

b. Cement paste

Clinker

Concrete petrography should be able to identify cement clinker phases in the hardened concrete and interprete information based on the knowledge of cement chemistry. The unhydrated phases alite, belite, aluminates, ferrite, lime and periclase constituting the Portland cement, can be identified in the polished thin-section variously under the transmitted and reflected lights. The presence of alkali-aluminate is suggestive of a high-alkali cement being used in concrete, and the abundant presence of periclase can be a cause of delayed expansion of concrete.

The rate of hydration of these constituents is, lime (CaO) > aluminate (C_3A with varying amounts of alkalis) > alite (C_3S) > belite (C_2S) > ferrite (C_4AF with varying Al/Fe ratios) > periclase (MgO), but free lime is seldom found in the hardened concrete because of its rapid hydration.

In high-alkali cement, aluminate occurs as elongated, optically anisotropic alkali-aluminate, which is often a characteristic feature of AAR-affected concretes. This aspect can be ascertained by EPMA analysis (see section 4.7.2) of each unhydrated clinker phase found in the hardened concrete [45]. In the past decade, alkali-aluminate has been identified worldwide from ASR-affected structures: UK (e.g. Plympton Hill Bridge), USA (e.g. Stewart Mountain Dam), Australia (e.g. Princess Highway Bridge) [49], eastern Canada (many bridges and dams: Ontario, Quebec, New Brunswick and Newfoundland), Turkey (bridges) [51] and Japan (many structures) [50].

Cement Hydrates

Under the polarizing microscope, portlandite, ettringite, monosulfate, and occasionally hydrated calcium aluminate (hydrocalumite and mono carboaluminate) can sometimes be seen in the air-voids of the cement paste. Portlandite ($Ca(OH)_2$) is a typical product of cement hydration, often surrounding the aggregate and cement grains. The nature and abundance of portlandite in concrete depends on several factors, including the cement type (normal Portland, blastfurnace slag, fly ash, etc.), water-cement ratio, and the degrees of carbonation, leaching and exposure to frost action. Ettringite formed during normal hydration of Portland cement is not apparent to optical microscopy. Any secondary ettringite usually occurs as fibrous crystals filling cracks and air-voids but can also be massive (the individual crystals may not easily be distinguished using an ordinary optical microscope), while monosulfate and hydrated calcium aluminate often comprise rosette-like aggregations formed after precursor ettringite in the air-voids. In addition, secondary ettringite may be concentrated in the air-voids just on the outer side of the carbonate front, as a result of migration of sulphate ions through carbonation of the cement paste. Heating during preparation may alter the optical property of ettringite (elongation and refractive index) perceptible in the polarizing microscopy.

Mineral Admixtures

These are sometimes used for replacing a substantial part of the Portland cement. They can have some useful effects, such as improving strength of concrete and/or water-tightness, reducing or retarding the heat of hydration, and increasing durability against AAR or seawater. Ground granulated blastfurnace slag, fly ash, silica fume, limestone powder, volcanic ash and calcined shale have been variously used as a hydraulic pozzolana or a supplementary cementing material in a blended cement. In mass concrete, blastfurnace slag and fly ash are often used as a partial replacement (30-50%) for Portland cement, to decrease heat of hydration thereby avoiding thermal cracking, but act as a secondary effect also as a preventive measure against AAR. (Although, some types of fly ash may not prevent AAR due to their high alkali content.) Ground granulated blastfurnace slag is visible in thin-sections as angular glassy shards (colourless, isotropic, refractive index between quartz and alite), often surrounded by one or more hydration rims. Fly ash includes distinctive spherical particles, ranging from large transparent hollow glass particles ('cenospheres') to small coloured solid glassy (sometimes opaque) grains, or, more rarely, as irregular-shaped carbonaceous matter (unburnt coal).

c. Cracks

General

It is important to record the distribution, width and pattern of cracks, and their relationship to any reacting aggregate particles and the core axis relative to structural stress field. With some aggregate types, if little or no gel is found in thin sections, AAR may be unlikely as a primary cause of the cracking of concrete provided that the thin sections are reliably representative of any potentially affected areas. However, the abundance of gel varies with different reactive systems encountered around the world. UK cases with chert often show very little dispersed gel even with very severe expansions (> 2.5 mm/m). It is also common for samples to be examined that do not include the most affected material, near-surface samples for example. Sampling and preparation of samples is of utmost importance, therefore, the abundance and the location of crack-filling materials, such as ASR gel, ettringite, monosulfate, portlandite and calcite, should also be noted.

If a fluorescence microscope (UV light) is available, impregnation by resin containing a fluorescent dye may be helpful in detecting cracks and void structures in concrete, that is:

- open cracks and air-voids in the cement paste;
- lining of hydrates within cracks and interstices between the aggregate and cement paste;
- capillary pores in the cement paste and gelatinised interior of reacted aggregate particles;
- orientation of microcracking relative to restraint and stress fields.

But the dye colour can obscure the details of mineralogical information and may interfere with normal observation under the polarizing microscope, when the same thin-section is used.

AAR Cracks

In concrete where AAR has induced expansion, fine cracks may radiate from reacting particles with or without reaction rims into the surrounding cement paste. Such incipient cracks are not evident in the visual inspection of field concrete. The rate of cracking varies widely within the structure and within a core, depending on the availability of water and variability of reactive aggregate concentrations and local alkali content. Even if the structure was built using the same concrete mix its composition will vary significantly between pours and within pours due to segregation [46].

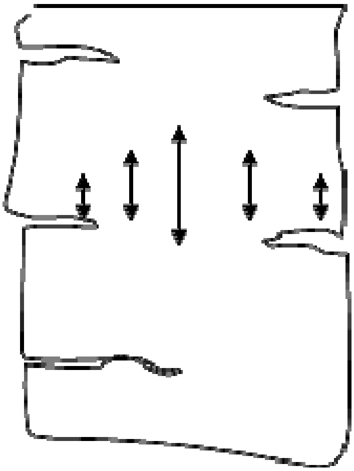


Fig. 20 Crack widths over the thickness of a concrete member. Arrows denote the expansion of the concrete: largest in the interior, smaller between cracks and smallest near the surface (B. Godart).

When AAR becomes active, expansion cracks propagate, and in severe cases they interconnect the reacting particles in a random network, some of which widen toward the concrete surface, see Figure 20, but their directions may be oriented by the internal stress caused by the compressive stresses and reinforcing steel bars in the concrete. Where the reactivity of aggregate is relatively high (containing opal, chalcedony, cristobalite and hydrated rhyolitic glass), cracks may be filled with abundant ASR gel, and the soaking of ASR gel often darkens the bordering cement paste.

Cracks may pass through unreacted aggregate particles, but usually skirt them. In older structures the field appearance of concrete damage, can become conspicuous, including the development of wide crack widths, exudations and any displacements. In such concrete, both cement paste and ASR gel near the cracks are likely to be more or less carbonated, and precipitation of calcium carbonate (calcite) into open spaces can be seen, particularly where the weathering (frost action, and drying and wetting) have been combined with AAR for a long time. However,radial cracks around aggregate particles are not always evidence of expansion resulting from AAR, but may be an artefact of the thermal expansion of aggregate during preparation of the thin-sections (overheating).

Cracking around aggregate can be induced by delayed ettringite formation which occurs in some unsuitable accelerated expansion tests, where concrete core is soaked with water after drying at high temperature(> 100°C)and then stored in a moist room for a long period. It can also occur in precast and massive pours where high temperatures (> 65°C) developed after casting.

ASR Gel

Gel is mobile in the wet condition (actually, a sol) and it consolidates on drying, creating distinctive desiccation cracks on its surface. ASR gel can be found far from the reacting particles, having penetrated into air-voids and migrated along cracks, as well as in cracks that cut through unreacted aggregate particles.

The reaction product seen in thin section is gel, a drying product of sol that is mobile in concrete in a wet condition. A reversible sol/gel transformation by wetting and drying can be a force of expansion. Gel may occur as a layered composite, lining walls of cracks and air-voids, which suggests that the gel had migrated periodically into these open spaces in concrete. It is important to assess what degree and stage of the reaction is represented by the concrete under examination, for example, the ‘mild’ ‘moderate’ ‘severe’ and 'early', 'middle' or 'later' stages.

In the later stage, gel may become crystalline and birefringent, which can often be identified as a rosette-like aggregation of lamellar crystals under SEM observation. The quantity of ASR gel that had exuded from cracks on the concrete surface does not necessarily reflect the intensity of deleterious expansion. For instance, late-expansive ASR related to cryptocrystalline or microcrystalline quartz in some rock types (including some sandstones, siltstones, argillites, siliceous limestones, slates, phyllites, quartzites, meta-rhyolites, hornfels and sheared granites) typically does not produce abundant ASR gel, even though internal cracking of concrete is intense. However, in thin-section, gel can be identified in cracks and air-voids around reacted aggregate particles inside the concrete. ASR gel is also scarce in some deleteriously reactive carbonate rocks in which any expansion can be attributed to AAR (siliceous limestone and argillaceous dolostone).

4.7 Additional Tests

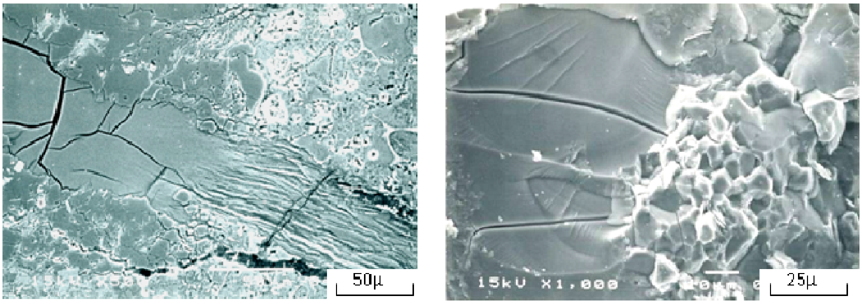
In addition to what might be considered as 'standard' tests to establish AAR damage to concrete in structures, there is a variety of tests that are intended to assist in the diagnostic process or to provide a measure of the extent of the reaction and its effect on the concrete properties [1, 2, 3, 6, 7, 48, 49]. It is recommended that these tests should not be used in isolation or in lieu of the petrographic analysis, but rather to supplement the primary tests and analyses or as part of the Assessment and Prognosis work covered in AAR-6.2.

4.7.1 SEM Observation

a. General

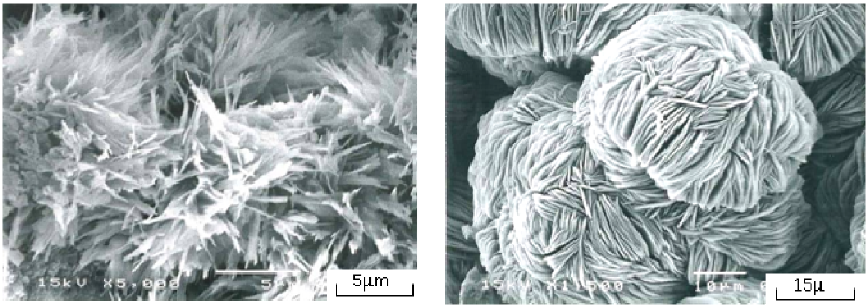
Scanning electron microscopy (SEM) nowadays is considered indispensable for detecting ASR gel and related products in concrete, see Figure 21, especially when thin section microscopy has difficulty identifying the presence of ASR gel. Such situations include:

- initial stages of AAR where only reaction rims are visible e.g. in concrete structures younger than 2 years, confirmation of incipient reactions is needed before a construction work can be made consecutively.
- scarcity of gel formation in cracks and around aggregate particles**,** while field and other laboratory evidence strongly suggests the occurrence of AAR**,** e.g. where reactive aggregate is quartzose, thin-sectioning process tends to loose fragile reaction products.
- compositional similarities between products of ASR and pozzolanic reaction, e.g. chemical and structural modification of reaction products may be expected, when pozzolanic materials used for the prevention of AAR may not have been effective.



a: ASR gel traversing aggregate into cement paste

b: amorphous ASR gel on reacted quartz in chert



c: foil-like ASR gel within air void

d: rosette-type ASR gel within reacted andesite

Fig. 21 SEM photomicrographs showing typical morphological types of ASR gel in concrete undergoing ASR. (a) polished thin section, (b), (c), (d) fracture surface.

b. On fracture surfaces

SEM observation is most commonly made on the fracture surfaces of concrete. Concrete portions including the areas of interest (reaction rims, exudations, gel-pockets, etc.) should be fractured into small pieces to prepare the test specimen (usually 10 x 10 x 5 mm), and then mounted on to a metal stage with conductive carbon tape.

In order to identify the target area, (colour) photographs of the test specimen should be taken up front, e.g. under the stereomicroscope (x10-30). Low-vacuum SEM can be used for observing materials without conducting coating treatment. Products of AAR are generally amorphous when they are young or mobile, but tend to become crystalline with age.AAR products include:

- massive-textured amorphous gel with desiccation cracks, which fill air-voids or interstices between reaction rims and cement paste;
- clusters of platy to foil-like crystals;
- rosette-like aggregations of lamellar to platy crystals, often found in the interior (open spaces formed inside the reaction rim) of the reacted aggregate particles in old concrete.

Cement hydrates and related substances can be identified clearly by SEM observation, particularly if aided by EPMA (EDS or WDS). Calcium-silicate-hydrate containing potassium or sodium (as an example CKSH) gel occurs in several morphologies, including:

- massive-textured amorphous gel composing a hydration rim;
- reticular aggregation of poorly crystalline gel;
- crystalline aggregation composed of foil-like crystals, facing the open space in concrete.

Other hydrates include:

- ettringite as tufts of hexagonal acicular crystals or rosette-like fillings of air-voids;
- monosulfate, hydrocalumite and monocarboaluminateas thin hexagonal plates or a card-house aggregation;
- Friedel's salt as small hexagonal plates;
- portlandite as large hexagonal tabular plates or thick composite layers;
- gypsum as thin rectangular plates;
- halite and sylvite as minute cubic grains.

Ground granulated blastfurnace slag particles may produce card-house aggregation of thin plates (containing Mg, Al, Si) within its hydration rim. Products of carbonation (calcite) and efflorescence are also identified. Details are referred to as "mapping of element", see section 4.7.2, with which distribution of elements in a concrete section is depicted using an EPMA.

c. On polished (thin) sections

SEM observation of a polished thin-section can only be done when no cover glass is present at the thin-section. Using SEM much higher magnifications (1000-5000) can be obtained, which is useful because:

- clear-cut boundaries can be obtained between the fine-grained reactive minerals and reaction products;
- ASR gel can be identified within minute cracks in concrete, even if it is only in a trace proportion.

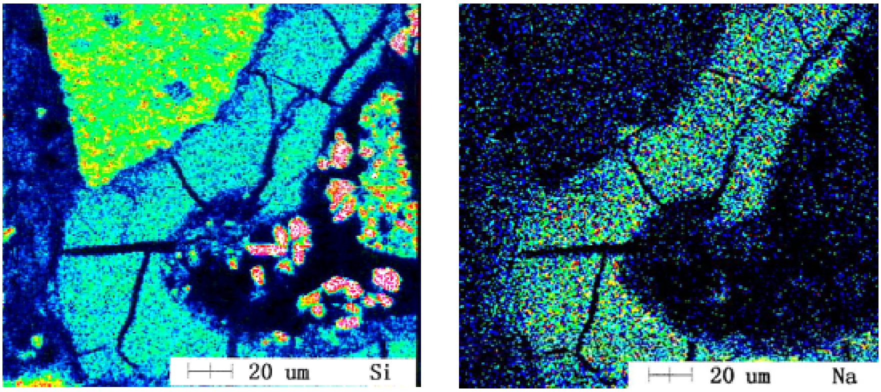
These details are usually not visible with transmitted optical microscopy.

4.7.2 EPMA Analysis

Often SEM's are also equipped with an electron-probe micro-analyser (EPMA), or similar system. Using such a system provides simultaneous observation of a sample with semi-quantitative chemical analysis. Hence, chemical analysis of ASR gel can be made on a very small portion (< 2 µm across), simultaneously observing its textural relationship in concrete. This option has great merit since all classical wet chemical analyses are based on the bulk sample and destructive.

The wavelength dispersive EPMA (WDS) is popular, but a well-adjusted energy-dispersive type (EDS) is also useful because the latter employs a weak electron beam current (1/100 that of WDS) and the damage to the sample is very small. Furthermore, EDS systems can analyse multiple elements simultaneously, while WDS systems generally can only cope with one or a few elements at a time. A well set-up WDS system can potentially detect smaller quantities than an EDS system. Polished (thin-) sections should always be used for the quantitative analysis [23].

It is an authentic procedure to use polished thin sections, as is in the usual EPMA analysis of rocks by geologists, to identify the target constituents under the polarizing/reflecting microscope before analysis is made. The fracture surface for common SEM observations can also be used for rough analysis, but this gives unreliable results characterised by an unbalanced ratio of elements, because some elements not present in the target but in the surrounding areas could be erroneously detected due to local topography of the fracture surfaces of the specimen. If we use polished slabs, instead of thin sections ignoring identification of the constituents in concrete, ambiguity is left with analytical results as to what portion of minerals and textures was analysed. This problem is important in the analysis of fine-grained interstitial glass in the volcanic aggregates.



a: Image of silicon within ASR gel in air void.

b: Image of sodium distribution within ASR gel.

Fig. 22 Mapping of elements by EPMA (EDS). Polished thin section showing distribution of principal elements of ASR gel in concrete affected by ASR.

a. Mapping of elements

The distribution of elements in the concrete section can be shown as a colour map by means of qualitative EPMA analysis, according to their concentration (Si, Al, Fe, Mg, Ca, Na, K, S, Cl, C, O, etc.), see Figure 22. This can have great merit compared with the destructive wet chemical analysis made of sliced core samples. Element mapping is very useful for identifying the composition of observed gels and also for evaluating the effects of carbonation, chloride attack and sulphate attack, as well as alkali-aggregate reaction.

Large-Area Mapping

An EPMA of the WDS type (wave-length dispersive spectroscopy), equipped with a large shifting stage, enables mapping of elements in a wide area of a concrete section. Some EPMA (EDS type) can accept large samples up to 200 mm across for mapping element distributions in the concrete section.

A polished slab for analysis should be prepared by cutting the core sample longitudinally (for example 70 x 80 x 7 mm) to include the outer surface of the concrete structure, then by grinding and polishing one side with lubricant oil. After removing the oil and abrasive powders by an ultrasonic vibrator, the polished slab is coated either with C or Au, depending on the elements of interest. It is most desirable to avoid impregnation of any material into concrete samples for which large-area mapping is planned, because the elements contained in the impregnated material present artefacts which interfere with or prevent meaningful analysis. For instance, epoxy resin is rich in C and O, and contains a varying amount of Cl. Therefore, if epoxy resin is used, then the air-voids and open spaces in concrete are filled with this resin, so that the C detected from these textures should not be mistaken as a sign of carbonation of concrete. Except for C, the effect of impregnation of the epoxy resin is generally small on this analysis.

The result of mapping may reveal the following aspects:

- movement of Ca, Na, K and Si ions resulting from AAR around the reaction rim of coarse aggregate;
- penetration of Cl, Na and K ions of de-icing salt or seawater into the concrete surface;
- secondary concentration of Cl and S ions associated with the moving carbonate front, located just inside the carbonated area;
- effectiveness of a sealant or repairing material used for blocking the ingress of Cl and S ions into concrete.

Confined Area Mapping

Element mapping should be performed on a small area using a polished thin-section under high magnification (up to 5000 times), after finishing the petrographic examination of the same thin-section. An EDS-type EPMA (energy-dispersive spectroscopy) is particularly suitable for identifying fine-grained materials of interest. Because EDS is capable of analysing multiple elements simultaneously under a weak electron beam current (1/100 of WDS), the damage to the delicate hydrous materials and flammable organic substances is kept relatively small. The thin-section for mapping and quantitative EPMA analysis should be prepared without use of a UV-hardening type of resin, because this resin is rich in S (contained up to 30%) and interferes with the analysis.

The following details can be clarified using this method:

- point of ASR gel formation on the reacted grain of silica ;
- chemical zoning within deposits of ASR gel that fills cracks and air-voids;
- point of dedolomitization of a carbonate aggregate particle adjacent to a carbonate halo;
- intimate precipitation of cement hydrates in the air-voids and interstices (e.g. ettringite, monosulfate, Friedel's salt and portlandite);
- hydration rims of blastfurnace slag and fly ash particles;
- differentiation of fine-grained interstitial clinker phases within unhydrated cement particles (eg glass, aluminate, ferrite and periclase);
- alteration of cement paste in the carbonate front (CSH gel, silica gel, calcite);
- impregnation of corrosion products into cracks of concrete;
- penetration paths of Cl ions into cement paste or organic sealants.

However, highly fragile or soluble efflorescence materials in concrete (such as halite, sylvite, thermonatrite and trona),which are often difficult to retain during thin sectioning, must be confirmed first by the mapping of a fracture surface of the test specimen prepared for SEM observation, preferably based on the EDS-type EPMA, then by the spot chemical analysis with the same equipment, although the ratio of the elements obtainable on this rough surface may not be correct.

b. Analysis of major constituents

ASR Gel

The composition of ASR gel varies widely in concrete, depending on its location relative to the cement paste and its stage of evolution (see Figure 22). Mobile or swelling ASR gel around reacting particles is a 'pure' alkali-silica gel, composed essentially of Na, K, Si and water, almost identical with a water glass. By contrast, old ASR gel that has long been in contact with the cement paste is hard and no longer expansive. Such ASR gel has taken up Ca and lost a part of Na and K (they do not loseall their Na and K) during migration along cracks from reacted particles into cement paste (and into air-voids), transforming chemically into CSH gel (Ca/Si around 1.2-1.3) or CKSH gel. A trend of transformation can be seen in references [50, 51]. Included rosettes of crystallized gel contain abundant Na, K and Si, but are no longer expansive. Obtaining a whole spectrum of the Ca/Si ratio and alkali content of any ASR gel in concrete is usually helpful in assessing whether the reaction is still in progress or nearly over, as well as the possibility of residual AAR expansion.

Cement Hydrates

CSH gel that forms a hydration rim of alite and belite in a sound concrete has a normal composition (Ca/Si ratio around 1.5-1.6), while this ratio decreases in the weathered area (if not carbonated), to 1.2-1.3. Where the cement paste is carbonated, CSH gel is altered into calcium carbonate and a silica gel (Ca/Si ratio of 0.1 or less). Both ASR and CSH gels in the non-carbonated area of the same concrete should be analysed, to check for any continuity or hiatus in the range of Ca/Si between these two gels, which will help to identify the stage of evolution of any ASR. EDS is also suitable for analysing the cement hydrates monosulfate, hydrocalumite, Friedel's salt and portlandite, but the vacuum employed during analysis may cause partial dehydration of more delicate ettringite resulting in a higher total than expected (say, up to 65%). Modern SEMs do not need a high vacuum, which reduces the dehydration rate. Thaumasite can be identified by the presence of C and Si, and should be examined using an EPMA (whatever EDS or WDS) capable of detecting lighter-elements including C and O, but its morphology and XRD patterns are very close to those of ettringite.

c. Determination of minimum amount of cement alkali

Quantitative EPMA analysis of unhydrated cement phases alite, belite, aluminates and ferrite in the hardened concrete, performed using polished thin sections, provides an estimation of the total alkali content in the original cement used, when the content of each phase is properly assumed. This is the minimum amount of total alkali in the original cement because this method omits water-soluble alkali sulphates, not preserved in the hardened concrete, resulting in an underestimation of possibly up to 20-30% (depending on the local conditions of the cement production which may also change with time).

This method has been developed in the past decade and may be of great use if the structure is old and construction records are absent. Applied to examples in Japan, this estimation almost invariably indicated that AAR-affected concrete structures, (construction: 1970's and 1980's) contained high-alkali cement, at least Na_2O equivalent 0.6-1.1%, and that aluminates found in such concretes were actually alkali-aluminates whose alkali occupied nearly a half of the total alkali in cement [45]. The method has also been applied to ASR-affected structures in Turkey (construction: 1980's and 1990's) [51] and Canada (Rapides-des-Quinze Dam; (construction: 1920's and 1940's) [52] and – with estimated minimum amounts of cement alkali Na_2O_{eq} of 0.7-1.0% and 0.8-1.0% respectively - has given similar results.

If concretes from different locations are to be examined, it is advisable to compare the abundance of minor elements in each cement phase (Mg, Na, K and S), because this may reflect the difference in the cement source and the raw materials used. Magnesium, preferably contained in alite and ferrite, can be derived from dolomite interlayers in the limestone. Alkalis Na and K, both concentrated in aluminates and belite, as well as occurring as alkali sulphate salts, typically derive from feldspar and illite in the clay-bearing component of cement clinker production. Sulphur in both belite and water-soluble alkali sulphates in the cement clinker, comes from pyrite in the clay and fuel coal.

The amount of Al and Fe in belite reflects the cooling rate of the cement clinker, and the ratio Al/Fe in both aluminates and ferrites suggests the type of cement, all of which serve to assess the original properties of cement.

4.7.3 Determination of Soluble Alkali Content

A more familiar method than the EPMA procedure to determine the minimum amount of cement alkali, is the analysis described in this section intended to determine the content of *soluble* alkali in a concrete possibly affected by AAR. It provides indication of the remaining active alkalis in the concrete and is therefore also relevant and informative for making a prognostic assessment. The alkali content of concrete in a structure, especially those exposed to harsh environments, is subject to considerable sample-to-sample variation. Accordingly, separate determinations should be made on a large number of samples taken at different depths from different positions that represent concrete exhibiting varying intensities of damage, that is, relatively best and worst cases and exposed to different environments [1].

The bulk wet-chemical analysis of the concrete cores, almost always overestimates the amount of alkalis of cement, because substantial amounts of alkalis obtainable in this method come from the aggregates contained or from some admixtures, even if the mildest water-extraction is employed. A correction method has not yet been established worldwide, because the alkali-release of aggregates (such as andesite, alkali-basalt, argillaceous sedimentary rocks, etc.) is regionally different.

Having said that, various methods are available for determining the soluble alkali content in concrete [53]. The amount of soluble alkali in concrete depends on the extraction method used, i.e. acid-soluble or water-soluble, hot or cold, etc. Which method is chosen depends on the circumstances (aggregate type, local experience, equipment, specific purpose of the investigation) of each country. The spatial variability of cement and alkali concentration in site concretes is substantial [46]. The initial composition is modified by migration and leaching. This needs to be considered both in the selection of samples and in presenting the results which should be of sufficient number to quantify the variability.

In most of the countries, a water-extraction is applied. In countries like Japan where main reactive aggregate is argillaceous rocks and alkali-bearing volcanic rocks and an estimation of the cement alkali amount is important, water-extraction is recommended, since acid-extraction (even HCl with 1/100 dilution) extracts considerable amounts of alkalis from illite, feldspars and feldspathoids. For instance, where andesitic aggregates and argillaceous rocks are common, even water-extraction of alkalis from concrete cores (40°C, water/concrete = 10, grain size < 0.3 mm, shaking 30 minutes) overestimates soluble alkalis from the cement. For example in an area where alkali-releasing argillaceous aggregate was used in Japan, wet-chemical analysis of concrete yielded water-soluble Na_2O_{eq} around 4.4 kg/m^3, while the total water-soluble alkali of the cement plus deicing salt, estimated by subtracting alkalis of the extracted coarse aggregate, was 3.2–3.5 kg/m^3, corresponding to 1.1-1.2% of the cement weight. If the amount of alkalis provided externally by deicing salt is to be estimated, the algorithm of calculating alkali budgets becomes even more complex [45]. Hence it is necessary to analyse dissolved alkalis of the separated aggregate particles to subtract their alkalis to estimate the amount of cement alkalis [45].

However, in other countries, a light acid-extraction is recommended, as in France where limestone aggregates and quartzite aggregates are the main reactive rock types, which are not particularly alkali-releasing, and where a light acid-extraction (HNO_3 with 1/50 dilution) is applied because this type of extraction is commonly used for the chemical analysis of concrete. The French experience shows that the difference between the alkali content measured by light acid-extraction and the one measured by water extraction is smaller than the scattering of the results obtained by several laboratories doing a water extraction during a round robin test. The choice between light acid or water extraction may also be guided by taking into consideration the duration of the period in which the release of alkalis is taking place in the structure, as well as the type of the reactive aggregate.

It must be cautioned that a high water-soluble alkali content does not necessarily imply that AAR has taken place or will take place in the structure under consideration. However, if this occurs in combination with potentially reactive aggregates in the concrete, this may indicate a potential for AAR, given conducive exposure conditions.

Engineers are sometimes asked by the owner of the structures to estimate the amount of cement alkalis (no records), or even to distinguish between the contributions of cement, aggregate and deicing salt, in order to confirm which of the three factors (cement, aggregate and environment) was the main cause for developing AAR in the structure. This information may also be needed when choosing the method of repair and its timing (see AAR-6.2).

4.7.4 Tests to Confirm Aggregate Reactivity

These tests are intended to rapidly evaluate the potential reactivity of the aggregate used in the concrete. They include [1]:

- residual expansion tests on concrete core samples;
- standard reactivity tests on aggregate materials retrieved from stockpiles, storage, the quarry used for construction, or even material extracted from cores from the structure [1, 54]; such tests include a petrographic analysis and the ultra-accelerated mortar-bar and concrete prism expansion tests (AAR-1, AAR-2 & AAR-4).

It must be cautioned that evidence of reactivity in such tests does not necessarily indicate that AAR has taken place or will take place in the structure under investigation, since the presence of reactive mineral components alone is not sufficient enough to cause AAR damage. On the other hand, aggregates extracted from the concrete may give less expansion than aggregates from the quarry used for construction.

4.7.5 Uranyl Acetate Test

The uranyl acetate test can be used as a screening test for ASR in core material or on site. The uranyl acetate (uranium) fluorescence method indirectly verifies the occurrence of AAR: The uranyl acetate solution when applied to a concrete surface containing gel, reacts with the gel, producing a fluorescing constituent visible in ultraviolet light.

However, some gels may not be detected and those that fluoresce by the uranyl solution are not always ASR gel, but may be a gel formed by hydration of cement, pozzolanic reaction or carbonation. Also it has to be remembered that ASR gel is water soluble and may have been washed away during coring. AAR should not be diagnosed solely by this method alone, therefore.

Uranyl acetate ($UO_2(C_2H_3O_2)_2.2H_2O$) is an internationally regulated substance, which is radioactive and hazardous to both human health and natural environment. Precautions should be taken for its storage, use and disposal. UV light will damage sight and protective glasses should be used. For further information on the method see [55].

4.7.6 Estimation of Cement Content

An estimation of the cement content is helpful for assessing the levels of alkali, sulphate and chloride. The cement content can be determined with reasonable accuracy by chemical analyses, especially if the type of the cement used is known. It may be necessary to analyse an aggregate sample, which can be extracted from concrete cores using the method given in [1]. Another method for extracting aggregates from hardened concrete is described in [54]. The estimation of the cement content is more difficult for concrete containing either blastfurnace slag or fly ash, if the origin of these substances is not known.

If the cement content and the alkali content of the cement are known and if the alkali contribution of any admixtures used is estimated, the original alkali content of the concrete mix can be established.

High cement contents often contribute to the development of AAR and also result in differential thermal cracking and shrinkage cracking and high creep deformations. In considering the range of factors leading to unusual deformations and /or cracking in a structure, a knowledge of cement content and w/c ratio is important. These will also give an indication of the likely original strength characteristics of the concrete.

5 Severity Investigation

5.1 Introduction

From the confirmation inspection and its subsequent test results the presence of AAR has either been confirmed or eliminated. Assuming the first outcome, the next step is to investigate the severity of the situation, see Figure 23. One should keep in mind that it is possible that some evidence of AAR may be found in concrete where siliceous material forms part or all of the aggregates, whether or not the concrete has cracked or expanded as a consequence of AAR. Concrete can have ‘sub-clinical’ AAR where isolated areas of reaction may be identified under the microscope, even where it has not caused significant expansion or cracking of the structure. Many concretes have very localised areas showing ASR gel and reactive particles which are not sufficient to produce significant cracking or damage to the structure. Diagnosis of this ‘Sub clinical AAR’ as “AAR” has frequently caused undue concern and overreaction by engineers and client organisations.

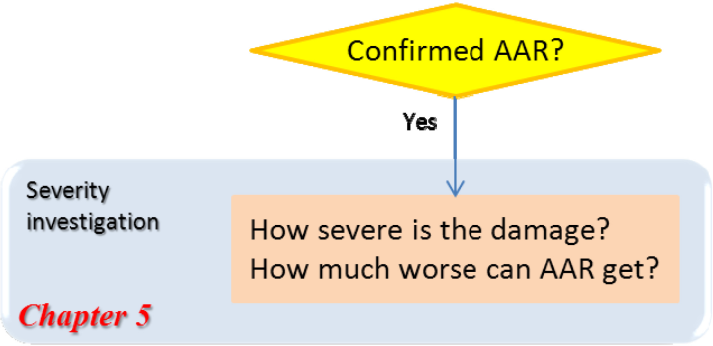


Fig. 23 It has been established that AAR is present, but how bad is it?

If significant AAR is diagnosed a more detailed search of archives for construction records will be justified. This should include discussions with those at all levels who worked on the original construction. Also, details of any other structures in the area known to be exhibiting signs of possible AAR can be very helpful.The engineer’s preliminary view on the potential sensitivity of structural elements to AAR, based on consideration of details shown on the reinforcement drawings, should be obtained before and during the site visit.

B. Godart et al. (Eds.): *Guide to Diagnosis & Appraisal of AAR Damage*, RILEM 12, pp. 65–78.
DOI: 10.1007/978-94-007-6567-2_5

Further diagnostic studies should run in parallel with appraisal of a structure. Comprehensive rigorous diagnosis and prognosis is normally only funded where the structural appraisal identifies significant potential serviceability and safety issues which have an impact on the function of a structure. IStructE guidance [3] provides a basis for establishing at an early stage a 'Structural Severity Rating' so investigations can be focused on those structures and/or parts of structures at risk. This rating is dominantly based on the effectiveness of the reinforcement configuration in containing the AAR damage in three dimensions and the magnitude of the free expansion to date. Part AAR-6.2 will develop and refine that approach. Often diagnosis will focus on the most sensitive structure in a group of structures built with similar reactive mix.

In this chapter more detailed field investigations are described as well as specific laboratory tests, both to establish the severity of the AAR damage now and its potential to increase in the (near) future.

5.2 Field Investigation

5.2.1 Quantification and Recording of Cracks in Structures

Registration and measurements of cracks due to ASR is probably the most important means for quantifying the amount of ASR damage in a structure. A crack width gauge, magnifying glass with measurement scale or a crack microscope can be used. Two methods for assessing the extent of cracking in a part of the structure are given in the following, both following a method of crack summation: the 'Expansion index to date' and the 'LCPC-cracking index'. Normally a few representative areas are selected for recording, some of which may then be selected for monitoring.

a. Expansion index to date

The Institution of Structural Engineers [3] suggests crack summation for initial appraisal of ASR damage in structures. An approximate indication of the expansion in the structure is obtained by measuring the widths of all the cracks crossed typically by 5 straight lines with a minimum length of 1m each and equal distance apart of at least 250 mm. The lines should be perpendicular to the principal crack orientation. Often a second orthogonal set of lines is required to record all cracks. The expansion can be assumed to be equal to the sum of the widths of the cracks divided by the length of the lines measured expressed as mm/m (see also Figure 24). The IStructE emphasises that this 'Expansion to date' in mm/m must be calculated from the sum of crack widths per m, after the deduction of cracks due to non-AAR effects and must be corrected for the restrain of expansion in each direction from compressive stress or reinforcement. Severity of cracking is rated in 5 bands I (< 0.6 mm/m) to V (> 2.5 mm/m).

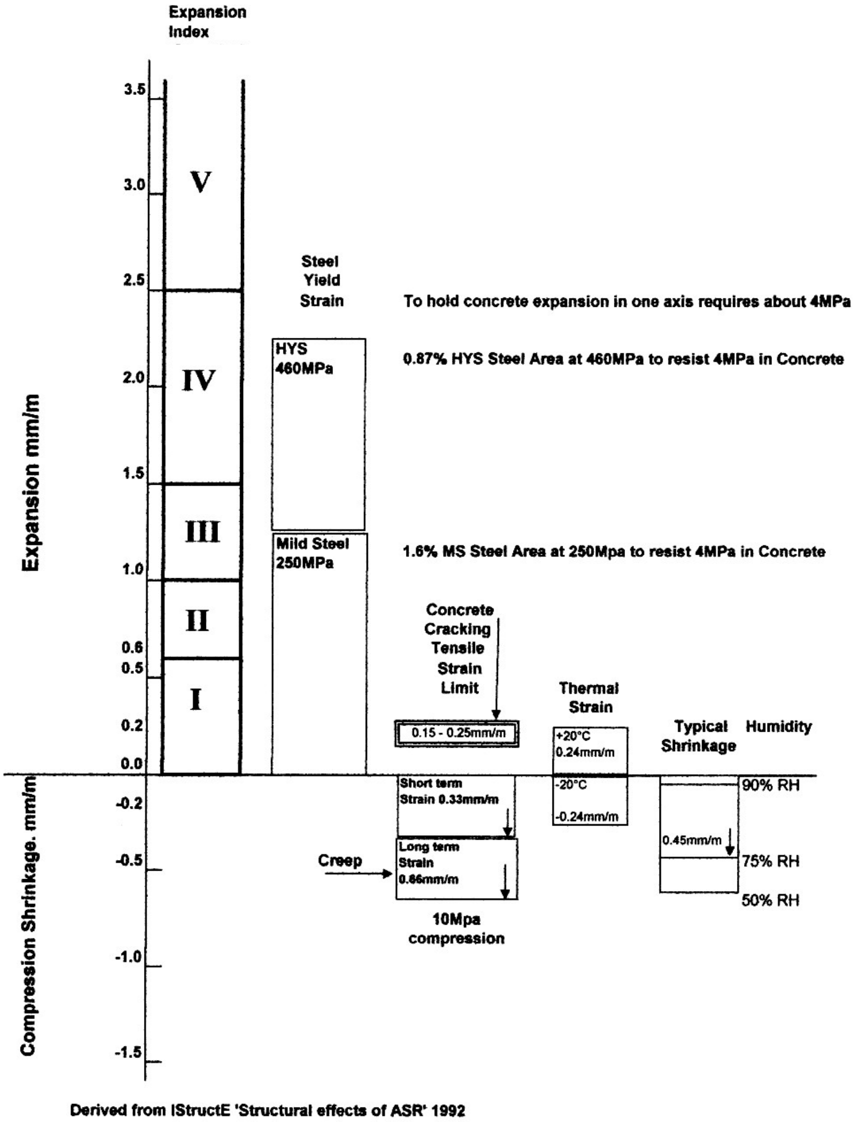


Fig. 24 Expansion index (derived from IStructE[3])

Changes in cracking are monitored using groups of Demec or similar gauges in triangular sets of points. Crack opening and shear movements can be calculated, corrected for temperature and moisture movement by the strain on the uncracked length parallel to the crack. Clear trends take at least a year to develop because of seasonal temperature and moisture movements [56].

b. LCPC-cracking index

A similar method adopted by the French LCPC [57] utilises a 1m-square drawn on the concrete surface and the widths of all the visible cracks intercepted by the bottom and the left-hand side and the two diagonals are measured, see Figure 25. The sum of the crack widths divided by the total length measured is the Cracking Index expressed as mm/m. In order to follow the development of the extent of cracking with time the measurements are repeated every 1 to 5 years in the same climatic conditions (season: temperature and humidity).

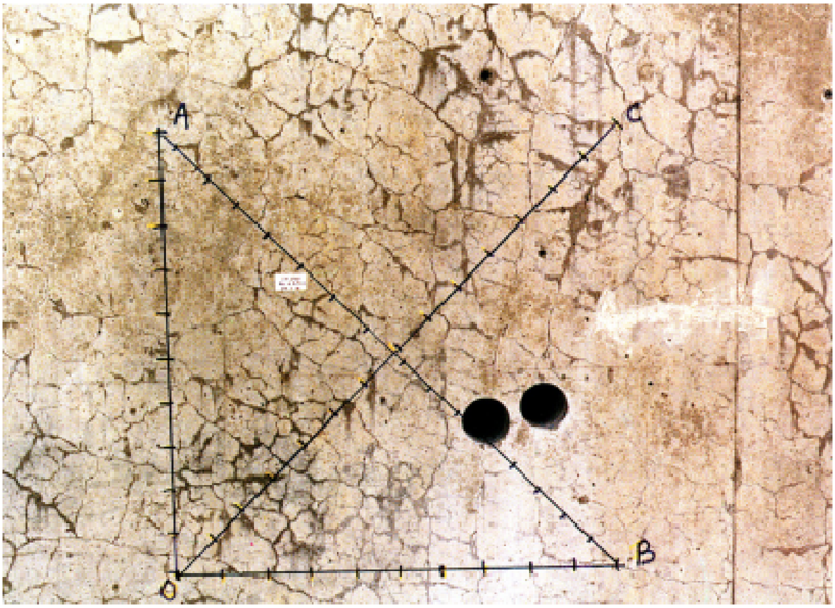


Fig. 25 Determination of the LCP-cracking index

As the extent of cracking varies widely within pours and between pours, the proportion(s) of the total area where cracking is visible should be given. The use of the French Cracking Index is recommended to describe the extent of the cracking and its development with time. In many cases it may be sufficient to measure only selected typical areas, including some of the widest cracks [37, 43]. It is also important to record those elements where no AAR type cracking is apparent so the later development of cracking in these areas can be reported as 'new' cracking.

These methods of crack measurement and estimation of "Expansion to date" are being reviewed and refined in developing AAR-6.2, both for recording the current condition and for monitoring.

5.3 Laboratory Tests

5.3.1 Expansion Tests on Concrete Cores

a. General

Expansion tests are informative for prognosis that is used as a guide to the potential for further expansion of the concrete material from which the cores were taken. The methodologies and basis for interpretation for prognosis will be set out in AAR-6.2. However, expansion tests may also be used to assist in diagnostic investigation to make an assessment of potential further expansion of the concrete from which the cores were taken if sufficient water is available.

The results of expansion tests on partially reacted material in site cores need to be used with care [58]. Methodologies used in accelerated testing of fresh laboratory concretes [59] are needed to be adapted with care. The extracted cores of partially reacted concrete can expand without restraint when supplied with additional moisture. It is essential in expansion testing to relate expansions to changes to moisture availability measured by weight changes of the core. Detailed consideration of this forms part of AAR-6.2. Restrained expansion tests will also be covered in AAR-6.2.

b. Testing cores stored at high humidity or with controlled water supply

These tests are usually performed at 38 ± 2 °C or at 20 °C and are often used to provide an indication of the potential for any further AAR expansion of the concrete. The method involves monitoring the changes in length of concrete cores over a period of time during which the cores are stored in controlled conditions. Many tests have been carried out at high humidity often referred to as "100%RH". However problems of maintaining consistent humidity and alkali leaching in longer term tests have given erratic results.

An alternative approach is given in [3, Appendix A]. Here each core is sealed in a small inclined container. The core absorbs water directly from a measured amount of added water. Initially 10g of water per kg of core is provided and as this is absorbed it is topped up when expansions and core weight are measured, to maintain 10g/kg of surplus water. The expansion measurements are then related to the amount of water absorbed and alkali leaching is minimised so it is suitable for very long term testing. The core strains are measured at intervals, for at least one year from the start of testing, and the readings used to calculate expansion in micro-strain or percentage linear expansion.

Concrete in which AAR has caused deleterious expansion will often exhibit rapid expansion during an initial stage, but the rate of expansion declines with time. This expansion may be caused partly by additional uptake of water (both by the paste and any existing mobile gel) (swelling), and part by new and continuing reaction (residual expansion). A means of distinguishing between the three forms of expansion has not been fully established. However monitoring weight uptake against expansion enables early paste swelling to be differentiated from longer term expansions from AAR and other phenomena.

Following is one hypothesis based on a specific structure. The liberated expansion starts at the time of coring and continues for one or two weeks until it decreases, reflecting the on-going activity of ASR in the concrete structure. Pop-outs may occur in this period. Attaching a belt with measuring studs immediately after coring, this expansion is measured in a moist chamber at ambient temperature (20°C). As soon as the expansion has ceased to increase significantly at 20°C, the core is transferred to a moist chamber at higher temperature (at 38 ± 2°C) to accelerate expansion until 6 months or more (preferably, up to one year). The expansion generated in this second stage is called residual expansion, which suggests the potential for future expansion of concrete if sufficient moisture is available in the structure. The sum of the liberated expansion and the residual expansion is considered to be the overall potential for expansion of concrete. It should be kept in mind, however, that on the one side, due to alkali leaching, the test may underestimate the expansion potential (more so with small cores than with bigger ones) and on the other side the structure may expand much less, especially if less humidity is available. For further guidance please refer to AAR-6.2.

The cores can expand asymmetrically, and it is a characteristic of AAR for considerable differences to exist between individual measurements of expansion along the length of a core. This is caused by the variable number of reactive sites and by variable alkali in the concrete. Measurement of this variability is an important aid to diagnosis and is important in considering structural effects of reaction.

The core expansion data should also be treated with caution since the expansion measured may be dependent on many factors and caused by mechanisms other than AAR, for example, moisture sensitive aggregates [1]. Research using cores stored at a temperature of 20°C, has indicated that the rate of expansion is greatly reduced from that observed at 38°C, but the magnitude of the expansion ultimately may be higher. Shayan and Quick [60] showed that AAR products formed at higher temperature of accelerated methods are the same as those formed at lower temperature, but at a faster rate. It follows that expansion measured at elevated temperatures is caused by the same expansion mechanism as that at lower or ambient temperature. Experience of the expansion test at temperatures of 20°C and less is limited compared with that of the test at 38°C, and it is not possible to provide more guidance at this time but data is being reviewed for AAR-6.2.

c. Expansion tests using NaOH or NaCl solutions

Some comparative expansion tests have been carried out on cores immersed in either a 1-molar sodium hydroxide solution, or a saturated sodium chloride solution. These tests have indicated that expansions and expansion rates can be increased in this way. It is considered that such tests may provide additional guidance on diagnosis, and on whether the reaction and its expansive effects are largely complete. However, experience with such testing is limited and it is not yet possible to give further guidance in some countries where chert and flint are dominant reactive rock types, because they dissolve into alkaline solution rather than producing larger expansion.

In other areas where volcanic rocks are the main reactant, the severity of field deterioration of the structures correlates well, with the expansion rates (diameter 55 mm, length 130 mm) in NaOH solution, and can be used as a local guideline [45]. The expansion in NaOH solution after 3 weeks (1 M 80°C) nearly corresponds to the expansion in NaCl solution after 3 months (saturated 50°C), while the latter exhibits a delayed expansion with a dormant period due to low OH ion concentrations, In these immersion tests, in which alkali-leaching is absent, smaller cores of about 50 mm diameter may be sufficient (if the aggregate size is less than 20 mm).

d. Alkali-immersion tests

A rapid, qualitative indication of the presence of potentially alkali-silica reactive aggregate particles may be obtained from the alkali-immersion test. This method does not prove that damaging AAR has occurred in the concrete, nor that such reactions will necessarily occur in the future, but it might enable the presence and type of potentially reactive aggregate particles to be identified.

Visual monitoring of the immersed test surface will enable any alkali-silica reactive particles to be recognized, because small gel growths will appear on the concrete surface near to the exposed aggregate particles involved in the reaction. A careful petrographic description of the test surface, prior to testing, may permit identification of the aggregate types reacting in the test. The observations should be confirmed and recorded by comparative photography before and after testing.

5.3.2 Mechanical Properties from Concrete Cores

Changes in the microstructure and characteristics of concrete in response to the development of stresses and cracks caused by swelling of gel and expansion can also considerably affect the mechanical properties. Measurements of the physical and mechanical properties of concrete can provide information on the severity of damage within the structure.

The testing and interpretation of this data will be fully covered in AAR-6.2. The determination of some physical properties of the concrete can provide useful insight concerning the severity of AAR, especially when used to compare concrete from different parts of the structure.

The mechanical and physical properties, using appropriate test methods which need to be suitable for the changed characteristics of micro-cracked concrete, may include:

- uni-axial compressive strength;
- tensile strength;
- modulus of elasticity;
- ultrasonic pulse velocity (UPV)

Experience shows that, in most cases, the reduction in tensile strength and in elasticity modulus of concrete affected by AAR is more pronounced than the reduction of compressive strength [1, 3, 61]. Standard compressive strength test on short specimens do not show the loss of compressive strength in concretes with

AAR, as friction on the platens constrains the specimen. Uni-axial compressive strength on longer specimens (l/dia > 2) are needed. As in conditions of constraint microcracking develops anisotropically, the compressive strength varies according to the development of the planes of microcracking.

Considerable reduction in the tensile strength and in the Young's modulus should be compared with the results of the microscopical studies on thin-sections. In general, when the bonding of cement paste to aggregate particles is poor, the concrete tends to yield considerably lower tensile strengths [61, 62]. This is especially the case when swelling of AAR-gel causes the cement paste to become de-bonded from reacted particles, creating cracks along the cement-aggregate interfaces. The strength of concrete in tension is reduced considerably by relatively small strains and locally becomes zero at the onset of cracking caused by AAR. Consequently, the ratio of tensile to compressive strength may be used to provide indication of the degree of mechanical damage resulting from the reaction [1, 63]. Changes in stiffness and development of hysteresis [64-66], provide the most sensitive measure of the development of mechanical damage from microcracking that leads to the degradation in tensile strength. These can be measured non-destructively, using a 0.5 to 5.5 MPa stress range, on cores in the Stiffness Damage Test [65] as a precursor to other tests.

Care should be taken in the interpretation of tensile strength values determined using splitting tests, especially those performed on cores smaller than 150 mm diameter, since these tend to overestimate the tensile strength. The results are also very sensitive to the orientation of the microcracking relative to the direction of splitting. Splitting test data cannot realistically be incorporated into structural assessment. For these reasons splitting type tests are of limited value for AAR testing. Methods of testing for tensile strength will be covered in AAR-6.2.

Since the velocity of stress wave propagation is related to the dynamic modulus of elasticity and Poisson's ratio, changes in the velocity may be expected as a result of AAR expansion [1]. UPV measurements are sometimes made to assess differences in AAR-damage within a core or between cores. However, it should be recognised that the pulse velocity is affected by many factors, and considerable variations in velocity may be observed even within a structure not affected by AAR. The method is dealt with in detail in AAR-6.2.

5.3.3 Quantification at the Microstructure Level

The volumetric ratio of individual rock types constituting the coarse aggregate can be determined by the point-counting or linear traverse procedures during the visual examination, using e.g. the method given in [67]. Either a scanned photograph of the core surface (see section 4.5.3), or a sawn section of concrete, can be used for this purpose. The proportion of particular rock types, such as any reacted rocks, physically unsound rocks and potentially reactive rocks in the coarse aggregate, can also be obtained using software for calculating the area of any particular phase in the scanned image.

Table 5 Classification system for site or laboratory findings [1]

Probability of significant AAR	Nature and extent of features
Low	No gel present, no sites of expansive reaction, presence of other indicative features rarely found. Small amount of isolated ASR-gel, sporadically presence in the cement paste, but very few reactive particles identified. Absence of other expansive-related products and features caused by some other mechanisms. Quality of concrete microscopically is reasonably good.
Medium to High	Presence of some or all features generally consistent with AAR, such as: cracking and microcracking, especially when associated with known reactive aggregates. presence of potentially reactive aggregates. internal fracturing of known reactive aggregates. darkening of cement paste around aggregate particles, cracks or voids. presence of reaction rims around internal periphery of reactive aggregate particles. presence of damp patches on core surfaces.
Very High	Presence of features such as: evidence of sites of expansive reaction, that is, locations within the concrete where evidence of reaction and emanation of swelling pressure can be positively identified, for example streaming of ASR-gel from a reacted and cracked aggregate particle into the adjoining cement paste with development of cracks both in the cement paste and along the paste-aggregate interface. presence of ASR-gel in cracks and voids associated with reactive particles and readily visible to normal or corrected-to-normal vision or under low magnification.

An alternative method is to extract the aggregates from the concrete cores and perform a petrographic analysis, e.g. according to AAR-1 [54], and a grading analysis.

The presence of AAR in polished surface or thin-sections can be positively diagnosed by two features: the presence of ASR-gel and sites of expansive reaction. Other features may be consistent with AAR but are not themselves reliably diagnostic, that is, they may be the result of some other mechanism. The result from the laboratory examination should be compiled, in order to give an overall assessment of the probability and severity of damaging AAR, using for example, the guidelines in Table 5 and taking account of any damage ratio (section 5.3.4) determined.

5.3.4 Determining Damage Ratios at the Microstructure Level

For assessing the degree of damage in the concrete, the crack pattern can be studied under the microscope on polished slabs from cores or by use of fluorescence technique. Two methods for assessing the damage rate on cores are given below:

- The degree of damage done can be evaluated by studying the ***crack pattern*** in core materials from the structure as described in the following. If the cores are from areas where quantification of cracks, compare section 5.2.1, has been carried out, then a relationship between observations from the laboratory investigation and field investigation can be made.
- Another damage ratio can be obtained by determining the reduction in ***modulus of elasticity*** on cores from damaged and non- or less damaged parts of the structure. Petrography is needed to identify how much of the damage has been caused by AAR or other damaging mechanisms. This technique has been extensively used on many structures in the UK for the last 20 year [46, 68].

a. Crack pattern

Norwegian Crack Counting Method

A simple and fast method was developed in Norway [69]. This method uses fluorescence impregnated polished half cores (FIPC-method) examined under UV-light where cracks and porosities (e.g. gel) are very visible, e.g. cracks as small as few micrometers can be observed without the use of a microscope, see Figure 26. Before the test, aggregate particles with cross sections > 4 mm visible on the plane section have to be counted and the area of the plane section in cm^2 to be measured. Three parameters examined under UV-light shall be registered and counted:

- aggregates (with cross sections > 4 mm) with internal cracks,
- aggregates (with cross sections > 4 mm) where cracks run into the cement paste (significant for ASR) and
- number of cracks in the cement paste.

Parameters for aggregates shall then be normalised to percent of aggregates with cross section > 4 mm and cracks in the cement paste to $cracks/cm^2$. The occurrence of gel or other signs of AAR shall be registered too. A modified Norwegian crack counting method with the use of “multiplying factors” has recently been suggested in [1].

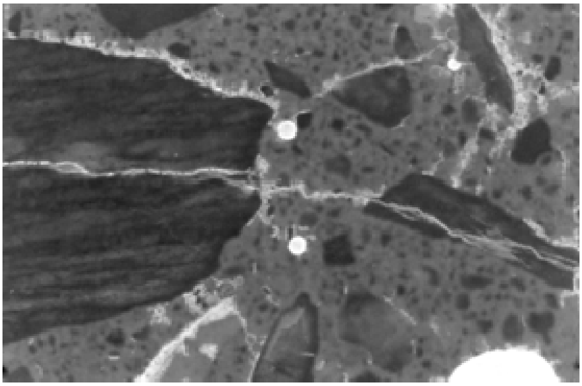


Fig. 26 FIPC (fluorescence impregnated concrete) photographed in UV- light where cracks are very visible (Jensen [70])

Damage Rate Index (DRI)

A method called "damage rate index method" (DRI-method) has been published and used around the world [71, 72]. Polished slabs from cores are examined under the microscope and defects are registered by use of a binocular microscope (16 x magnifications) in a minimum area on 180 cm^2. Defects are coarse cracks, coarse particles with cracks and gel, debonded coarse particles, reaction zones, cracks in the cement paste, cracks and gels in the cement paste, air voids with gel and coarse particles with "wide" cracks. The different parameters are multiplied with a specific weighting factor (see Table 6), normalised to 100 cm^2 and summarized. The weighting factors need to be adjusted to suit different reactive aggregate types. As the extent of AAR damage usually varies within a structure, cores from different parts of the structure should be investigated. The method has with success been used on several structures and has given important quantified information on the current condition of concretes affected by AAR [73].

The weighting factor for debonded aggregate is high in Table 6. Since frost or chemical attack can also cause debonding, it is essential to ensure that the concrete is frost resistant and any signs of chemical attack are absent, before the DRI-method applied.

b. Modulus of elasticity

Obviously, mechanical tests on concrete cores should provide a good means for quantifying any damaging effects, as such test results are used to describe the quality of the concrete and to design structures.

However, the concrete may be seriously cracked and the short specimen compressive strength may not have been reduced very markedly. Tensile strength is more sensitive to AAR-damage and is critical for shear, bond and anchorage of reinforcement. The modulus of elasticity has a great influence on how the structure deforms and it also responds very sensitively to AAR-damage. This is why this property is often used to quantify the damage that has occurred. Determination of the modulus of elasticity can be non-destructive if the stress range is limited to less than 5.5 MPa and after the test the core can still be used for other purposes. An important advantage of Stiffness Damage Test [64-66] is that it characterises the average damage to a significant volume as distinct from the assessment of a small surface volume in petrographic techniques.

Table 6 Weighting factors* for determining the damage rate index [1]

Petrographic features	Multiplying factor
Coarse aggregate with cracks but no ASR-gel	0.25
Coarse aggregate with cracks and ASR-gel (ASR-gel streaming from aggregate in adjoining cement paste)	2
Coarse aggregate de-bonded *from cement paste*	3
Reaction rims around aggregates	0.5
Cement paste with cracks	2
Cement paste with cracks and ASR-gel	4
Air-voids with ASR-gel	0.5

** These factors are applied to the total number of each type of defect to modify the raw numbers and consequently to reflect the probable impact of that defect on the deterioration of the concrete. This calibrated for reactive coarse aggregate and needs to have separate weightings for other aggregate types.*

The static modulus of elasticity (Young modulus) is determined by subjecting cores from the structure to repeated loading in compression. A core from an AAR-affected part of the structure will show considerable plastic deformation the development of hysteresis and a much smaller modulus of elasticity, for example only 50% of a core taken from a less damaged part (see Figure 27) [66]. There are better examples, in the earlier literature [64, 65]. A correlation of stiffness loss to expansion to date is given in [46, Figure 27] and a developed version of this will be in AAR-6.2.

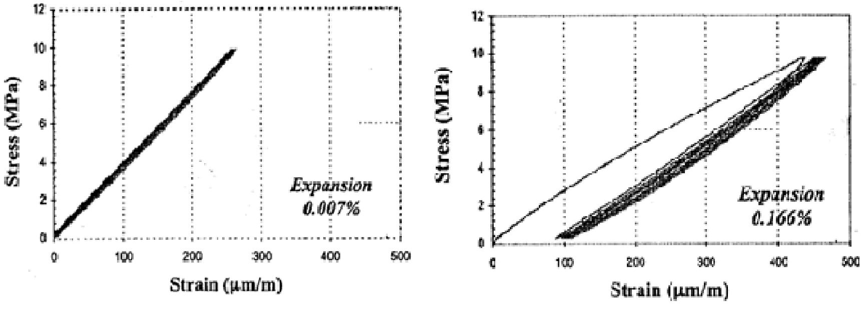


Fig. 27 Effect of 5 loading cycles with two cylinders of different expansion levels [66]. Other examples in Crouch and Chrisp[64, 65] with 0.5 to 5.5MPa stress range to limit damage.

5.4 Summary of Diagnosis

A diagnosis of the presence of AAR in the concrete of a structure and the extent of damage it has caused is made by combining the site and laboratory classifications, using for example Table 7.

Table 7 Summary of diagnosis of field and laboratory findings [1]

Evidence of AAR		**Interpretation**
Field	***Laboratory***	
Low	Low	If neither site nor laboratory investigations produce significant evidence of AAR, the reaction can be positively eliminated as a possible cause of damage, and alternative mechanisms must be sought. The presence of considerable displacement, movement, or cracking of the structure is not sufficient to suggest AAR if neither the type of damage observed on site nor the results of laboratory examinations are consistent with AAR.
Low	High	If the evidence from site indicates a low probability of AAR, but a high incidence of reaction is observed in the laboratory, it is not possible to establish a causal link between the deterioration on site and AAR. The most likely explanation for this result is that AAR has occurred, but the operation of other mechanisms has prevented typical manifestation of AAR in the structure. Other possible mechanisms must be sought and eliminated before AAR is implicated as the main or sole cause of damage.
High	Low	If the evidence from site indicates a high probability of AAR, but no evidence of reaction was observed in the laboratory examination, three possibilities exist: a. first, the sampling programme excluded locations where significant reaction had occurred b. second, the features observed on site, although consistent with AAR, are a result of another mechanism (for example DEF) c. third, the reaction is not sufficiently advanced to show up clearly in samples. A judgement must be made whether to carry out further sampling, seek the presence of alternative mechanisms, or both.
Medium	Medium	If the evidence from both site and laboratory investigations indicates a medium probability of AAR, then it may be concluded that AAR has occurred and may be a contributory cause of damage, but that it is likely that other mechanisms exist and have contributed to the overall deterioration of the structure.
High	High	If the evidence from site and laboratory investigations both imply a medium to high probability of AAR, it may be concluded that AAR is at least a significant contributory cause of damage to the structure. In the absence of any other mechanism, it may be reasonable to assume that AAR is the principal or sole cause of damage.

While these generalised tables provide a check list, the materials specialist must base his judgement and reasoned conclusions on the totality of available information with a particular emphasis on the known characteristic of the particular reactive aggregate type.

If the AAR damage is such that there is the need to determine its consequences on the structural members, then a detailed structural assessment, prognosis and planned remedial measures are required as outlined in [74] and to be described in detail in AAR-6.2. Material from the cores taken for diagnosis may well be required for testing for prognosis and assessment and so they should be maintained in stable sealed conditions until required.

6 Reporting

6.1 Purpose

The purpose of the report is to present an accurate summary of the results of the investigation and to establish whether or not the damage to the concrete in the structure was caused at least in part by AAR.

6.2 Scope

The nature of the report dealing with diagnosis of AAR damage to concrete in structures depends on the type and the depth of investigation performed, but in general, it should encompass each phase of the investigation as presented in Figure 1. In addition to the particulars concerning the client, the report (of a routine investigation) should begin with a clear definition of the objectives of the study agreed with the client and a short presentation of background information concerning the structure(s) involved. This should be followed by a brief description of the methods used, then the results obtained at each phase of the investigation and an explanation of their subsequent interpretation.

The report will need to be read by the client with the engineer's report on the assessment and prognosis for the structure. The interface and exchange of information between the engineering team and the material science team, which should have been agreed with the client as part of the investigation brief, should be set out in the report.

Finally conclusions should be drawn in the light of the results obtained and the objectives of the investigation. Specific aspects of the report can be presented in tabular, graphical or both forms, preferably illustrated with photographs and photomicrographs.

The report should clearly indicate if the sampling and laboratory programme is sufficient to provide a reliable conclusion and indicate what further testing would be required to clarify any remaining uncertainties.

6.3 Objectives of the Investigation

A brief, yet clear definition of the objectives of the investigation as agreed with the client should be given.

6.4 Information Concerning the Structures

This aspect should deal with the type(s) of structure(s) involved and their ages (if known), a description of their location and accessibility, and finally information

B. Godart et al. (Eds.): *Guide to Diagnosis & Appraisal of AAR Damage,* RILEM 12, pp. 79–81.
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concerning the members of the structures where AAR is suspected to have occurred and any information on their concrete composition and constituents.

6.5 Methods and Techniques Used

This part should be concerned with a brief description of the methods and techniques used in the investigation and the results obtained.

6.6 Interpretation of Results

This aspect should deal with a systematic evaluation of the results of the various phases of the investigation. It should start with the observations made in the field, followed by the results of the laboratory tests and analyses, including the results of the petrographic examination of cores, and finally the results of any supplementary tests, such as XRD, TGA, SEM-EPMA.

The results of the various phases should not be treated in isolation but should be used jointly to establish whether AAR is the primary cause of distress in the members concerned. In other words, all the data obtained during the site and laboratory investigations should be used together to determine whether or not the evidence obtained is consistent with an AAR cause. Such treatment of the results should enable the occurrence of AAR within each concrete member and in the core samples to be established or discounted with a high degree of certainty.

With regard to field inspection the part of a report should, in general, include:

- type of structure, for example, bridge, viaduct, a building or a dam;
- acquired information on the structure, such as the members showing clear evidence of apparent AAR damage or those that appear possibly to be affected by AAR;
- information concerning other possible causes of distress in the structure with similar features to those of AAR;
- information concerning areas in the structure where core samples were removed for laboratory studies;
- number of cores removed.

The part of the report dealing with observations during the field inspection should aim at drawing a link between that phase of the investigation and the laboratory studies on the core samples.

Information concerning the laboratory study should include:

- description of the core samples: number received, dimensions and condition;
- method of treatment or storage of cores;
- type of analyses or tests performed on cores and the results obtained.

6.7 Conclusions

This should be deal with the specific questions in the brief relating to the durability and prognosis for the structure. Conclusions should be drawn on the basis of the joint interpretation of the site and laboratory results, particularly whether or not the evidence obtained is deemed wholly or partially consistent with an AAR cause. It should include recommendations for any necessary further studies, especially structural studies.

6.8 Author

Owing to the complexity of the subject of AAR, especially with respect to its diagnosis in a structure, it is recommended that the diagnosis section of the report should be written by a specialist or an expert in the field of AAR and preferably the concrete materials engineer or petrographer, who was actively involved in the investigation.

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Appendix 1.
Proceedings of ICAAR

Proceedings of International Conferences on Alkali Aggregate Reaction:

14th	ICAAR	Austin	2012
13th	ICAAR	Trondheim.	2008
12th	ICAAR	Beijing.	2004
11th	ICAAR	Quebec.	2000
10th	ICAAR	Melbourne.	1996
9th	ICAAR	London	1992
8th	ICAAR	Kyoto Japan.	1989
7th	ICAAR	Ottawa.	1986
6th	ICAAR	Copenhagen.	1983
5th	ICAAR	Capetown.	1981
4th	ICAAR	Purdue USA.	1978
3rd	ICAAR	Wexham UK.	1976
2nd	ICAAR	Reykjavik.	1975
1st	ICAAR	Koge DK.	1974

Appendix 2.
Diagnosis of AAR within an Overall Investigation