GLOBALISING AAR: 26 YEARS OF RILEM ENDEAVOUR

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Abstract

Following research in the USA during the 1930s, alkali-aggregate reactivity (AAR) was announced to a distracted world in 1940, as a major mechanism of concrete deterioration. During the following decades, countries around the world gradually discovered their own cases and varieties of AAR. A feature of the spread of the AAR experience was that countries frequently regarded their own materials and practices as exceptional, leading to a proliferation of test methods for assessing aggregate reactivity potential and/or diagnosing affected structures.

RILEM[1] has an established reputation for practical research in the field of construction materials. In the late 1980s, Prof Micheline Regourd proposed the formation of a RILEM Technical Committee (TC) to review the growing plethora of AAR tests, with a view to providing guidance on a set of procedures that would be equally applicable everywhere in the world. As a result, the authors were invited to lead TC 106, which first met in 1988 and primarily focused on international tests for assessing the ASR potential of aggregates for concrete. TC 106 would be succeeded in turn by TC 191-ARP and then by TC 219-ACS, which completed its work in 2014, when the baton passed to Prof Borge Wigum and Dr Jan Lindgard, who now lead the current TC 258 AAA. This paper summarises the achievements of the RILEM TCs from 1988 to 2014.

KEYWORDS Concrete, Aggregates, Alkali-Aggregate Reactivity (AAR), Testing, Specification.

1. INTRODUCTION

Stanton [1] first identified alkali-aggregate reactivity (AAR), more specifically alkali-silica reactivity (ASR), in 1940 as a major mechanism of concrete deterioration in concrete structures in California. Research in the US then led to the standardization by ASTM of a number of test methods that for many years were adopted around the world as the benchmark way of identifying aggregates that were susceptible to alkali reactions. These methods, the mortar-bar method [2] and the chemical method [3] worked well for the rapidly reacting aggregates involved in the cases that Stanton and his co-workers had investigated. However, during the following decades, countries around the world gradually discovered their own cases and varieties of AAR, including some manifestations that appeared to represent significantly different mechanisms (including 'alkali-carbonate reactivity' (ACR) and 'alkali-silicate reactivity'), and it became clear that AAR is a family of related reactions affecting different rock types in different ways. Frequently it was found that the original ASTM tests did not identify alkali reactions in these different rock types and accordingly, each region began to develop tests appropriate to its own geology and experience.

This proliferation of regional test methods began to pose real problems for engineers and testing laboratories working around the world and accordingly, in the late 1980s, the eminent French scientist, Professor Micheline Regourd, proposed that RILEM should undertake a review of the growing plethora of AAR tests, with a view to providing guidance on a set of procedures that would be equally applicable everywhere in the world. As a result, the authors were invited to lead a RILEM Technical Committee, TC 106, which first met in 1988 and primarily focused on international tests for assessing the ASR potential of aggregates for concrete. RILEM is a non-governmental, member-funded, international organisation, based in Paris, with an established reputation for practical research in the field of construction materials. Its Recommendations are regarded as pre-normative and are

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[1] Paris based RILEM is an acronym (in French) for International Union of Laboratories and Experts in Construction Materials, Systems and Structures.

frequently adopted by Standards bodies as the basis for later Standards. TC 106 was succeeded in 2001 by TC 191-ARP, which expanded its brief to include guidance on the diagnosis and appraisal of structures affected by AAR and also began work on the specification of concrete to minimise the likelihood of AAR damage. In 2006, TC 219-ACS took over the work and included in its programme the development of performance tests for actual concrete mixes and guidance on the modelling of alkali reactions. This TC completed its work in 2014 (Figure 1), when the baton passed to Prof Borge Wigum and Dr Jan Lindgard, who now lead the current TC 258 AAA.

This paper summarises the achievements of the RILEM TCs from 1988 to 2014, and considers the extent to which the original brief was satisfied. Some comments are made that will hopefully assist TC AAA in building on this encouraging start.

2 ACCELERATED TESTS FOR AGGREGATE REACTIVITY

This was the original brief for the RILEM TC and was based on concerns about the proliferation of regional tests for alkali reactivity because of the very diverse geology of the rock types found to be affected. A second reason for this proliferation was the need to accelerate the reaction in any test method. Alkali reactions take many years to exhibit damaging expansion. So for a test to be useful for assessment and contractual purposes, fairly drastic acceleration is necessary. This, however, almost certainly distorts the test results from the reality of field concrete and the search for a solution that satisfies both the desire for a speedy result and the requirement that laboratory findings should reliably reflect field experience has generated a multitude of methods. Moreover, there was a tendency for proposed new tests to be 'validated' against existing tests of uncertain reliability, rather than against actual performance in the field. Against this background, the primary objective of RILEM TC-106 was to recommend a suite of test methods that would be:

- reliable;
- closely related to field experience;
- sufficiently accelerated to be practically useful;
- internationally accepted.

After considering a wide range of methods, TC 106 initially concentrated upon three procedures: petrographic examination (AAR-1), an accelerated mortar-bar expansion test (AAR-2) and a concrete prism expansion test (AAR-3). AAR-2 and AAR-3 were published in RILEM's 'Materials and Structures' (M&S) in 2000 as draft RILEM Recommendations and considerable progress was made in developing AAR-1. The results of AAR-2 and AAR-3 were assessed against the known field performance of a wide range of aggregates, of different geological types and in different countries, in an international inter-laboratory trial. Also, to improve the reliability of the methods, sources of reference high-alkali cements and non-reactive aggregates were established. Work was also started by TC-106 on an accelerated concrete prism test (AAR-4) and on specialised procedures for carbonate aggregates.

The succeeding TC, RILEM TC 191-ARP, began work in 2000 to integrate the test methods already developed by TC-106 into a coherent assessment system. Under the aegis of TC 191-ARP, AAR-1 was published as a draft RILEM recommendation and the AAR-4 procedure was finalised and an international inter-laboratory trial carried out. Also, the preliminary screening method for carbonate aggregates (AAR-5) was developed, assessed in an inter-laboratory trial, then published in M&S as a draft RILEM Recommendation.

The inter-laboratory trials were a key route to ensuring that the tests met the objectives outlined above. The trials were conducted by asking participants to identify aggregates from their particular country with a known field performance in terms of alkali reactivity, either having been found as the reactive component in damaged structures or known to be non-reactive. The participants then tested the aggregates from their country using the test in question. The results for the trial on the 38°C concrete prism test, AAR-3, are shown in Figure 2 and indicate a high degree of agreement between the test results and field experience. There are, however, some anomalies, which on investigation were mostly caused by uncertainties in the field experience, or where field behaviour could only be replicated in tests by boosting the alkali content.The inter-laboratory tests and the results, including an assessment of the anomalies were described in some detail in Nixon & Sims [4].

Similar inter-laboratory tests were carried out on the accelerated mortar bar test and the 60°C concrete test and the results reported [4]. Overall, these inter-laboratory tests gave a high degree of confidence that these RILEM methods were effective in differentiating reactive and non-reactive aggregates and this conclusion was backed up by the EU funded project, PARTNER [5], which was undertaken to assess the RILEM methods as the possible basis for European (CEN) Standard methods. In this project, 24 partners from 14 European countries evaluated the RILEM methods using 22 different aggregates. Some regional methods were also evaluated and field trials with large concrete specimens established for long term tests. Broadly, this project showed that the RILEM methods could successfully identify the reactivity of the aggregates tested. The work also included an inter-laboratory precision test and recommendations for improvements in the procedures were made. The suite of test methods now comprised:

AAR-1.1: Petrographic Examination Method
AAR-2: Accelerated Mortar-bar Test Method for Aggregates
AAR-3.1: 38^{o}C Test Method for Aggregate Combinations using Concrete Prisms
AAR-4.1: 60^{o}C Test Method for Aggregate Combinations using Concrete Prisms
AAR-5: Rapid Preliminary Screening Test for Carbonate Aggregates

These methods were developed into an integrated assessment scheme in AAR-0, 'Outline Guide to the Use of RILEM Methods in Assessments of Alkali-Reactivity Potential of Aggregates'. This scheme is shown in Figure 3. It is recommended that such an assessment should always begin with a petrographic examination using AAR-1.1, which usually allows the aggregate to be assigned to one of three categories:

Class I – very unlikely to be alkali-reactive
Class II – potentially alkali-reactive or reactivity uncertain
Class III – very likely to be alkali-reactive
Class II or III materials are then further assessed using the RILEM methods. If the rock type is primarily siliceous the material is designated as Class II-S or III-S and is subjected to the RILEM screening test AAR-2, or to the AAR-3.1 or AAR-4.1 concrete prism expansion tests. Materials that are mainly carbonate are designated II-C or III-C and are first assessed using screening test AAR-5 and then further tested using AAR-3.1 or 4.1, as appropriate.

Under the third TC, RILEM TC 219-ACS, Alkali-Aggregate Reactions in Concrete and Structures, the lessons of the PARTNER programme were incorporated into the RILEM methods, the Specifications were finalised and the entire suite of methods and specifications integrated, reassessed, updated and prepared for publication in RILEM's State-of-the-Art Report (STAR) 17 [6] (Figure 4).

Experience in the PARTNER project showed the great difficulty that petrographers had in correctly identifying and assessing rock types with which they were unfamiliar. To help overcome this, under the third TC, RILEM TC 219-ACS, a worldwide petrographic atlas of reactive aggregates was compiled, under the expert leadership of Prof Isabel Fernandes, to assist in the examination of aggregates using AAR-1.1. This impressive work has been published separately as RILEM AAR-1.2 [7], and an example page from the Atlas is shown in Figure 5. It is hoped that a further guidance document will be developed by RILEM in due course, giving detailed information on the application of petrographic examination and supplementary methods for establishing the reactivity potential of aggregates (see also [8 & 9]).

3 SPECIFICATION OF CONCRETE TO AVOID AAR DAMAGE.

Under the auspices of RILEM TC 191-ARP, work was also begun on model specifications to avoid or minimise the risk to concrete structures from alkali-aggregate reactions. This followed from discussions and a specific request at the 11th ICAAR in Québec, Canada, in 2000, and reflected concerns that, as with test methods, a great range of specifications were being developed in different countries and regions, as would be explained at the 12th ICAAR in Beijing four years later [10]. Initially this work concentrated on ASR and the resulting model specification has been published in RILEM's STAR 17 [6] as AAR 7.1. The principle followed in this has been to produce a framework specification, based on the best information from around the world, so that a country could draw from it the best practice most appropriate to its particular climate, geology and materials. For an alkali-aggregate reaction to lead to damaging expansion in concrete, all of the following conditions must be present simultaneously:

- a sufficiently alkaline pore solution;
- a critical amount of reactive silica;
- a sufficient supply of water.

So any effective specification must be based on avoiding at least one of these. To make sure that the extra costs and environmental effects of achieving this are needed, the first steps in developing a specification should be to:

1. Determine the necessary level of precaution;
2. Undertake recommendations appropriate to the necessary level of precaution.

The necessary level of precaution will depend on the structural sensitivity of the structure, including its service life and function and the environment to which it will be exposed in service. By combining these factors four levels of precaution can be identified:

P1 No special precautions against AAR;
P2 Normal level of precaution;
P3 Special level of precaution;
P4 Extraordinary level of precaution.

Precautionary measures are then applied appropriate to the determined level of precaution. For P1, no special precautions against AAR are necessary. P2 will apply where minor AAR damage is acceptable and the specification should ensure that <u>one</u> precautionary measure is applied. P3 will also be appropriate where minor damage is acceptable, but then where additionally the structure is subject to environmental factors, such as freezing and thawing cycles, which could exacerbate the AAR damage. In this case <u>one</u> precautionary measure against AAR must be applied but additionally the concrete should be designed to resist the aggravating factor. Finally, P4 will apply when the consequences of deterioration are not acceptable. This will normally necessitate the combined application of at least <u>two</u> measures.

The precautionary measures are categorised as:

M1: Restricting the alkali level of the pore solution (e.g.by limiting alkali level in the concrete);
M2: Ensuring the use of a non-reactive aggregate combination;
M3: Reducing the access of water;
M4: Modifying the gel so that it is not expansive.

The details of applying these measures and their strengths and weaknesses are discussed in AAR-7.1 [6].

In AAR-7.2 [6], the particular considerations applying to structures containing reactive carbonate aggregates are considered. The issues governing the identification of an appropriate level of precaution are the same as in AAR-7.1, but the precautionary measures that can be employed are much more limited, as it has been found that the precautionary measures that are effective for ASR do not prevent damage with reactive carbonate aggregates. At present, the only reliably effective measure seems to be avoidance of using such aggregates, once identified using AAR-5 [6]. It should be noted that recent research has established that at least many, and perhaps most, carbonate aggregates that have exhibited expansive AAR in concrete actually display a form of ASR [11].

In AAR-7.3 [6], the issues involved in developing a specification to avoid AAR damage in concrete dams and other hydraulic structures are discussed (Figure 6). This is designated as a *preliminary* specification, as for these highly exposed, very long service structures, uncertainties remain on how best to specify and protect them. The importance of such structures, their very long service lives and the fact that they are permanently exposed to moisture mean that the highest levels of precaution are needed and they must be designated *P4, Extraordinary level of Precaution*, as described in AAR-7.1. For P4 the combined application of at least two of the four precautionary measures is recommended and additionally the concrete should be designed to resist any aggravating factors such as freezing and thawing cycles. However, for these large, long-service structures there are special factors that need to be taken into account, such as the need to resist very long, slow reactions, their sensitivity to even low levels of expansion of the concrete and the fact that they are often built in remote areas where the choice of materials is limited. Overall it is concluded that the preference is still for the application of at least two separate precautionary measures, but that there may additionally be the need to apply more rigorous limits when testing materials and the design and construction will need to allow for any unavoidable expansion.

4 DIAGNOSIS AND APPRAISAL OF AAR DAMAGE TO CONCRETE IN STRUCTURES

The correct diagnosis of damage in structures as a result of alkali-aggregate reactions can be difficult and uncertain because of the similarity of the external characteristics of the damage with those caused by other actions such as freezing and thawing, shrinkage or delayed ettringite formation. In recognition of this, TC 191-ARP undertook to prepare guidance on the most effective procedures. Part 1, dealing with diagnostic procedures, has been published as RILEM STAR 12 [12].

Part 1 has two primary objectives:

- To identify whether the observed damage has been caused by AAR and whether or not AAR is the only cause or a contributory one;
- To establish the intensity of the damage in various parts of the structure.

The guidance begins with advice on carrying out an on-site inspection, evaluation of the visible signs of damage and then, where necessary, the taking of samples for further laboratory inspection. Optical microscopy is the primary method for establishing whether AAR is present, which materials are affected and if other deterioration mechanisms are also contributing. This may be supplemented by SEM and/or EPMA analysis. Supplementary tests to determine the distribution of soluble alkalis through the concrete, to determine the cement content and to assess the reactivity of the aggregate rock type may then also be carried out.

Once there has been a diagnosis that AAR is the cause of the damage, the engineer will probably want to know the severity of the damage and the prognosis for its future development. STAR 12 discusses a number of techniques for this, beginning with methods for assessing the extent of cracking in the structure and going on to laboratory tests, in particular expansion tests on concrete cores, but also including measuring changes in mechanical properties of the concrete. It also considers a number of methods for quantifying damage at a microstructural level, such as the damage rate index. Finally it proposes a tabular method for drawing together the results from various tests and making an overall judgement.

Work also began in TC 219-ACS on Part 2 of AAR-6, being guidance on the appraisal, management and modelling of structures affected by damaging AAR. This will be published by RILEM in the near future, as a separate STAR, designated AAR 6.2.

5 PERFORMANCE TESTS

The test methodologies given in STAR 17 [6] enable the assessment of aggregate reactivity, but the findings then have to be transferred to the likely performance of an actual concrete mix, which will almost certainly contain different levels of alkali and may also incorporate cement additions such as granulated slag, fly ash or silica fume, in addition to various combinations of all the constituents. With increasing knowledge of the performance of actual concrete mixes, particularly from long term outdoor exposure trials, there now seems the possibility of developing a reliable laboratory performance test procedure for the actual mix to be used in concrete. Work began on this in TC 219-ACS and is now the main objective of the current RILEM TC, TC 258-AAA, under the chairmanship of Prof. Borge Wigum (Figure 7).

6 ALKALIS IN AGGREGATES

Some rock types used for aggregate in concrete, for example geologically altered granites, contain significant amounts of alkalis in a form than can potentially be released over time into the concrete in service. So far, there has never been a consensus on whether or to what extent such alkalis contribute to alkali reactions in concrete, nor how to test for them (though several procedures have been standardised, despite their uncertain relevance). Work began in TC 191-ARP on the development of a test method for such 'releasable' alkalis and continued intermittently in that TC and its successor TC 219-ACS. The test method being developed by those TCs was designated AAR-8, but the work was not finalised. The finalisation and validation of AAR-8 is now a work programme in TC 258-AAA.

7 CONCLUSIONS

The work undertaken in three RILEM TCs on AAR, from 1988 to 2014, has successfully fulfilled the original brief of developing a comprehensive assessment scheme to determine the alkali-reactivity potential of aggregates, which can be used with a wide variety of rock types. It is hoped that this can form the basis for a worldwide consensus on the testing for potential reactivity in aggregates. The work on aggregate testing has been extended to include a set of model specifications for avoiding damage in new concrete and guidance on the diagnosis and assessment of AAR damage in structures. These should also form the basis for worldwide consensus on best practice.

Important work is still to be completed on the development of a performance test procedure for assessing actual concrete mixes and a valid test for releasable alkalis in aggregates. There is also a need to promote the use of the tests and specifications collected in STAR 17 [6].

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FIGURE 1: Members attending the final meeting of TC 219-ACS in Vienna, Austria, in 2014.

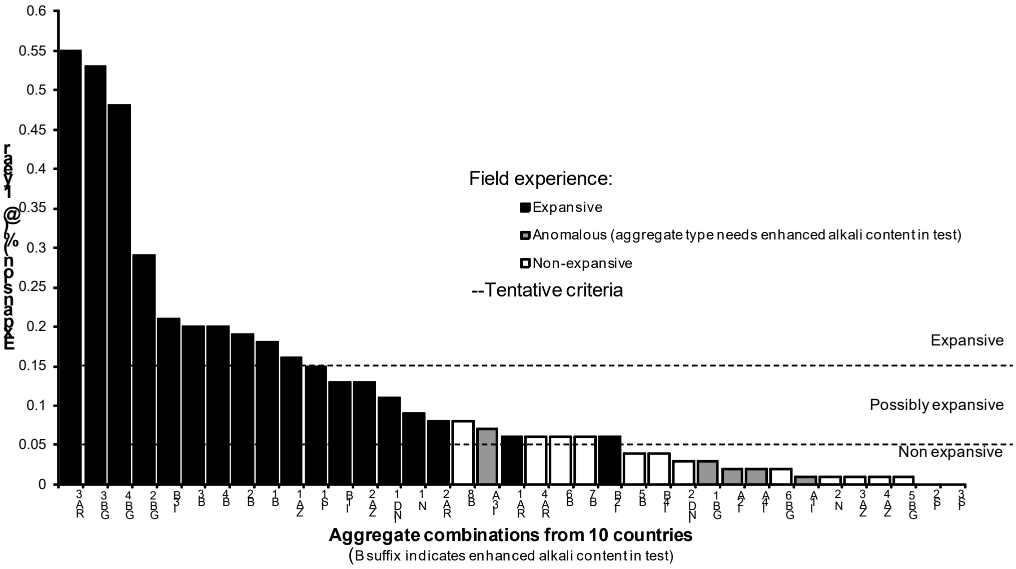

FIGURE 2: Chart showing the interlaboratory trial results for the AAR-3 (38°C) concrete prism test.

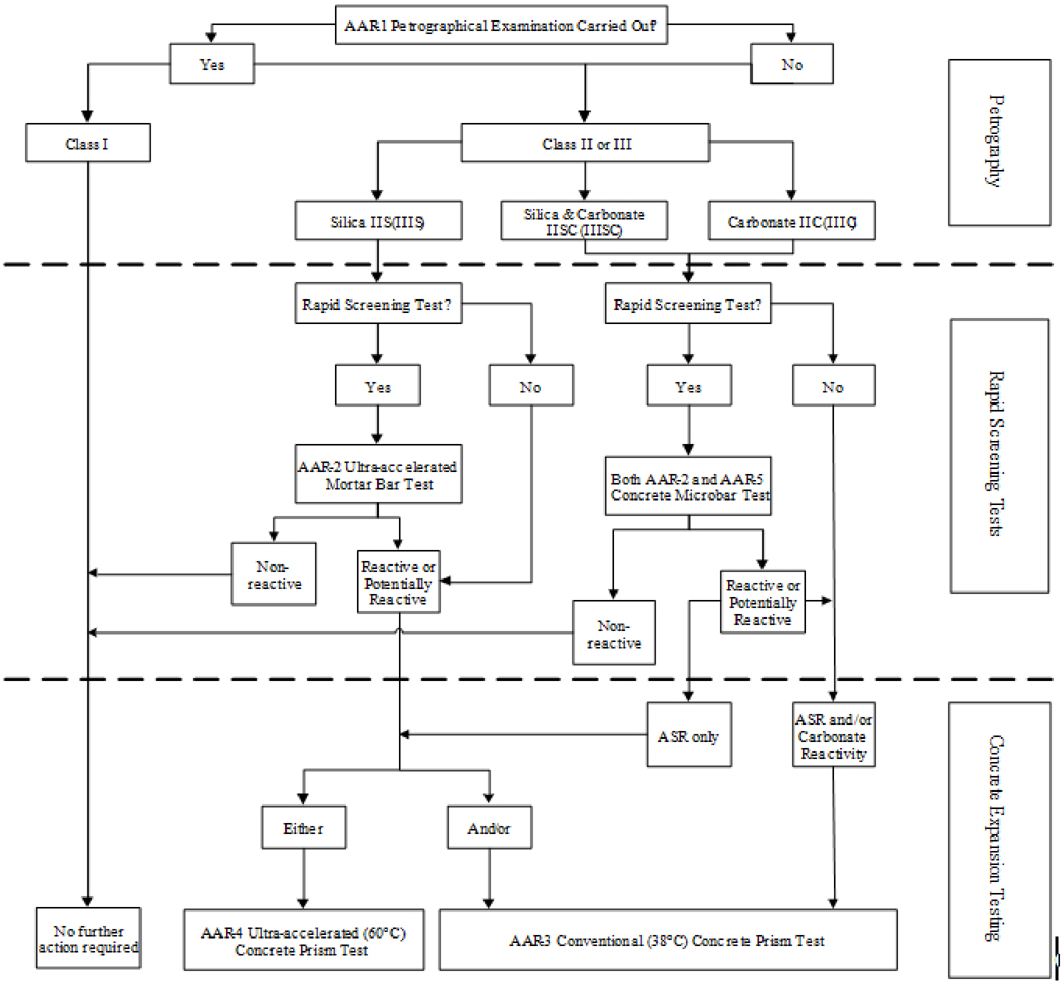

FIGURE 3: Flow chart showing the AAR-0 aggregate assessment scheme.

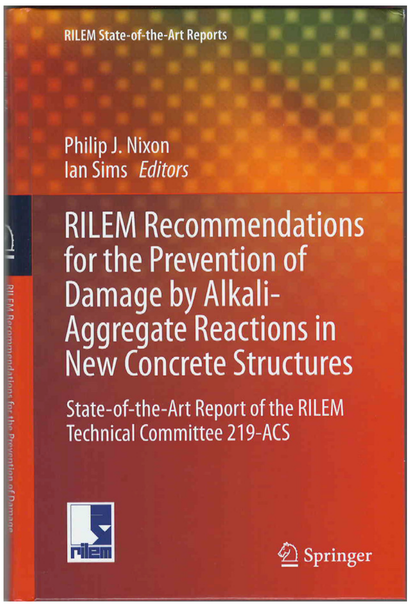

FIGURE 4: Cover of RILEM's State-of-the-Art Report 17 [6].

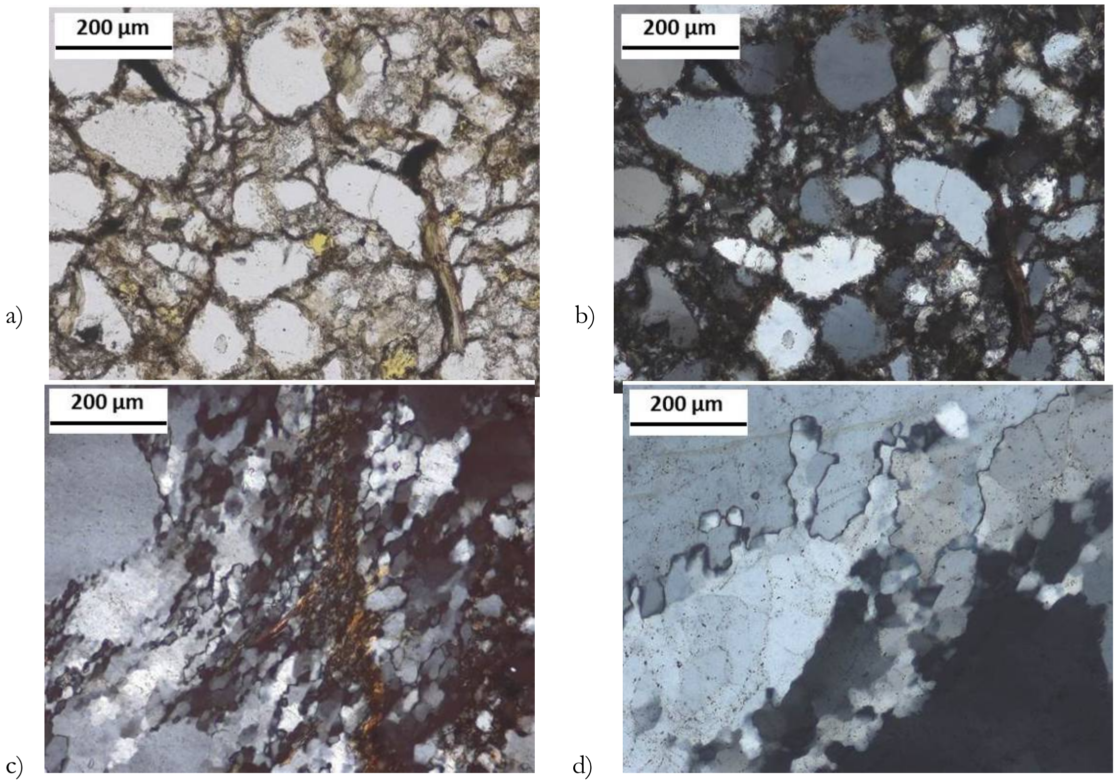

FIGURE 5: Example photomicrographs from the Petrographic Atlas, RILEM AAR-1.2 (7): a & b are sedimentary rocks, in plane & cross polarised light, respectively, whilst c & d are metamorphic rocks in cross-polarised light. Full details are given in the Atlas. [7]

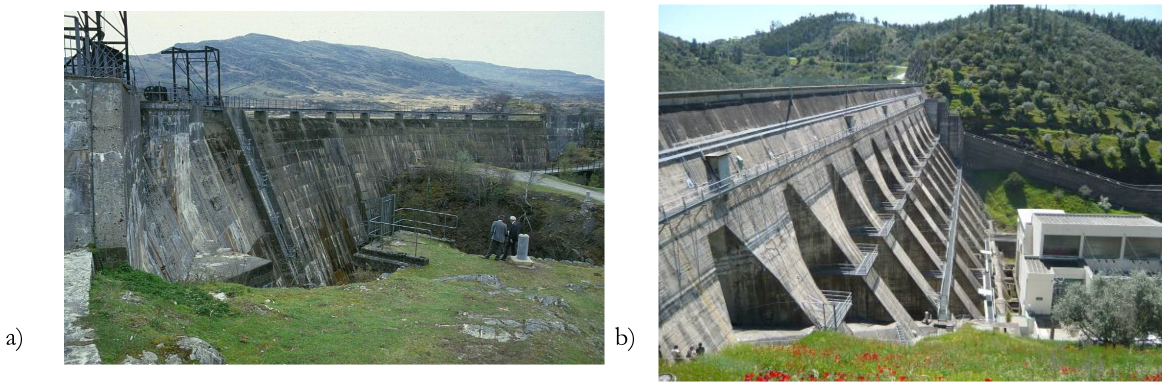

FIGURE 6: Some dams affected by ASR: a) old Maentwrog (Wales, UK, now superseded) and b) Pracana (Portugal, after repair) .


FIGURE 7 Prof Borge Wigum, then leading a TC 219-ACS field visit in Iceland in 2011 (showing the demands of AAR fieldwork?!).