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ALKALI-SILICA REACTION IN THE REPUBLIC OF IRELAND: RECENT RESEARCH AND REVISIONS TO NATIONAL GUIDANCE

Mark G. Richardson*
(Department of Civil Engineering, University College Dublin,
National University of Ireland Dublin, Belfield, Dublin 4, Republic of Ireland)

ABSTRACT

There have been no reported cases of damaging alkali silica reaction (ASR) in the Republic of Ireland to date. This situation is unusual in an international context given the presence of significant amounts of chert in aggregates used for concrete and the existence of a sustained period during which high alkali content cements were used. National guidance on minimizing the risk of ASR in the Republic of Ireland was first published in 1991. It was an interim document that represented the best available knowledge of ASR at the time in the context of conditions and practice in the Republic of Ireland. The working party that wrote the report recommended that the document should be reviewed periodically as new materials and findings became available and that further study would be of value in the topics of testing and the role of chert in ASR behaviour. The working party was recently reconvened to review the intervening decade of national and international research and developments on ASR. This resulted in new national guidelines being published in 2003.
This paper reviews the new national guidelines and outlines the background to the revisions by reference to national research. Particular reference is made to a detailed study of the petrography of Irish chert-bearing aggregates; the behaviour of greywacke aggregates; the influence of slag alkali content and experience with draft international test methods

Key words: Alkali-silica reactivity, Ireland, Chert, National guidance

1 INTRODUCTION

No cases of damaging alkali-silica reaction (ASR) have been reported in the Republic of Ireland to date. Guidance on minimizing the risk of its occurrence has been in place for over ten years. The first assessment of the issue in Ireland was conducted by Bannon [1] in 1986. He found that contemporary United Kingdom precautionary measures (the Concrete Society [2] 'Hawkins Report') would be unnecessarily restrictive in Irish practice. Many Irish practitioners use British standards and guidance documents where equivalent national or harmonized European documents are not available. Later editions of the 'Hawkins Report' therefore specifically noted that the advice was not applicable in the Republic of Ireland. Therefore the Institution of Engineers of Ireland (IEI) and the Irish Concrete Society (ICS) established a joint working party, chaired by Professor J. W. deCourcy, to prepare national guidance and this was published in 1991 [3].

*Ph. +353 1 7167241, Fax. +353 1 7167399,
E-mail: mark.richardson@ucd.ie

It was recommended that the document should be reviewed periodically as new materials and findings became available. Recently the text of European standard EN206-1 was approved and published by national standards authorities as a non-harmonised standard, for example as Irish Standard I.S./EN206-1 [4]. Clause 5.2.3.4 of I.S./EN206-1 refers the practitioner in Ireland to the IEI/ICS report on ASR. It was timely therefore to update the 1991 document. Submissions from national and international experts were invited. Five aspects were noted for review. These were:

- the reactivity of Carboniferous chert,
- the alkali trigger level for reaction,
- the reactivity of greywacke aggregates,
- the alkali contribution of secondary cementitious materials,
- international developments in test methodologies.

The guidance was updated in the light of this review and was recently published by the IEI and the ICS [5].

This paper reviews the international and national developments in the five areas that underpinned change in national practice. It presents the findings of the working party's review and the consequent latest guidance for Irish practice.

2 REVIEW OF DEVELOPMENTS

2.1 Reactivity of Carboniferous chert

Limestone is a common source of aggregates for concrete in Ireland. Limestone may incorporate significant quantities of chert. Chert is a constituent that has given rise to concern internationally in the context of ASR. The bedrock of Ireland is dominated by Carboniferous limestone, as illustrated in Fig. 1. High alkali levels pertained in cements used during a significant period of construction prior to 1990 but there are no documented cases of reaction indicating that the aggregates did not have a strong potential for reaction. This curious phenomenon was studied by Strogen [6] and later by McNally *et al.* [7].

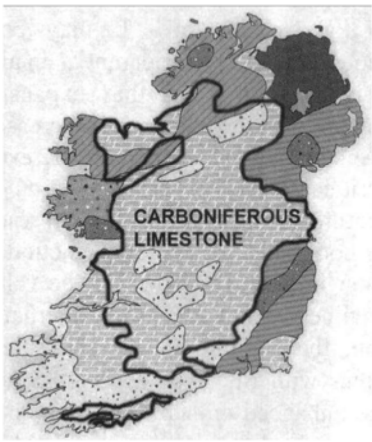

Fig. 1 Map of Irish Carboniferous limestone.

Strogen used the Quartz Crystallinity Index (QCI) method of Murata and Norman [8] to compare the crystallinity of Irish chert with reactive material from the neighbouring United Kingdom (U.K.). He found that the Irish cherts were kinetically more stable than the reactive U.K. flints, which were Cretaceous in origin and had been exposed to temperatures of up to 200°C. However the older Irish Carboniferous cherts had been subjected to temperatures of up to 350°C. He postulated that the Irish cherts had been annealed to some degree and that the consequent enhanced crystallinity made them more resistant to reaction. The crystallinity of the chert in an aggregate is a very significant influence in its reactivity. Perfectly crystalline materials have no free energy associated with the crystal lattice but deviations in degree of perfection increases free energy.

McNally *et al.* built on Strogen's hypothesis by determining both QCI and domain size in a wider sample of materials. Domain size was determined through the methodology of Klug and Alexander [9] and Cullity [10] applied to X-ray diffraction studies. The number of dislocations is higher in materials with low domain size and, by implication, predisposition to alkali-silica reaction is increased. The difference in crystallinity between Irish cherts and English flints was confirmed with the wider sample, as illustrated in Fig. 2. The Irish cherts had an average QCI of 7.0 whereas the English reactive flints had an average value of 2.2. The corresponding values for average domain size were 634 Å and 290 Å respectively.

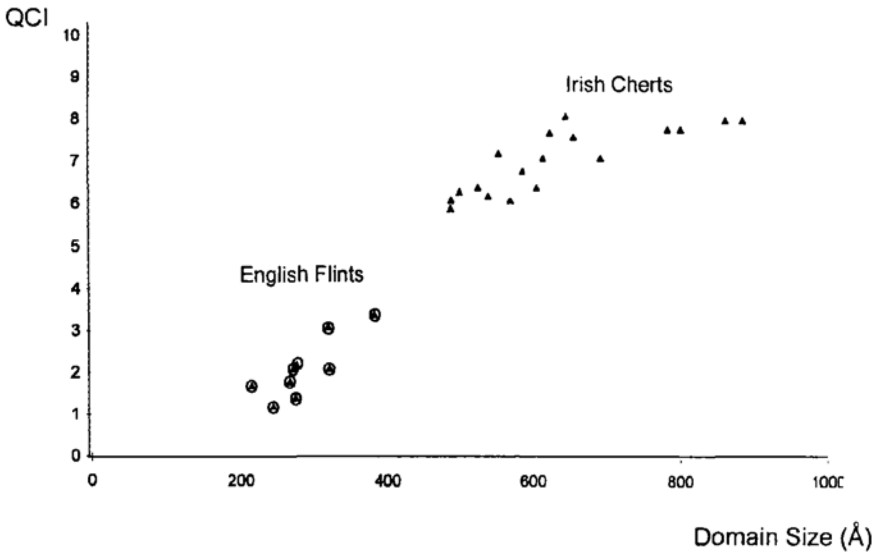

Fig. 2 Distinction between English flints and Irish cherts through QCI and domain size.

It was concluded from the crystallinity studies that the difference in free energy distinguishes the kinetic stability · of reactive English flints and Irish cherts and that this supported a proposition that the trigger level for ASR in Ireland would be higher than average for constituents of similar classification in other countries.

A surprising finding was that the lower bound domain size found in the Irish aggregates, 487 Å, was not far removed from the upper bound of the reactive English flint domain size, 382 Å. This limited spread diminished the case for having a higher alkali load limitation for cherts of Carboniferous age compared with other Irish aggregates. Such a differentiation had been a feature of the Irish national guidelines for minimizing the risk of damaging ASR [3].

2.2 Alkali trigger level for reaction

Despite the innocuous behaviour in service and geological evidence of stability, a significant number of Irish aggregates and aggregate combinations demonstrated expansions in standard tests for reactivity, as reported for example by McNally and Richardson [11]. It was postulated that the anomalous behaviour of the aggregates and aggregate combinations, that failed to demonstrate innocuous behaviour in the tests, was due to the lower alkali levels found in service. The test levels, for example about 7 kg Na_2O eq/m^3 in the concrete prism tests, are typically double the highest value that might be found in practice. Hobbs [12] suggested that there is a critical alkali content above which abnormally high expansion occurs, a level that he found to be about 5 kg Na_2O eq/m^3 in flint bearing U.K. aggregates.

The potential existence of high critical alkali threshold levels in respect of certain Irish aggregates, as opposed to an uncharacteristic immunity to reaction, was investigated in two studies under the author's supervision. The findings of the initial pilot study (McNally and Richardson [13]) supported the proposition of threshold levels of about 6 kg Na_2O eq/m^3 and further supportive evidence was found in the unpublished second study. The trend illustrated in Fig. 3 is typical of the findings. This shows the expansion profile in tests on concrete prisms cast from CEM I concrete with an argillaceous limestone coarse aggregate and a fine aggregate containing 30% chert. The mix parameters were similar except for the alkali level. The test methodology was based on the British Cement Association [14] protocol for greywacke aggregates. This protocol is a variation of standard concrete prism tests and it allows variation of the alkali content. Three alkali levels were tested: 4, 5 and 6 kg Na_2O eq/m^3. It may be seen that innocuous behaviour is apparent at an alkali level of 4 kg Na_2O eq/m^3 but that expansion become significant when the alkali level increases.

An alternative viewpoint to the existence of a high critical alkali level for reaction is that the temperature of test (38°C), unrepresentative of service conditions, promotes a reaction that would not occur in practice. However the validity of the test regime is not disputed internationally. In addition, the finding of a high critical level is consistent with the hypothesis of Strogen [6] in that the enhanced crystallinity of Irish aggregates may have raised the reaction threshold level rather than eliminated the potential for reaction.

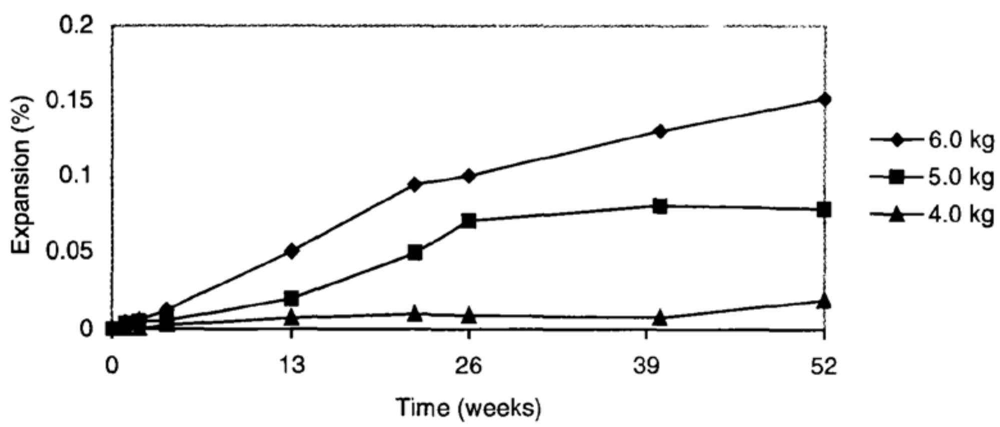

Fig. 3 Expansions of similar concrete prisms made with alkali levels of 4, 5 and 6 kg Na_2O eq/m^3

2.3 Reactivity of greywacke aggregates

The reactivity of aggregate classed as greywacke varies enormously throughout the world, from innocuous to deleterious. However particular concern has been generated in recent years in respect of the potential reactivity of greywacke aggregates. Such aggregates are considered by many to be highly reactive though slowly expansive. For example, in the United Kingdom a special protocol for greywacke aggregates has been published by the British Cement Association (BCA) [14]. The test protocol allows the general United Kingdom limit for highly reactive aggregates (2.5 kg Na_2O eq/m^3 [15]) to be increased, to a maximum of 3.5 kg Na_2O eq/m^3, if prescribed expansion limits are not exceeded.

The behaviour of greywacke aggregates has not been extensively researched in the Republic of Ireland due to the lack of significant commercial sources to date. However a small comparative study was done under the author's supervision, which served to highlight the need for caution when considering the use of greywacke aggregates. A selection of greywackes was tested including those that could, in certain circumstances, be imported into Ireland. The BCA [14] test protocol was used. Most demonstrated innocuous behaviour at alkali loads of less than or equal to 4 kg Na_2O eq/m^3. However one was potentially expansive, judged by the BCA criteria, when tested at alkali loads in excess of 3.5 kg Na_2O eq/m^3, as illustrated in Fig. 4.

2.4 Secondary cementitious materials

The alkali contribution from secondary cementitious materials, such as ground granulated blastfurnace slag (ggbs) and pulverised fuel ash (pfa), is influenced by two factors. The first is the alkali content of the material and the second is the fraction of this content that is available for reaction. It has long been accepted that not all of their alkalis were available for reaction. The IEI/ICS 1991 guidance [3] in respect of ggbs and pfa therefore reflected international practice at the time and the alkali contribution of ggbs and pfa to concrete was computed as 50% and 17% of their alkali content respectively. However some changes have been introduced in other countries since then with some liberalisation at high replacement levels but a more conservative approach at lower levels. For example, the latest Building Research Establishment [15] guidance for U.K. practice ignores the alkali contribution of ggbs above about 40% replacement but takes it fully into account below the 25% level.

Another aspect of the U.K. advice is that it is restricted to ggbs and pfa with maximum acid soluble alkali contents of 1% and 5% respectively. This presumably covers commonly used sources of the material in U.K. practice. The working party who drafted the new guidelines for the Republic of Ireland were mindful of these developments but were also conscious of the fact that ggbs could be imported into the country with alkali contents higher than 1%.

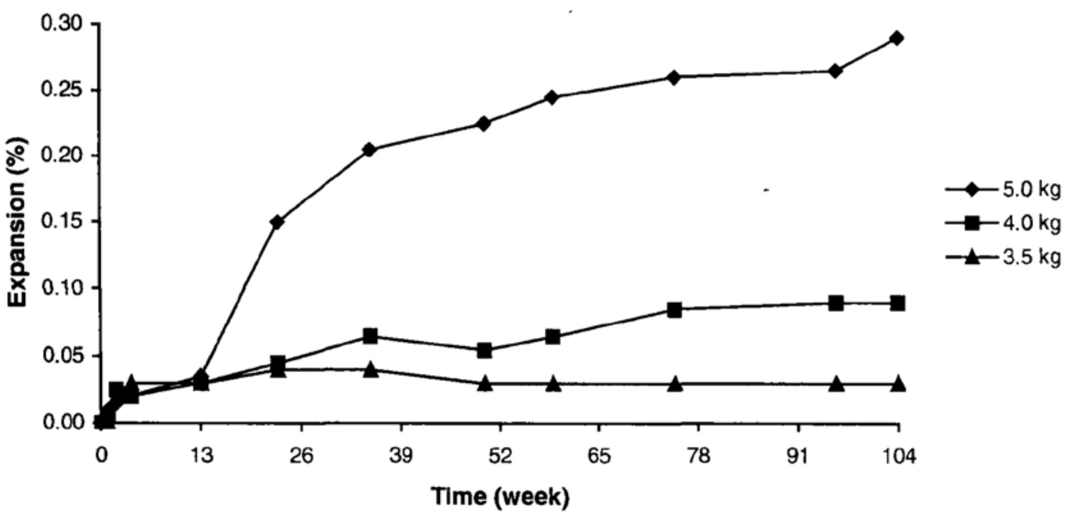

Fig. 4 Expansion profile of greywacke aggregate concrete prisms made with alkali levels of 3.5, 4.0 and 5.0 kg Na_2O eq/m^3

A study was initiated under the author's supervision of the influence of ggbs alkali level on alkali-silica reactivity. The findings of the first phase of the study were reported by Hester *et al.* [16]. Expansion tests were conducted at a replacement level of 50% using two sources of ggbs. One source ('Slag 1') had an alkali content below 1% whereas the other ('Slag 2') was above this level. Several alkali loads and aggregate combinations were tested and similar trends emerged in all cases. Examples of the trends are illustrated in Figs. 5 and 6 for argillaceous limestone and greywacke aggregate concretes respectively.

The slag concretes had very low expansion levels and the difference between the behaviour of slag mixes was marginal. It was concluded that the alkali content of the slag is not a factor at high replacement levels. This assertion is supported by the findings of Arano and Mitsunori [17]. They tested slag concretes at replacement levels of 5%, 10%, 20%, 30%, and 60%. It was demonstrated that the degree of expansion decreased as the replacement level increased. Their hypothesis is that the mobility of the ions may be reduced in the pore solution of the slag concrete, thereby delaying or reducing the extent of expansion.

The trends indicate that the alkali contribution of ggbs could be ignored at high replacement levels irrespective of its acid soluble alkali content. Studies with pfa and at lower ggbs replacement levels have yet to be concluded.

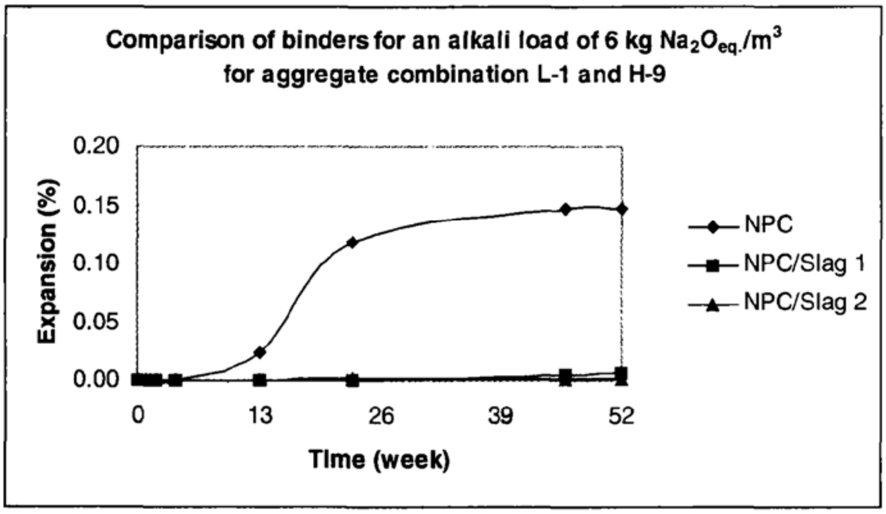

Fig. 5 Expansions of argillaceous limestone aggregate concrete prisms made with NPC and ggbs combinations of differing alkali content

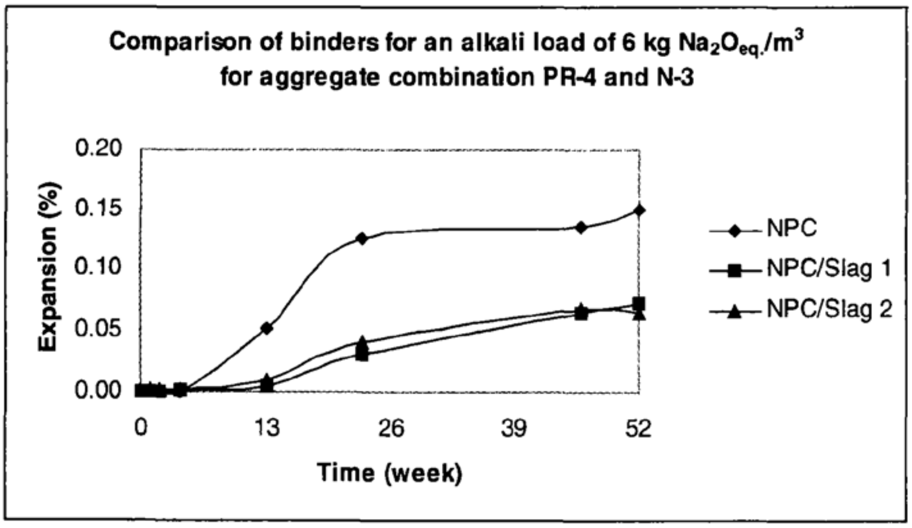

Fig. 6 Expansions of greywacke aggregate concrete prisms made with NPC and ggbs combinations of differing alkali content

2.5 International developments in testing

The IEI/ICS guidance published in 1991 [3] could not be definitive in relation to testing due to the absence of an extensive national database of results. Nevertheless the practitioner was advised that these tests, though not definitive, could be helpful in assessing the acceptability of an aggregate. A review of developments since 1991 was conducted by the working party that drafted the revised guidance in 2003.

A good database of results has been built up at University College Dublin from research and *ad hoc* testing for aggregate suppliers. Significant commercial Irish aggregate combinations have been tested according to the methodology of the RILEM ultra-accelerated mortar bar test [18] and the concrete prism test according to BS 812: Part 123 [19]. The performance of the Irish aggregate combinations in the two tests is shown in Fig. 7 and Fig. 8 respectively.

It may be seen in Fig. 7 that only 3 of the 14 combinations tested satisfied the draft requirements for classification as 'non-expansive' in the mortar bar tests and that longer term concrete prism testing of the others was warranted. The results of the concrete prism tests presented in Fig. 8 indicate that of the nine aggregate combinations tested, only one meets the non-expansive criteria, while five combinations are classified as expansive.

Maximum expansions were associated with the use of combinations incorporating argillaceous limestone coarse aggregate. These represent very significant commercial sources of aggregate near the capital city, which is developing rapidly and accounts for a major portion of the country's construction output.

It is accepted that the tests are not definitive in the Republic of Ireland because reactive aggregates have not been found in practice. However the test results, in conjunction with petrographic examination, may be helpful in deciding if the aggregates are classifiable as 'unlikely to be alkali-reactive'. The working party therefore also reviewed other developments in test methodologies, particularly in the U.K. and the work of RILEM TC-106-AAR and TC-ARP, as summarized by Sims and Nixon [20]. It is generally the case in Ireland that alternative routes, such as meeting the alkali limit, can be used to satisfy requirements if the reactivity of the aggregate is not established. However information on international test methods is useful as informative guidance for those who must make a judgement on an aggregate's suitability for a particular project.

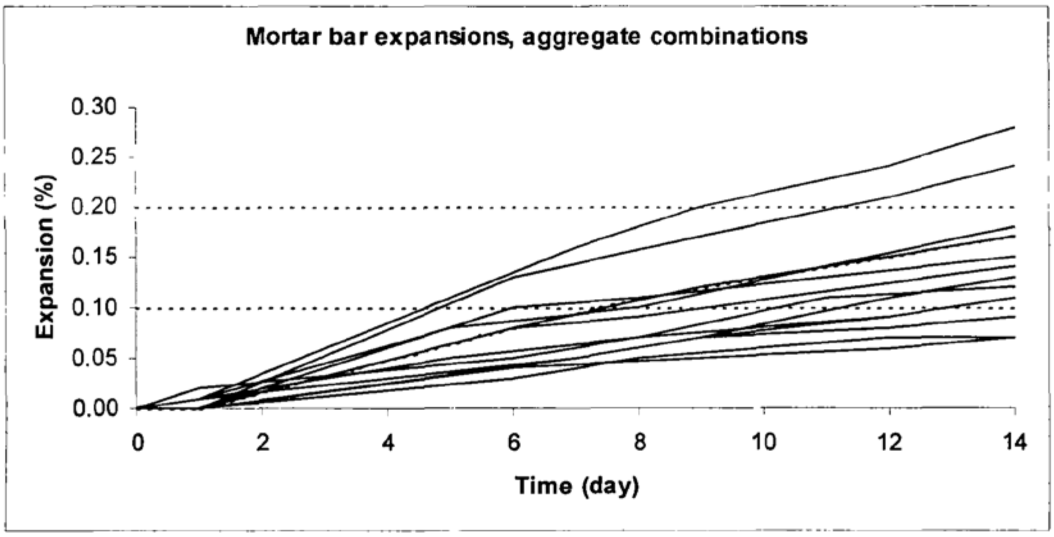

Fig. 7 Performance of Irish aggregate combinations - ultra-accelerated mortar bar test, average expansions

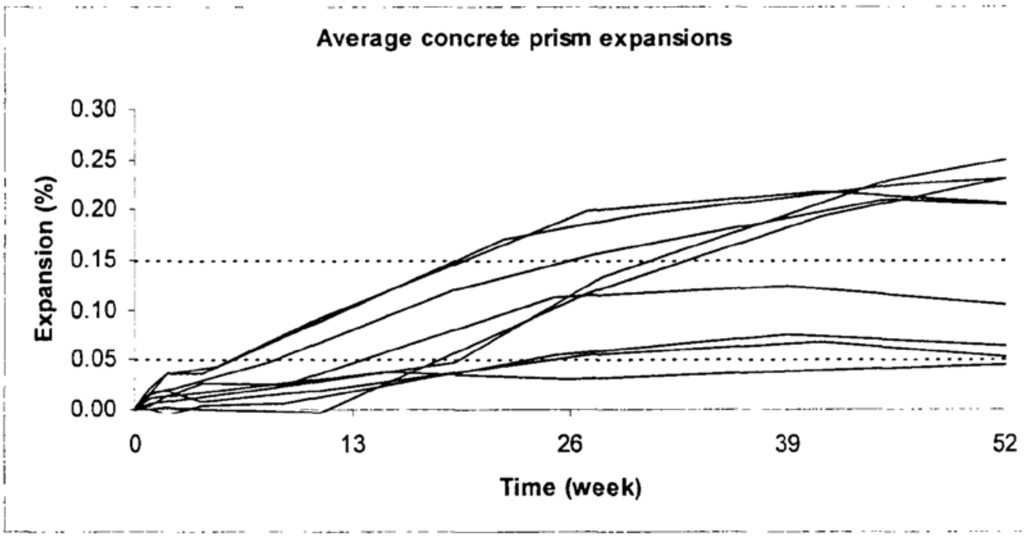

Fig. 8. Performance of Irish aggregate combinations – concrete prism test, average expansions.

3 REVISED GUIDANCE

The reconvened IEI/ICS Working Party considered the developments described in Section 2 and updated the 1991 guidance. The revised guidance was published in 2003 [5]. The opportunity was used to streamline the advice as much as possible. Judgement was exercised to strike a careful balance between minimizing the complexity of the guidance and maximizing the effectiveness of risk management in the context of a phenomenon that has yet to manifest itself in Irish concrete practice. A summary of the revised guidance is presented in flowchart form in Fig. 9 and the rules associated with the calculation of alkali content are presented in Table 1.

In summary, the main points are as follows:

- the guidelines do not apply to concrete mixes with cement contents in excess of 500 kg/m^3 due to the lack of any track record in service regarding reactivity;
- three parallel routes for minimizing risk are presented, based on the established routes of control of moisture, aggregate reactivity or alkali content,
- a combination of petrography and satisfactory history of use may be used to establish the acceptability of an aggregate combination, subject to a prescribed definition of 'satisfactory history of use';
- general advice is presented on the subject of available test methods but is not presented with definitive interpretation limits;
- a general alkali limit of 4.5 kg/m^3 applies where the reactivity of aggregates is unknown or deemed worthy of control but a lower limit of 3.5 kg/m^3 applies for greywacke aggregates;
- the alkali limitations, for example 4.5 kg/m^3, includes an allowance for variability as indicated in Table 1;
- the alkali contribution of ggbs, including an allowance for variability, may be assumed to reduce to fifty per cent of the acid soluble alkali content, except where the replacement level is less than 40%;
- the alkali contribution of pfa, including an allowance for variability, may be assumed to reduce to twenty per cent of the acid soluble alkali content, except where the replacement level is less than 21%;
- the alkali contribution of chloride in aggregate must be taken into account except where the chloride ion content is less than 0.02 %;
- a 'low alkali' cement may be used as an alternative to other precautions. Such a cement is defined as one with an alkali content less than or equal to 0.6 kg Na_2O eq/m^3, including an allowance for variability of 1.64 standard deviations.

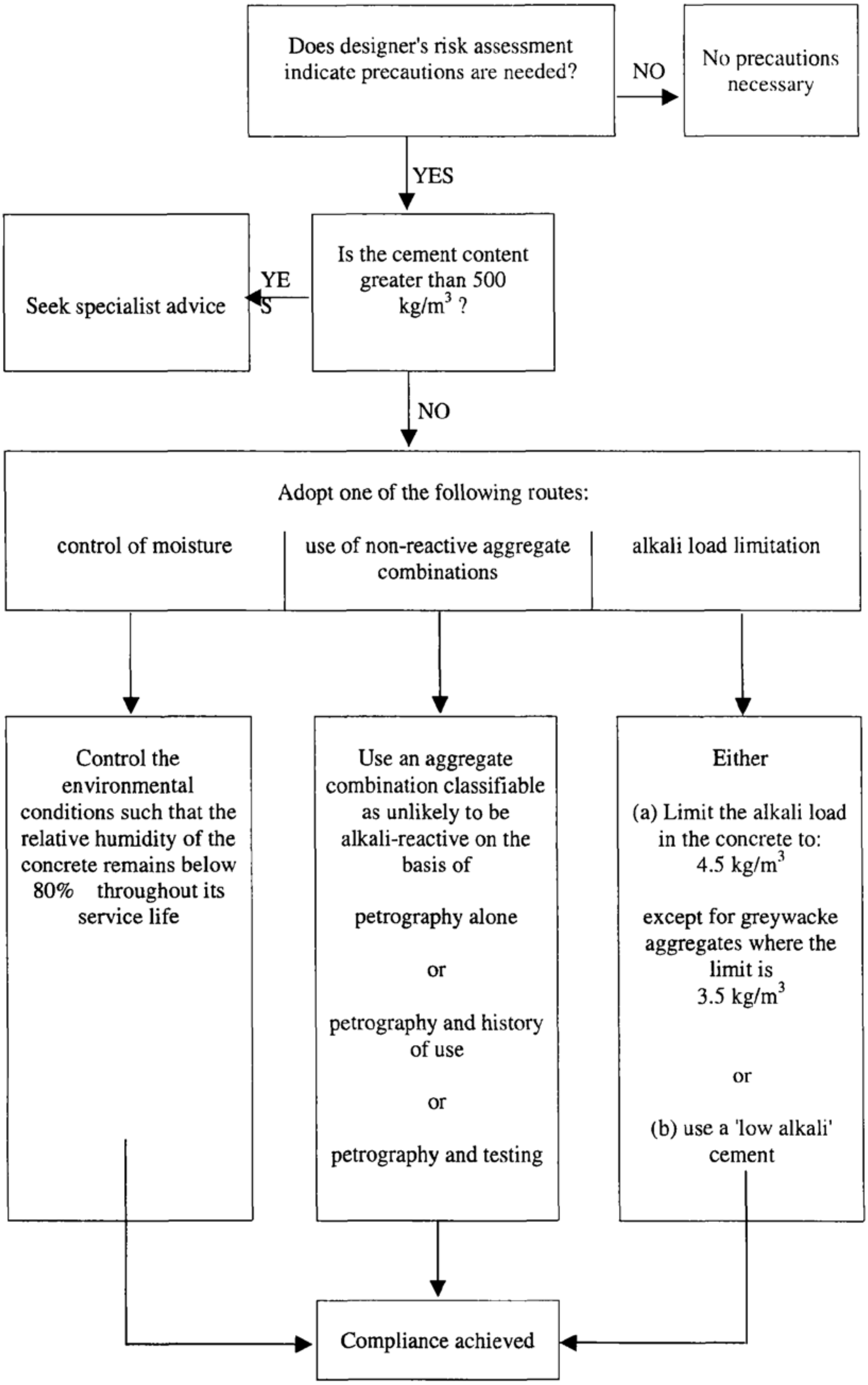

Fig. 9 Flowchart summarising proposed recommendations for future Irish practice (from IEI/ICS [5])

Table 1: Summation of alkali load value (from IEI/ICS [5])

Contributor	Contribution	Determination
Cement	Certified average alkali content plus an allowance for variability of 1.64 standard deviations, factored by cement content	Cement content x (Average Na_2O_{eq} + 1.64 std. dev.) $Na_2O_{eq} = Na_2O + 0.658\ K_2O$
Aggregates	Chloride ion content, expressed as a percentage by mass, factored by 0.76. May be ignored if the chloride ion content is less than 0.02 %.	0.76 x (Cl^- content) unless $Cl^- < 0.02$ %
Ground granulated blastfurnace slag	If ggbs content is less than 40%: One hundred per cent of acid soluble alkali content plus an allowance for variability of 1.64 standard deviations, factored by ggbs content	ggbs content x (Average Na_2O_{eq} + 1.64 std. dev.) if ggbs content < 40%
	If ggbs content is equal to or greater than 40%: Fifty per cent of acid soluble alkali content plus an allowance for variability of 1.64 standard deviations, factored by ggbs content	ggbs content x 0.5 (Average Na_2O_{eq} + 1.64 std. dev.) if ggbs content $\geq$ 40%
Pulverised fuel ash	If pfa content is less than 21%: One hundred per cent of acid soluble alkali content plus an allowance for variability of 1.64 standard deviations, factored by pfa content	pfa content x (Average Na_2O_{eq} + 1.64 std. dev.) if pfa content < 21%
	If pfa content is equal to or greater than 21%: Twenty per cent of acid soluble alkali content plus an allowance for variability of 1.64 standard deviations, factored by pfa content	pfa content x 0.2 (Average Na_2O_{eq} + 1.64 std. dev.) if pfa content $\geq$ 21%
Admixture	Alkali content of admixture, if any, factored to take account of dosage rate.	(Na_2O_{eq}) x dosage rate factor

4 CONCLUDING REMARKS

The task of framing national guidelines to minimise the risk of damaging ASR is difficult in a country where the problem has yet to manifest itself. In these circumstances the possibility of being too lenient is as likely as being too conservative until one is wise after the event. Thankfully the Republic of Ireland does not as yet have examples of damaging ASR in practice but specifiers and producers are mindful of the fact that similar conditions prevailed for decades in other countries before the problem was first detected. The IEI/ICS Joint Working Party on ASR hope that they have struck a fair balance between prudent restrictions and the efficient use of Ireland's abundant resource of aggregates for concrete.

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