Second International
Dam World Conference
PORTUGAL • LISBON • LNEC • April 21-24, 2015

ALKALI-AGGREGATE REACTION, AAR – DEALING WITH AAR IN LARGE CONCRETE STRUCTURES

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Keywords: Concrete structures, Deterioration, Alkali-silica reaction.

Abstract. *A significant number of problems related to concrete deterioration have been detected in large concrete structures in Portugal and worldwide, the leading cause being AAR. The importance of these structures, the number of for which AAR has already been identified or is very likely to be diagnosed in a near future, as well as the number of structures that are under or planned for construction, which may also come to develop AAR is why it is still nowadays a major concern. Therefore, a study is being conducted at LNEC to diminish the negative impact of AAR by increasing knowledge on how to reliably control AAR in new structures and on how to properly assess its extent and potential for future development in the existing ones, so that the risks to structural integrity and need for mitigation/remediation actions can be properly assessed. This paper presents methodologies, based on state-of-the-art knowledge collected on that study, which may be used by the construction industry stakeholders in the prevention of AAR in new concrete structures and on AAR diagnosis and prognosis in existing concrete structures. The presented information also provides an insight to LNEC specifications that LNEC will soon publish on this thematic.*

1 INTRODUCTION

Currently, two types of alkali-aggregate reactions are recognized depending on the nature of the reactive mineral: Alkali-Silica Reaction (ASR), which involves various types of reactive silica minerals; and Alkali-Carbonate Reaction (ACR), which involves certain types of dolomitic rocks. In Portugal, up to this moment, only one case was detected in a building and, since then, no more problems have been detected concerning concrete deterioration due to ACR. However, in respect to deterioration of concrete infrastructure by ASR the situation is different, and the number of affected structures has increased significantly in recent years. ASR occurs between alkali hydroxides in concrete pore solution and some siliceous minerals present in certain aggregates, and results in the formation of a hydrophilic gel that expands in the presence of water and, in certain conditions, may disrupt concrete. ASR has important economic implications, since it is normally observed in very large structures (e.g. dams, bridges) and the work necessary to remediate the problem involves large areas of reconstruction and complex and expensive repairing techniques and materials. In addition, ASR diminishes the affected structure

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service life, may involve the interruption of its function and, ultimately, can lead to its decommissioning and demolishing.

Due to the rhythm at which ASR is being identified in existing structures and the number of new ones under or planned for construction in Portugal, which may also come to develop ASR, it is predicted that concrete deterioration will continue to increase. The reasoning for this is that distress signs appear decades after construction; numerous structures were built with aggregates which are now known to be reactive; concrete formulation considered that the only alkali source was the cement, this is now known not to be true; structures can now be built free from deleterious ASR, but several are being constructed with aggregates for which reactivity tests give unreliable results; large structures require vast amounts of aggregates, so in many cases local rocks are used, thus some new structures use potentially alkali reactive aggregates.

2 NEW CONCRETE STRUCTURES

Presently, only two European standards deal with ASR, EN 206 [1] and EN 12620 [2], and they just state that actions shall be taken to prevent ASR in new structures using procedures of established suitability. Due to the complexity and multiplicity of factors involved in ASR together with the variability of the materials used (e.g. cements, aggregates, admixtures, supplementary cementitious materials - SCMs), no such established procedures exist, and each country has to rely on national specifications. Because of that, in Portugal, LNEC Specification E 461 [3] was created in 2004. However, due to the scientific developments occurred since then, a new revised version will soon be published to better support stakeholders on how to prevent ASR in new concrete structures. The main differences between the revised and original version reside in the methodology followed to identify an aggregate reactivity and in the assessment of the level of precaution and choice of appropriate precautionary measures.

The methodology envisaged to identify a deleteriously reactive aggregate is presented in Figure 1. It can be seen that in order for a rock be used as an aggregate for concrete in Portugal it is always necessary to assess at the laboratory its ASR reactivity. The petrographic examination shall be made according to LNEC Specification E 415 [4] and will allow to classify the aggregate as belonging to Class I (very unlikely to be alkali-reactive), Class II (potentially alkali-reactive or alkali-reactivity uncertain) or as Class III (very likely to be alkali-reactive). Although, petrography may be used to classify an aggregate as potentially or likely alkali-reactive, expansion tests are required to determine the extent of the reactivity and appropriate levels of prevention. According to the presented methodology, aggregates may be accepted as non-reactive solely on the basis of petrography but that decision has a certain risk associated; therefore, in some situations, like dams and other very long service life structures, it is advisable to perform the expansion tests as well.

The expansion tests prescribed comprise accelerated mortar-bar tests – AMBT [5, 6] and concrete-prism tests – CPT [7, 8]. From all existing tests, it has been considered that those tests produce results more consistent with the ones observed in the field. If the aggregate is considered to be non-deleteriously-reactive (i.e. obtained an expansion lower than the maximum expansion limit defined in the tests), it can be accepted for use in concrete with no further consideration of mitigation actions (as long as it complies with NP EN 206-1). If the aggregate is found to be deleteriously reactive, either it is not used or preventive measures shall be used to prevent the development of deleterious ASR in the concrete structure.

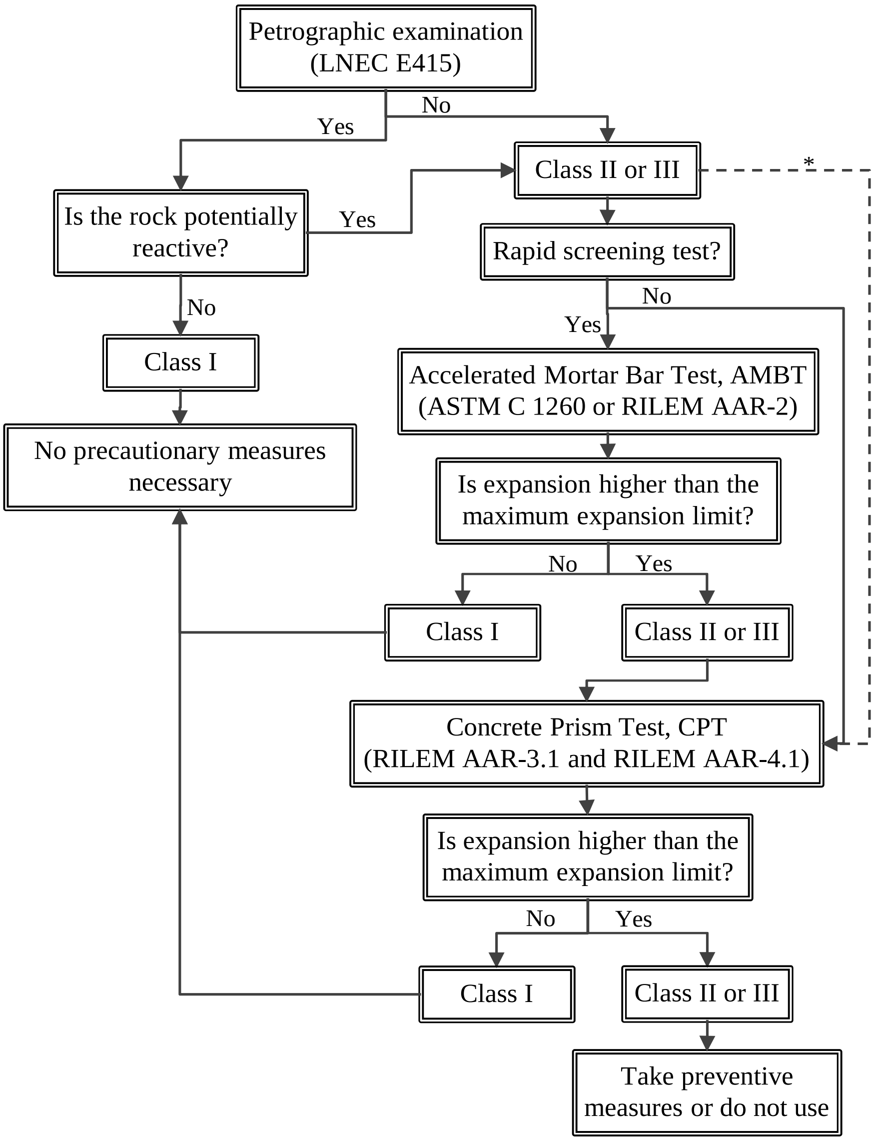

Figure 1: Methodology for evaluating aggregate alkali-silica reactivity.

The maximum expansion that can be attained by the mortar in the expansion test, which is likely to indicate non-deleterious expansive materials, has not received a consensus up to this moment. Nevertheless, materials that exhibit an expansion of less than 0.10 % at 14 days of testing will be of innocuous behaviour in most cases, whilst an expansion exceeding 0.20 % is likely to indicate expansive materials. Aggregates providing results in the intermediate range of 0.10 % to 0.20 % shall be considered as being potentially alkali-reactive and, in such situations, comparator readings should be taken until 28 days of testing.

It has been shown that, for some aggregates, the AMBT might incorrectly identify a deleteriously reactive aggregate as being non-deleteriously-reactive; therefore, in spite of the most reliable approach for determining aggregate reactivity being the CPT, its duration does not make it feasible for all situations and the AMBT is still essential in the alkali-silica reactivity appraisal (Figure 2). Furthermore, for aggregates containing porous chert as a potentially reactive constituent, and in the case of the so called slowly reactive aggregates (e.g. granites and certain basalts), the AMBT shall not be performed, as it does not provide a reliable result (Figure 3); in this case the route marked with a dashed line in Figure 1 shall be followed instead.

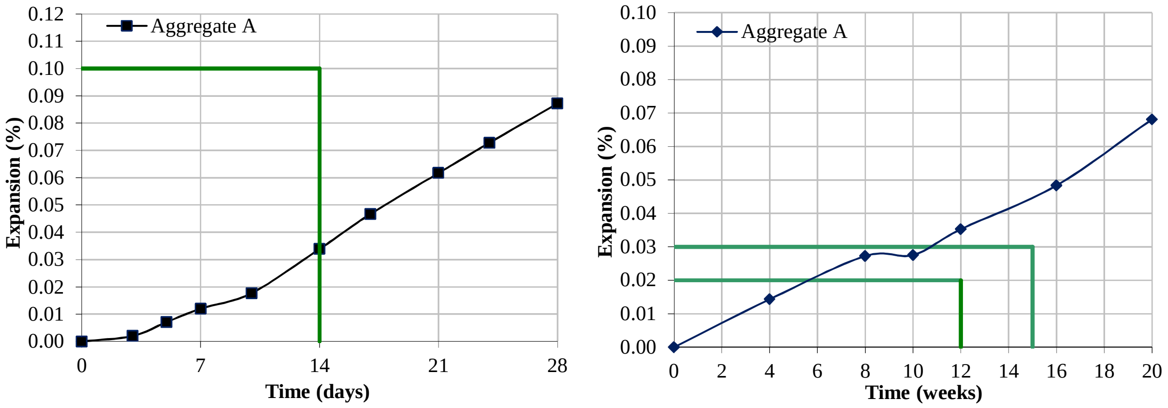

Figure 2: Example of an aggregate passing the AMBT (expansion at 14 days lower than 0.10 %) and failing the CPT at 60 ºC (expansion at 12 weeks higher than 0.02 % and at 15 weeks higher than 0.03 %).

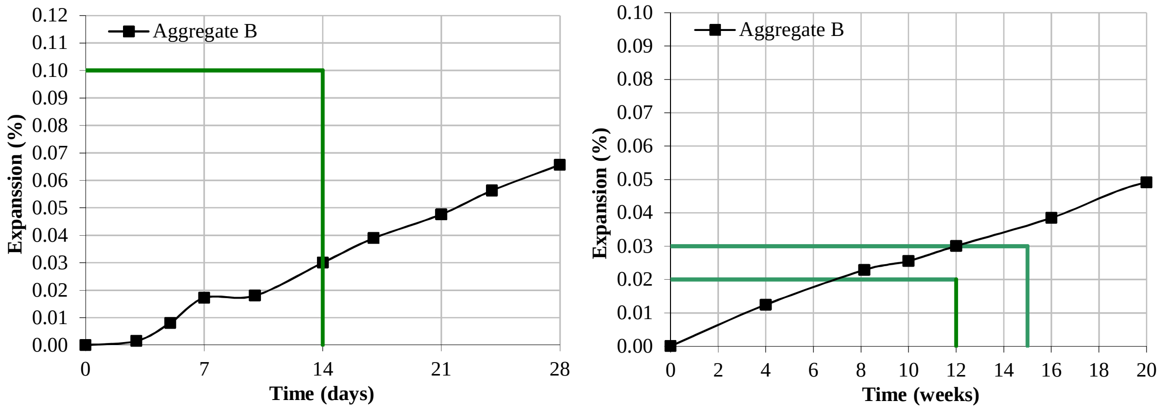

Figure 3: Example of a slowly reactive aggregate passing the AMBT (expansion at 14 days lower than 0.10 %) and failing the CPT at 60 ºC (expansion at 12 weeks higher than 0.02 % and at 15 weeks higher than 0.03 %). This aggregate has been found to be deleterious reactive in a structure.

The limit of the maximum expansion that can be attained by the concrete in the expansion test, which is likely to indicate non-expansive materials, has not received yet a broad consensus. However, it seems that results in the AAR-3.1 test (usually after 12 months) of less than 0.05 % are likely to indicate non-expansive materials; whilst, results exceeding 0.10 % indicate expansive materials. Aggregates yielding results in the range of 0.05 % to 0.10 % shall be considered as being potentially alkali-reactive. For slowly reactive aggregates, a lower criterion of 0.03 % at 12 months should be used instead or, preferably, the test shall be prolonged to 24 months (Figure 4). Independently, of the aggregate evaluated, if expansion is still occurring at 12 months of testing, it is recommended that the test continues until expansion ceases or it has become clear if the criteria will or will not be exceeded. If such continued testing is not feasible, then a decision will have to be made from the inspection of the shape of the expansion curve up to 12 months, as to whether or not the criteria would be likely to be exceeded during the extended testing period. In terms of the AAR-4.1 test, it is believed that a maximum expansion in the test of 0.03 % at 15 weeks indicates a non-reactive aggregate. The findings from the CPT shall always take precedence over the results from petrography examination and AMBT. For large concrete structures with a long-service life, it is recommended that the maximum expansion limit for concrete shall be 0.03 % at 1 year and/or 0.04 % at 2 years in the AAR-3.1 tests; and 0.02 % at 12 weeks and/or 0.03 % at 15 weeks or longer in the AAR-4.1 test (Figure 5).

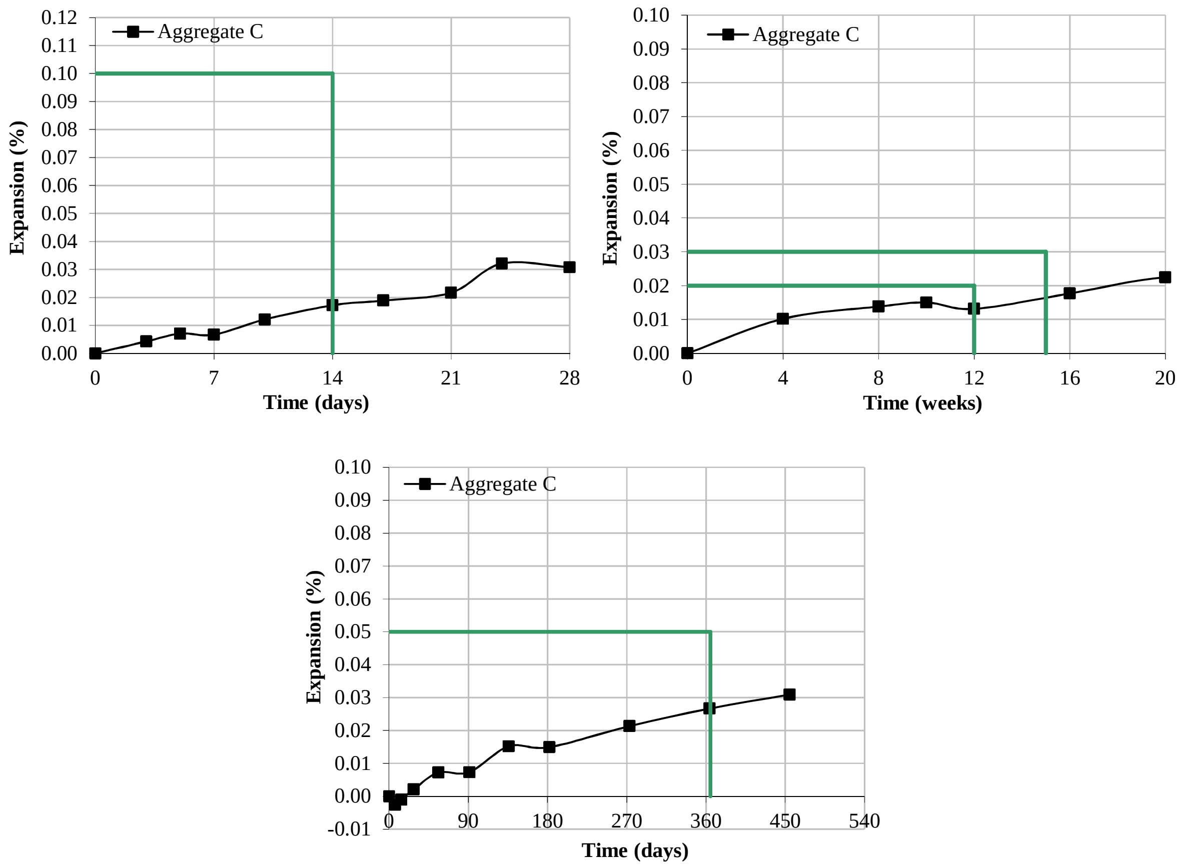

Figure 4: Example of a slowly reactive aggregate passing the AMBT (expansion at 14 days lower than 0.10 %) and both the CPT at 60 ºC (expansion at 12 weeks lower than 0.02 % and at 15 weeks lower than 0.03 %) and the CPT at 38 ºC (expansion at one year lower than 0.05 %). This aggregate has been found to be deleterious reactive in a structure.

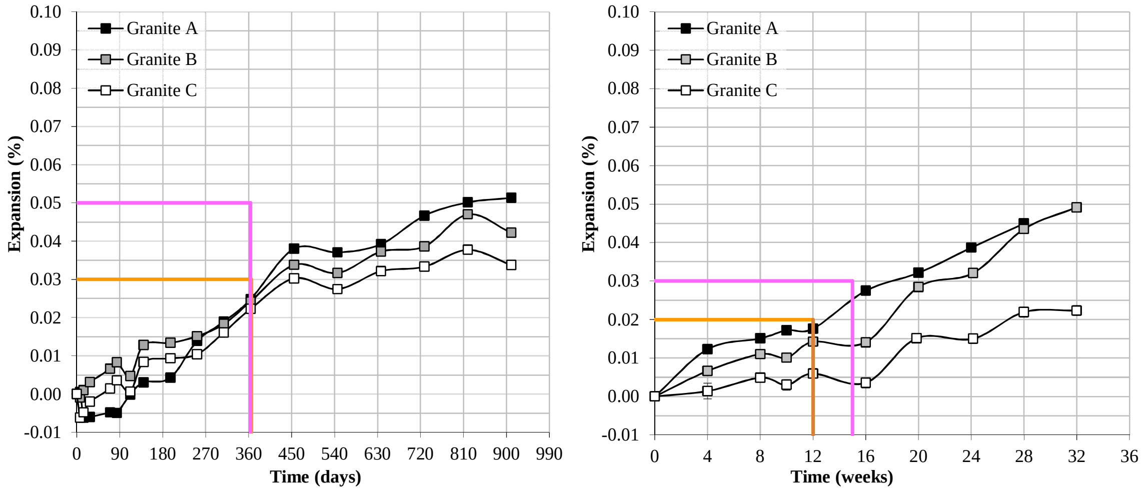

Figure 5: Expansion curves obtained in AAR-3.1 and AAR-4.1 tests for three slowly reactive aggregates to be used in a new dam (left and right hand graphs respectively). For the AAR-3.1, it is observed that at 12 months all of them fulfil the traditional AAR-3.1 expansion limit (0.05 %) and even that proposed for slowly reactive aggregates (0.03 %). For the AAR-4.1, the same trend is observed, with all aggregates satisfying both the common expansion limit (0.03 % at 15 weeks) and that proposed for slowly reactive aggregates (0.02 % at 12 weeks). In both AAR-3.1 and AAR-4.1 tests, after the normal test duration, the aggregates still exhibit an increase in expansion.

From the above, it is readily seen that an expert review of the petrographic examination results and the AAR-3.1 and AAR-4.1 test results, considering also the potential impacts of the expansions attained in the tests or at least the test limits on the structure, is essential for a reliable prevention of deleterious expansion effects in new structures.

The assessment of the level of precaution and appropriate precautionary measures is summarized in Figure 6.

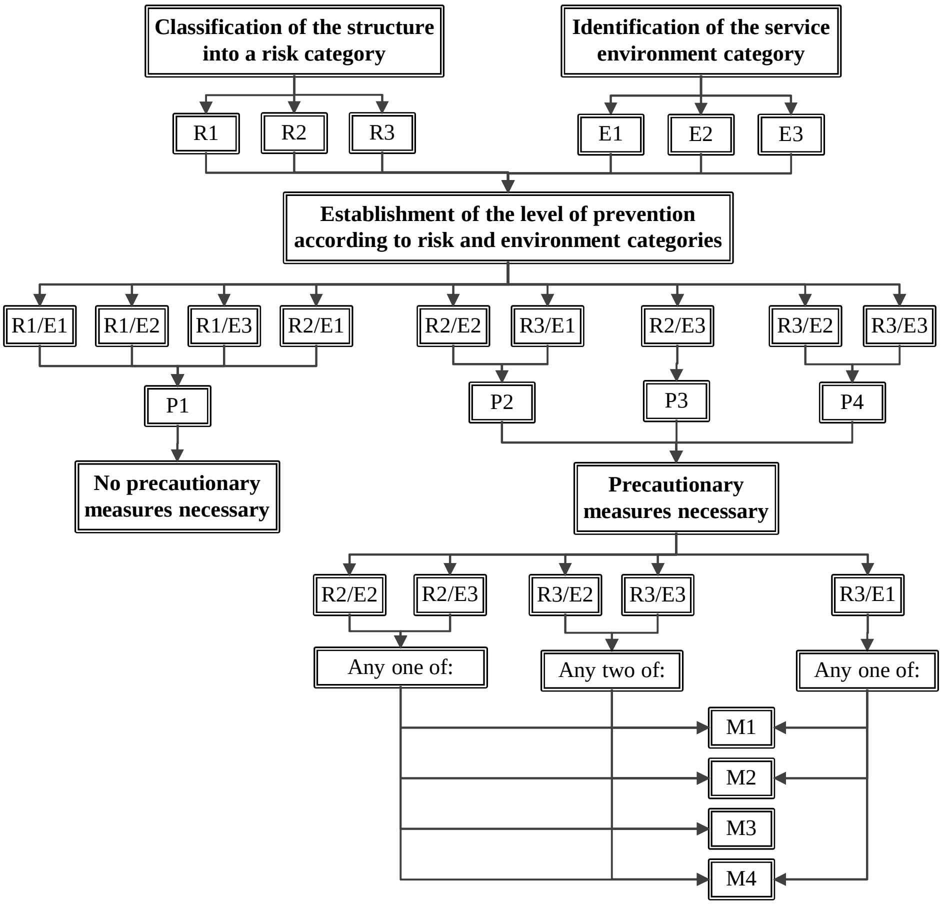

Figure 6: Methodology for selecting preventive measures (adapted from [9]).

The process starts by a categorisation of the structure according to the risks associated with ASR occurrence in the structure, namely into three risk categories: R1 – low risk (e.g. non load-bearing elements inside buildings, temporary or short service life structures, easily replaceable elements); R2 – normal risk (e.g. most building and civil engineering structures); and R3 – high risk (e.g. long service life or critical structures where the risk of deterioration from ASR damage is judged unacceptable - nuclear facilities, dams, tunnels, important bridges or viaducts, structures retaining hazardous materials). Then, the service environment to which to structure will be exposed is identified from three possible categories: E1 – the concrete is essentially protected from extraneous moisture; E2 – the concrete is exposed to extraneous moisture; and E3 – the concrete is exposed to extraneous moisture and additionally to aggravating factors, such as sodium chloride based de-icing salts, freezing and thawing or wetting and drying in a marine environment. The previous two categorizations shall be made by the responsible for the structure, in collaboration with the designer. Next, the structural and environmental categorisations are combined to provide the level of precaution. Four levels of precaution exist: P1 – no special precautions against ASR; P2 – normal level of precaution; P3 – special level of precaution; and P4 – extraordinary level of precaution. To each precaution level a specific set of preventive measures are then applied. There are four possible measures: M1 – restricting pore solution alkalinity; M2 – ensuring the use of a non-reactive aggregate; M3 – reducing moisture ingress to maintain the concrete in a sufficiently dry state to prevent deleterious expansion of the gel; and M4 – modifying the properties of the ASR gel so that it becomes non-expansive.

There are several ways to restrict the alkalinity of the pore solution (M1), for instance, by limiting the alkali content of the concrete, by using a low-alkali cement, and by including in the concrete mixture a sufficient of low lime-fly ash, or other SCMs that have demonstrated to be effective in the concrete.

Measure M2, avoiding the use of a reactive aggregate combination (i.e. total aggregate combination of coarse and fine aggregates), is not always feasible in the case of large concrete structures; therefore, in those cases emphasis shall be placed in measures M1, M3 and M4.

In the case of bridges, dams and other hydraulic concrete structures the application of measures to restrict the access of moisture and maintain the concrete in a sufficiently dry state (M3), for instance through the use of coatings or membranes, is not always viable due to the large areas that would have to be protected, to concerns about their efficacy, and to their limited durability (in comparison that of the structure). Thus, the structure should be designed to avoid, as much as possible, water accumulation and allow for a rapid drainage.

Currently, measures to modify the properties of ASR gel so that it becomes non-expansive (M4) comprise only the use of lithium salts. However, their long-term effectiveness is not yet established and their cost may make them prohibitive for large concrete structures.

3 EXISTING CONCRETE STRUCTURES

Diagnosis and prognosis of ASR in existing structures are not currently covered by any European standard or regulation. Because of that, LNEC is going to publish a LNEC Specification to provide support to the construction industry stakeholders on how to deal with ASR in existing concrete structures.

The methodology that can be followed to appraise an ASR affected structure is summarized in Figure 7. The assessment process can be divided broadly into three stages: (1) initial survey; (2) diagnosis; and (3) prognosis.

The first stage consists on the visual observation of the structure, where the visual symptoms of deterioration are annotated and compared to those commonly observed on affected structures (e.g. expansion causing deformation, relative movement, and displacement; cracking; surface discoloration; gel exudations; occasional pop-outs). At this stage, any documents relating to the structure (e.g. exposure conditions; age of structure, details and dates of modifications or repairs; plans, drawings and specifications of the structure; previous surveys or investigations on the structure) and the materials used for the construction (e.g. concrete mix design and details of analyses or tests carried out on concrete constituents) are also gathered and reviewed to assist in the appraisal process and decide upon the likelihood of ASR presence. In the case of being decided that ASR is most likely not present, then a routine inspection plan is defined.

If the probability of ASR being present is determined to be significant, then the information collected on the previous stage is used in stage 2 to define the preliminary sampling program to be carried out on a selected number of elements from the concrete members showing visual signs of deterioration. These samples are then subjected a series of destructive tests (e.g. observation by optical and scanning electron microscopes, determination of alkali and cement contents) that allow the diagnosis of the cause(s) of the concrete deterioration and the obtainment of a general assessment of the extent of deterioration.

In the case of ASR presence is confirmed and damage to concrete is observed in Stage 2, then the appraisal process advances to Stage 3. In this stage, an extensive inspection programme is devised to allow a structural integrity assessment, and an additional and broader sampling plan is defined to allow a detailed testing program in the laboratory, which quantifies current condition of concrete (i.e. degree of expansion/damage attained to date), evaluates potential for future expansion (i.e. trend for future concrete deterioration), and predicts future structural risks. This sampling plan envisages core extraction in several locations at the structure, including visually deteriorated and sound areas. In the case of a massive structural element, it is also important to extract cores from deep inside the affected element in order to evaluate the degree of the reaction throughout the element thickness. The number of samples required depends on the type and complexity of the structure. The results of the detailed investigation are then analysed and decisions made regarding the need to plan and implement in-situ monitoring programs (measuring expansion and deformation) and repair and/or mitigation strategies.

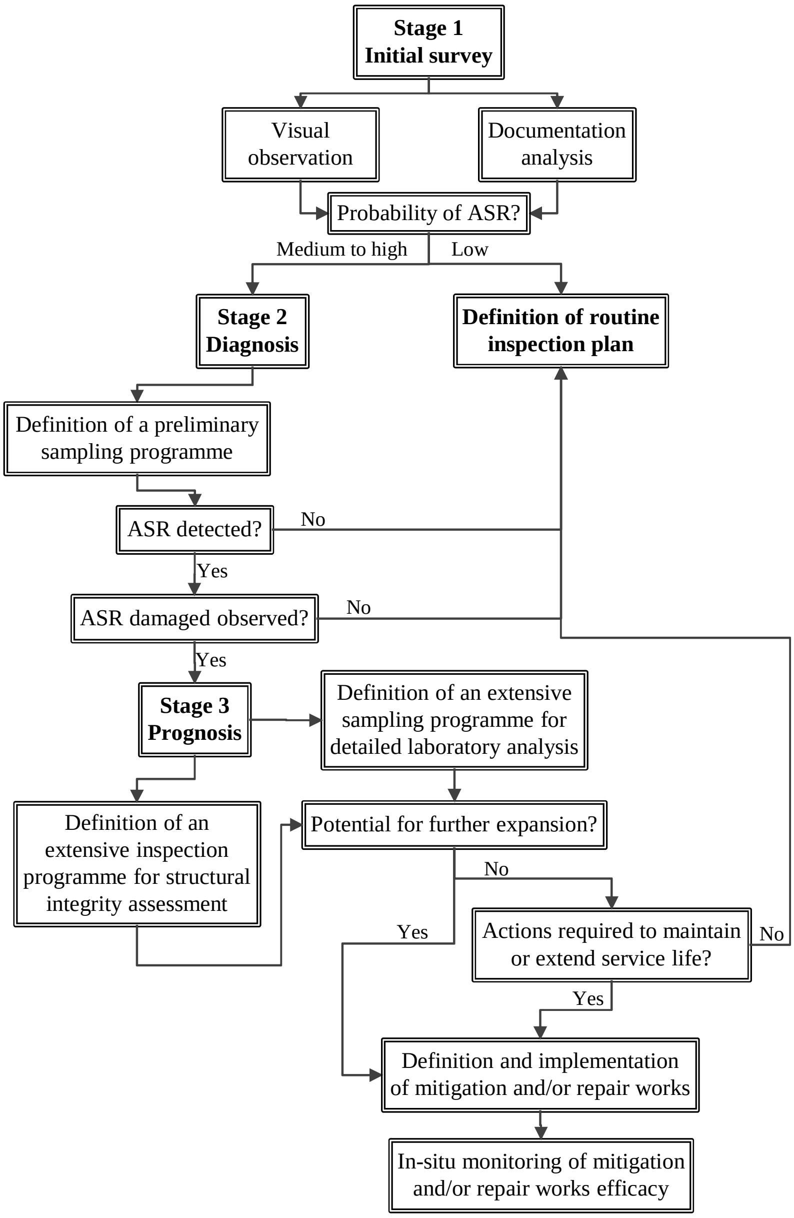

Figure 7: Methodology for the diagnosis and prognosis of ASR in concrete structures

4 FURTHER RESEARCH NEEDS

4.1 New structures

Even though, current knowledge is, in most cases, sufficient to prevent ASR in new structures, several issues still require further investigation. For instance, petrographic examination is still unclear about the potential reactivity of some minerals present in granite like rocks; current expansion tests may produce unreliable results with some aggregate types (e.g. granites), cannot assess concrete compositions with cements other than CEM I at the prescribed alkali level, have limited comparability with real concrete compositions; current concrete alkali content limits do not consider alkalis coming from concrete constituents other than the cement; SCMs effectiveness varies and some SCMs may themselves release alkalis in the long-term; the very long-term effect of SCMs is still unclear, especially with slowly reacting aggregates; when the use of non-reactive aggregates is not an option, the reduction of the reactive silica, for example, through the replacement of the reactive sand with a non-reactive sand does not always lead to a reduction of the expansion in the AAR tests (Figure 8).

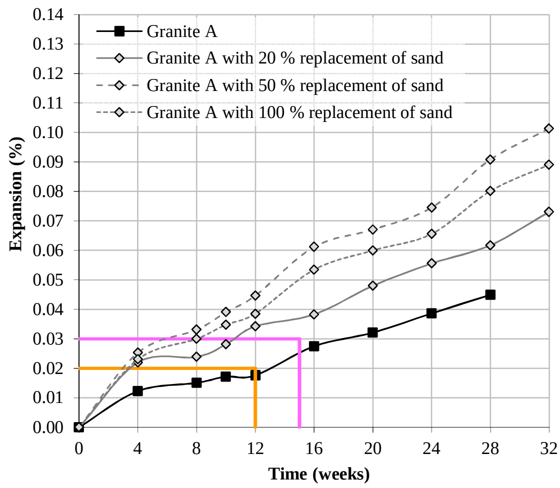

Figure 8: Example of an aggregate for which the replacement of the reactive sand by a non-reactive sand does not lead to a decrease in the expansion attained in the AAR-4.1 reactivity test.

4.2 Existing structures

Concerning existing structures, current knowledge it is clearly deficient, not allowing to assess rigorously the actual condition of an affected structure and to accurately predict the mechanical properties deterioration and the period during which it will effectively perform its function; all essential to determine current safety level and timely and cost-effectively plan eventual mitigation/rehabilitation/reconstruction works. One of the main drawbacks still existing pertains to the accurate prognosis about the future development of ASR in a structure, because to make such a prognosis it is necessary to know what the residual expansion in the concrete will be. However, to rigorously determine the actual residual expansion that will occur in the structure, it is necessary to overcome the limitations of current test procedures, for instance, they often lead to results more severe than those observed from in-situ monitoring, or less severe and providing expansion curves dissimilar to those observed in practice, e.g. due to alkali leaching during the laboratory tests.

5 CONCLUSIONS

This paper presented methodologies, resulting from LNEC's accumulated expertise and from the most recent findings of the international scientific community, that may be used by the construction industry stakeholders to better control ASR in new concrete structures, and to more adequately manage affected structures; thus, enabling a more sustainable and effective use of the country's economic and natural resources.

Because of this, LNEC, in collaboration with the international scientific community, is conducting several studies to contribute to the clarification of some of the abovementioned aspects and, consequently, to allow a more effective prevention of ASR in new concrete structures and a more reliable management of ASR affected structures.

6 ACKNOWLEDGEMENTS

This work was carried out within the scope of a research project (PTDC/ECM/115486/2009) financed by Fundação para a Ciência e a Tecnologia – FCT (Foundation for Science and Technology, Portugal). The authors wish to acknowledge this financial support.

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