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Alkali Silica Reaction in concrete: the Argentinian experience

1. Introduction

Alkali Silica Reaction (ASR) has been studied for more than 80 years and has been reported in more than 50 countries around the world. The mineralogical composition of the aggregates is one of the main factors affecting ASR, amorphous silica (opal), chalcedony, cristobalite, tridymite and volcanic glass appear as the reactive components leading to a rapid or normal reaction rate, showing visible signs of reaction in concrete at ages as low as 1 year, depending on the surrounding environment. Other aggregates, as those composed by granitic and metamorphic rocks, that include mineral species as polycrystalline and strained quartz, need very long induction periods usually higher than 10 years [1, 2]. Different levels of damage and cracking appear in concrete microstructure according to the kinetic of ASR. Rapid reaction rates induce internal stresses at the interfaces and cement pastes, producing micro and macrocraks. On the other hand, in concretes with strained quartz, the reactions are localized inside the aggregates in reactive zones (intercrystals), where pore solution can reach. This process takes place very slowly and the attack is not generalized all around the aggregate surface [1, 2, 3, 4].

Argentina is an extended country where a large variety of aggregates is available even in the same region. More than 100 examples of structures, placed in regions with different climates, damaged by ASR have been reported since 1950 [5]. Many tests on mortar or concrete involving different temperatures, alkali contents, and sample volumes have been studied in order to find the most suitable conditions for the evaluation of reactive aggregates. This paper summarizes the present knowledge and design criteria adopted in Argentina in order to avoid or mitigate ASR in concrete.

2. Background

2.1 Applied standard methods

More than 60 years have passed since the first case of a concrete structure damaged by ASR in Argentina was verified. It was the pavement of the La Plata - Punta Lara road, built in 1949-1950. The combination of cements with high alkali content (greater than 1%), reactive sands from the Paraná River and favourable humidity conditions gave rise to ASR. This led to the first local and systematic studies on ASR that were performed at the LEMIT since 1956 [5].

In 1964, the Argentinian Project for Regulation of Concrete Structures, PRAEH, established prescriptions to avoid it. Later, new methods were incorporated improving the criteria for evaluation and prevention of the reaction. Since 2012, the CIRSOC 201-2005 Code [6] admits the evaluation of structures in service as a reference element to prevent damage by ASR. In this section, the historical development of the methods used for the detection and prevention of ASR in Argentina is summarized. Initially the IRAM 1637 Mortar Bar Method (similar to ASTM C227) was used following the recommendations of the U.S. Bureau of Reclamation and the ACI, and the criteria to prevent ASR were incorporated into the PRAEH, 1964. IRAM 1637 had a great historical importance; it was applied for many years to evaluate many structures as the Dike Salto Grande (1963) on the Uruguay River, the Paraná - Santa Fe Subfluvial Tunnel (1965), the Nihuil Dam, the El Chocón Dam, the Ezeiza Airport, among others. Its results correlate well with the experience in the case of rapid reaction aggregates, but it does not detect slow reactivity. In addition, it has the disadvantage that it requires a long time (6 to 12 months) before defining aggregate reactivity degree.

In the 80', in South Africa appeared evidences of ASR in concrete dams with 50 years in service. These structures had been constructed with granitic aggregates which satisfactorily passed the evaluation with the ASTM C-227 standard. Studies conducted at the NBRI showed that the stressed quartz contained in the aggregates produces slow ASR. The accelerated test method on mortar bars was applied in Argentina since 1988, IRAM 1674 [7] (ASTM C-1260). Although the NBRI method is safe and detects in some cases the slow reaction, it can also classify as potentially reactive some innocuous aggregates. Thus, different alternatives were proposed. One of them, the concrete prism method developed in Canada was adopted as IRAM 1700 [8] (ASTM C 1293-95). In Argentina, the use of IRAM 1674 and 1700 methods was generalized.

The CIRSOC 201-2005, considering the recommendation of the PCA and the ACPA of 1998, incorporates as a criterion to prevent ASR the performance of structures in service, the petrographic analysis, IRAM 1649 [9] (ASTM C-295), and the IRAM 1674 and IRAM 1700 methods. The IRAM 1874-02 standard [10] "*Aggregates for concretes. Evaluation of structures in service.*" does not have an equivalent ASTM standard and was developed locally. It establishes the conditions for which, the antecedents of the behaviour in service of the aggregates used in an existing structure can be used to evaluate if aggregates of the same composition and origin will produce potential ASR in a new structure to be built.

2.2 Typical reactive aggregates

In Argentina there is a large variety of aggregates. Some typical reactive aggregates characteristic from different regions are descripted as follows:

- Basalts from Mesopotamia: these are rocks with low percentages of volcanic glass, tridymite and cristobalite and montmorillonite type clays.
- Gravel and sands from Uruguay and Paraná rivers: these aggregates may contain particles consisting of opal, micro or cryptocrystalline bands of chalcedony alternating with opal bands, and sandstones cemented with opal.
- Siliceous orthoquartzite from Chaco and Corrientes provinces: these very reactive compact fine to medium-grained rocks consist of quartz grains embedded in a groundmass of opal, chalcedony and microcrystalline quartz.
- Granitic crushed stone, centre of Buenos Aires Province: these slow reactive rocks are composed by feldspars (orthoclase and plagioclase), quartz, micas, epidote, zircon and dark minerals. Strained quartz grains can show undulatory extinction.
- Gravels and sands from the West and South region: this area is influenced by the geological formation of the Cordillera de los Andes. The most significant reactive component is the volcanic glass. Rocks containing cristobalite and tridymite in metastable conditions and stressed quartz can also be found. Gravel deposits on the sea coast of Patagonia were originated from the rocks of these mountains

Fig. 1 compares expansion test results obtained with IRAM 1674 and 1700 standard methods for different aggregates from Argentina. It can be seen that the mortar bar test can give some false positive results for aggregates with minerals as chalcedony or strained quartz. In addition, the 52 weeks expansion of concrete prisms stored at 38°C is plotted vs. the 13 weeks expansion of similar prisms cured at 60°C, which is an alternative accelerated test included in the last version of the IRAM 1700 Standard.

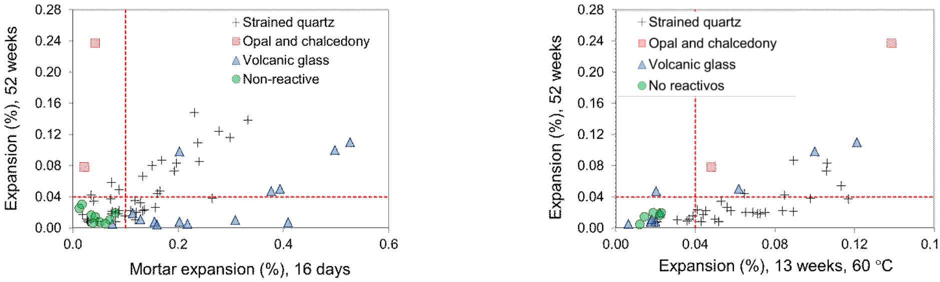

Fig.1: Relationships between the results of different expansion test of Argentinian aggregates.

2.2 Selected cases

In Argentina, most of significant concrete structures were built in the second half of the XX century and the code including rules to prevent ASR was available since 1964. Nevertheless, there were some structures with significant ASR damage. This section presents some cases of damaged structures that show the criteria that an engineer should use when projecting a concrete structure. In addition, the cases of a dam where uncommon precautions were taken to prevent ASR and a pavement where control in the concrete alkali loading was adopted as inhibitory strategy are briefly commented.

2.2.1 ASR damaged structures

The **concrete bases** for the towers of the high voltage transmission line Salto Grande – Ezeiza, located at the Entre Ríos province, were built with an 18 MPa compressive strength reinforced concrete. In service since 1978, they showed a high level of ASR damage in less than ten years (1984). Despite the estimated Na_2O_{eq} content in cement ranged between 0.2 and 0.6%, the high humidity and important average temperatures, the use of gravel and sands with presence of opal, chalcedony, sandstones cemented with opal and stressed quartz, enhanced the development of ASR pathology consisting of numerous erratic fissures. In 1996, the crack openings ranged from 0.01 to 0.9 mm, in some bases exceeded 0.9 mm and in three cases they had 4 to 9 mm. ARS was confirmed by macroscopic observation of the structures and by core evaluations (microscopy, X-ray and residual expansion). At present, a few very affected bases were rebuilt and the rest are in service with periodic maintenance.

In Bracho, Tucumán Province, close to the Salí River, there is a thermoelectric plant with three turbines on **concrete blocks** supported on piles. They were built between 1995 and 2002. During the rainy season, the groundwater reaches 0.50 m below the level of the floor of the plant. Two plants have the basements above the groundwater but the third is in contact with water. The concrete volumes are approximately 400, 150 and 1000 m^3 respectively. In 2006, cracks were observed on the blocks and, although no cracks were found inside, ASR was confirmed by microscopic observation. The aggregates were potentially reactive with alkalis; their main components are quartzites and siliceous sandstones. The cements were not alkali resistant, the average cement contents were near 270 kg/m^3, and the soluble alkalis varied between 1 and 1.5 %

(exceptionally 2%) by weight of cement. Residual ASR tests performed during 2011-2012 showed similar behaviour in all concretes, indicating that they still have some capacity to develop ARS expansions. However, the degree of ARS and the existing damages are different according to the dimensions and the humidity of concretes. The damage is higher in the structure with the greatest volume in permanent contact with the groundwater. On the contrary, in the other plants there is no significant ASR.

Pavements are structures particularly sensitive to ASR. The paving slabs at Camba Punta Airport (Corrientes) are a typical example of ASR deterioration produced by the use of aggregates from the Mesopotamia Argentina. In service since 1960, worrying signs of deterioration were detected in 1978. Observed pathologies include slab edge lifting, erratic cracks, concrete spalling, joint closures, among others. The deterioration level was very important in 1985. Ordinary Portland cements from various sources were used, estimating the Na_2O_{eq} content between 0.6% and 1%. The used coarse aggregates were basalt, quartzite, sandstone and gravel and the sands contained opal and chalcedony. The reactive material was provided by sandstones and quartzites cemented with opal and chalcedony. Another case of ARS is the RN127 pavement between Federal (Entre Rios) and Cuatro Bocas (Corrientes); while many sectors are in good conditions, in other parts there is an important ASR pathology, with slabs containing abundant cracks, and closure of joints appears. Crushed basalt was used as coarse aggregate, being the main reactive minerals volcanic glass and cristobalite. ASR damage was associated to the cement alkali content used in different sectors.

ASR damage was also found in the **interior columns** of a building, built near 1950s in the Buenos Aires city. The Central Hall, at the ground floor, has columns whose cross section and height are greater than 1 and 9 m, respectively. For architectural reasons, these columns are covered with masonry of ceramic brick and granitic stone cladding. In 1998, stone cladding that covered some columns came off. The masonry that covered these columns was removed and significant cracking was revealed on the surface of concrete columns. Initially, the fact that some stone plates came off and cracks were found in the columns was attributed to structural causes. Nevertheless, in 1999, a new study concluded that the cracks had been caused by ASR. The used aggregates were fine-grained sandstone cemented by amorphous silica, chalcedony and strained quartz in lower proportions. The alkalis were derived from the cement itself. The cement contents ranged between 255 and 306 kg/m^3 and equivalent alkalis, as weight percent of cement content, ranged between 0.42 and 1.18 %. The most severe damage occurred in columns with a cross section greater than 1 m^2, covered with masonry of ceramic brick and granitic stone cladding. The concrete volume and the linings have undoubtedly maintained the humidity conditions required for ASR to take place during the early ages of the structure. The analysis of the crack pattern and microscope observations showed that cracks had occurred long ago; the reaction is not presently increasing as the concrete moisture is not enough to trigger the process.

2.2.2 ASR inhibition measures

The hydroelectric central of Piedra del Águila dam, located on the Limay River, is an example of extreme preventions against ASR in a structure with high strategic implications. The total volume of concrete is 3.5 million m^3. The coarse aggregates are potentially reactive due to the presence of volcanic glass in tuffs, andesites and basalts, and stressed quartz in granites, quartzites and sandstones. The sands have clasts of stressed quartz, volcanic glass and chalcedony. It was specified a pozzolanic Portland cement with a low heat of hydration. Once started the construction, as the expansions at 18 month of mortar bars test (ASTM C-227) were significant, the ASR risk was analyzed again and it was decided to use a pozzolanic Portland cement with 30% of pozzolan made with a clinker with a mean alkalis content ≤ 0.5%. This dam was built between 1985 and 1992 and, at present, shows no signs of ASR.

The experience gained during the construction of large engineering works in Argentina has shown that the use of low alkali cements or the use of mineral additions to inhibit ASR. However, in many cases, these solutions have technical-economic limitations, so it is necessary to implement other alternatives. In the construction of **RN 14 route** (Entre Ríos and Corrientes provinces) the methodology proposed by the CSA, based on the control of the concrete alkalis provided by the cement, was followed. In this case the aggregates were similar to those used in the RN 127, basalt and natural siliceous sand and the available cement had 0.67% Na_2O_{eq}. According to IRAM 1700 the combination of aggregates shows a 52-week expansion of 0.047 %, which is classified as moderate reactivity, knowing that the pavement will be in contact with a medium of high humidity it was assumed a ASR risk equal to 3. For this level of risk and a service life of 25 years, it was necessary to adopt a "moderate" level of prevention, which implies limiting the alkali content of concrete to 2.4 kg/m^3 Na_2O_{eq}. Considering the cement content and the contribution of alkalis of the aggregates the content of soluble alkali in the concrete resulted in the order of 2.0 kg/m^3 Na_2O_{eq}. To date, no ASR manifestations were observed; after 10 years of construction, concrete cores were extracted and no reaction products were observed on thin sections.

3. Proposed criterion for ASR detection and prevention

The general guidelines indicated in ASTM C 1778-16 [11] and CSA A23.2-27A [12], verified on the performance of the RN14, represent an alternative for ASR prevention. The criterion for avoiding ASR and their consequent damages is presented as follows.

Firstly, it is accepted that there are no risks of ASR if data from *constructions in service without expansions or other pathologies associated to* ASR are available with the following requirements: built with *similar materials* (aggregates, cement, mineral additions, chemical admixtures), with the *same structural typology*, exposed to *similar or more rigorous environmental conditions* and *in service during more than 15 years*.

When there is no information or doubts about potential reactivity of some fine and/or coarse aggregates, the following steps must be followed:

1. Petrographic analysis (IRAM 1649): this analysis represents a good approach for ASR risks and it is useful for expansion tests selection and interpretation. However, it is not conclusive and one aggregate cannot be accepted or rejected by this test.
2. Accelerated mortar bar test (IRAM 1674, ASTM C-1260): an aggregate is considered potentially reactive when the 16 day expansion in the mortar test exceeds 0.10 %. This test is rapid and reliable for many aggregates but it must not be applied for aggregates containing strained quartz particles and also for the gravel from Uruguay River, as it contains extensive opal and chalcedony contents.
3. Accelerated concrete prisms test (IRAM 1700 at 60°C): this is a contribution from the Argentinian experience on ASR. It is similar to the ASTM C1293 test but the storage temperature is 60 °C and the testing period is reduced. An aggregate is potentially reactive when the 13 weeks expansion exceeds 0.04% for aggregates containing opal, chalcedony, cristobalite, tridymite and volcanic glass, or when it exceeds 0.08% for those containing strained quartz particles. The results of this

method agree with those of ASTM C1293, being very low the percentage of false negatives (Fig.1). It is a good alternative to evaluate low reaction rate aggregates.

4. Traditional concrete prisms test (IRAM 1700 at 38°C, similar to ASTM C-1293): the traditional concrete prism test is still considered today the most reliable method. An aggregate is potentially reactive when the 52 weeks expansion exceeds 0.04%.

When fine and/or coarse aggregates are identified as potentially reactive, they can be used in concrete if preventive actions for ASR inhibition are adopted, which may consist on **prescriptive** or **performance requirements**.

Verification of **performance** requirement implies testing a concrete prism (IRAM 1700) prepared with the whole materials that will be used. The concrete must be done with total cementitious material content of 420 kg/m^3, w/cm between 0.42 and 0.45, and increasing the cement alkalis content up to 1,25% Na_2O_{eq}. The following alternatives are given: use cements for general purpose, combine cements for general purpose and active mineral additions (MA), add a lithium-based admixture, or perform a partial replacement of reactive by non-reactive aggregates. A concrete mixture can be used if the 104 weeks expansion is lower than 0.04%. Similar criteria should be applied using the mortar bar test (IRAM 1674) for aggregates not including strained quartz.

Potentially reactive aggregates can also be used adopting **prescriptive** requirements which are similar to those included in the Canadian Standards:

- Use a highly resistant to alkali-aggregate reaction cement (IRAM 50001)
- Apply one of the following actions: limit the concrete alkali loading, add MA of recognized efficacy or, for the most demanding conditions, combine a low alkali loading concrete plus MA incorporation. The options depend on the aggregate, the ASR risk of the structure, and the tolerable damage level.

The aggregate reactivity degree (RD) is obtained from expansion tests (Tab.1). When tests results are not available, the RD can be adopted from Tab.2; if the aggregate type is not in this table, it should be considered extremely reactive (R3). Based on the ASR risk (Tab.3) and the concrete structure class (analysing the consequences on safety, economy or environment and the tolerance for ASR damage, Tab.4) **required prevention levels** are suggested (Tab.5). Finally, for each prevention level alternative solutions are given: for instance, when the maximum concrete alkali content is adopted as unique requirement, No limits, 3, 2.4 and 1.8 kg/m^3 Na_2O_{eq} are indicated for the prevention levels V, W, X, and Y, respectively. In the case of Z or ZZ, combination of 1.8 kg/m^3 Na_2O_{eq} plus MA must be used. In addition, there are recommendations for each prevention level, if the MA content is used as unique requirement, as a function of the MA type (fly ash, blast furnace slag, silica fume) and cement alkali content.

Tab.1:

Expansion limits (%) for different aggregate reactivity degree (RD).

RD	Aggregate reactivity level	IRAM 1674 mortar, 16 days	IRAM 1700, 60°C concrete, 13 weeks	IRAM 1700, 38°C concrete, 52 weeks
R0	Non-reactive	E < 0.10	E < 0.04 (0.08[1])	E < 0.04
R1	Moderate	0.10 ≤ E < 0.30	0.04 (0.08[1]) ≤ E < 0.12	0.04 ≤ E < 0.12
R2	High	0.30 ≤ E < 0.45	0.12 ≤ E < 0.24	0.12 ≤ E < 0.24
R3	Extremely high	0.45 ≤ E	0.24 ≤ E	0.24 ≤ E

[1] For aggregates containing strained quartz particles

Tab.2:
Expected reactivity degree (RD) of aggregates from different regions of Argentina.

Region	Aggregate	Reactive minerals	RD
Buenos Aires (centre)	Crushed stone and crushed sand	Strained quartz grains	R2
Buenos Aires (south)	Gravel and sands	Volcanic glass	R3
Mesopotamia	Crushed basalt	Cristobalite, tridymite and volcanic glass	R2
Uruguay River	Gravel and sands	Opal, chalcedony and microcrystalline quartz	R3
Chaco, Corrientes	Siliceous orthoquartzite	Opal, chalcedony and microcrystalline quartz	R3
Mendoza	Mendoza River gravel	Volcanic glass	R1
	Diamante River gravel	Volcanic glass	R2
Tucumán	Salí River gravel	Microcrystalline quartz and volcanic glass	R2
Córdoba, San Luis	Crushed basalt	Volcanic glass	R1
Patagonia	Gravels and sands	Mainly volcanic glass, some rocks include tridymite, cristobalite and strained quartz	R2

Tab.3:
ASR risk for different types of structures and exposure conditions

Size and concrete environment	Aggregate reactivity degree			
	R0	R1	R2	R3
Non-massive and dry	1	1	2	3
Massive and dry	1	2	3	4
Concrete exposed to humid air, buried, or immersed	1	3	4	5

Tab.4:
Concrete structure classes as a function of ASR damage tolerance

Class	Safety, economy or environment effects	ASR damage tolerance	Examples
S1	Small or negligible	High	Temporary structures (< 5 years)
S2	Moderate	Moderate	Sidewalks, curbs, gutters, Structures for service life < 40 years
S3	Significant	Minimum	Highway pavements, low volume bridges. Service life 40 to 75 years
S4	Serious	None	Bridges, airfield pavements, tunnels, dams. Service life > 75 years

Tab.5:
Required prevention level for Concrete structure classes S1 to S4

ASR risk	S1	S2	S3	S4
1	V	V	V	V
2	V	V	W	X
3	V	V	V	V
4	W	X	Y	Z
5	X	Y	Z	ZZ

4. Conclusion

Argentina has a long experience on the study of ASR in concrete. A large variety of aggregates is available and examples of structures affected by ASR, placed in different regions, have been reported since 1950. Cases of ASR damage produced aggregates with reactive minerals as amorphous silica (opal), chalcedony, cristobalite, tridymite and volcanic glass, as well as, aggregates including polycrystalline and strained quartz have been observed. Argentinian standards and regulations have considered the problem of ASR for decades; nowadays, there is a clear knowledge of this pathology based on laboratory and field evaluations. The present design criterion adopted in Argentina for avoiding or mitigating ASR in concrete was also summarized. In addition, results from a 13 weeks concrete prism test, which is proposed for aggregate characterization, are given and compared with those of traditional concrete prism test.

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