FLY ASH TO PREVENT ASR WITH SLOWLY-REACTIVE AGGREGATES IN PORTUGAL

João Custódio[1]*, Felipe Río Iglesias[2], Óscar Herrero Domínguez[2], António Santos Silva[1], António Bettencourt Ribeiro[1], Dória Costa[1]

[1]LNEC – National Laboratory for Civil Engineering, Lisbon, PORTUGAL

[2]Endesa Generación, S.A., Madrid, SPAIN

Abstract

Alkali-Silica Reaction (ASR) is recognised as a durability problem in last years in Portugal. Several cases have been identified in bridges and dams, mainly due to the use of potentially slowly-alkali reactive granitic aggregates. These granitic aggregates are still being used in new constructions in Portugal, and particularly in large concrete dams. The Portuguese regulation on ASR refers the need of using supplementary cementitious materials (e.g. fly ash, granulated blast furnace slag) to counteract the pernicious effects due to ASR development. This paper describes the methodology applied in the evaluation of concrete granitic aggregates to be used in a Portuguese hydroelectric project. The results obtained by modified concrete prism tests, with fly ashes from different sources and cement and sand replacement levels, and incorporation two alkali boosting levels, are presented and discussed.

Keywords: ASR, prevention, fly ash, concrete, expansion test-methods

1 INTRODUCTION

Deterioration of concrete structures by ASR has increased dramatically in recent years in Portugal. 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 service life, may involve the interruption of its function and, ultimately, can lead to its decommissioning and demolishing. In Portugal, ASR has been detected in more than thirty bridges and dams. Due to the rhythm at which ASR is being identified in existing structures and the large number of structures under or planned for construction in Portugal, which may also develop ASR, it is predicted that concrete structures deterioration due to ASR will continue to increase in the near future.

Presently, in Europe, only two standards deal with ASR, namely 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, 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 and revised in 2007 [3]. However, due to the scientific developments occurred since then (e.g. creation of RILEM recommendations on ASR [4]), a new revised version is in preparation and will soon be published [5].

In the case of large concrete structures, which require vast amounts of aggregates, it is often necessary to use local rocks which are alkali-silica reactive. LNEC Specification E 461, states that whenever potentially alkali-silica reactive aggregates have to be used then appropriate precautionary measures shall be undertaken to avoid the occurrence of deleterious ASR in the structure. In the case of dams, the only feasible measure is to restrict pore solution alkalinity, this can be achieved by using a low alkali cement and include a sufficient proportion of fly ash or other supplementary cementitious material, which has demonstrated to be effective in minimizing the development of ASR in the concrete. To assess the effectiveness of a fly ash in mitigating ASR, concrete-prism tests, CPTs (e.g. [6]), can be performed; however, in the case of the so called slowly reactive aggregates (e.g. granites), those tests may not provide a reliable result. Therefore, to contribute to the current ongoing discussion on the methodologies that shall be used to mitigate ASR in new structures that use reactive and potentially reactive aggregates, this paper presents the methodology that was followed to assess

* Correspondence to: jcustodio@lnec.pt

mitigation measures that can be applied to a new dam, which will have to use a concrete having a potentially alkali reactive granitic aggregate, in order to prevent damage by ASR.

2 MATERIALS AND METHODS

2.1 General

The approach followed to assess the effectiveness of fly ash in preventing deleterious development of ASR in the concrete made with granitic aggregates comprised a test campaign that included petrographic examination and chemical analysis of the aggregates, expansion tests on mortar and concrete prisms and their microscopic observation after the expansion tests, using a scanning electron microscope coupled with an energy dispersive X-ray spectrometer (SEM/EDX). The option of replacing the granitic sand by a non-reactive sand was also evaluated. The test campaign is summarized in Table 1.

2.2 Materials

The study comprised the evaluation of three granitic rocks from different sources (hereinafter designated by granite ACG, granite PB and granite CB), and of two fly ashes (also from different origins, being designated by fly ash CTP and fly ash CTC). The mortar bars and concrete prisms used in the potential alkali-silica reactivity tests, detailed below, were made using a Portland cement CEM I 42.5R (EN 197-1 [7]). A limestone aggregate was used as the ASR non-reactive sand. The chemical and physical characteristics of the cement and fly ashes are presented in Table 2. The granitic aggregates ACG, PB and CB were prepared by crushing cores drilled from rock bodies in prospective quarries. The sands were tested as received.

2.3 Methods for assessment and analysis

Petrographic analysis

The petrographic examination was performed according to LNEC Specification E 415 [8] and aimed at characterizing the rock materials and identifying the presence of potentially alkali-silica reactive constituents. It was performed on thin-sections prepared from cores of ACG, PB and CB granite varieties, using the conventional preparation method complemented with a specific staining technique for identifying of K-feldspars. A petrographic microscope from Zeiss (Axioplan) equipped with 10x ocular and objectives of different magnifications (5x, 10x and 20x) was used for the observation complemented with microphotographs taken with a digital camera from Sony (Cybershot DSC-S800). In this type of analysis several characteristics were considered relevant, namely the characteristics and the quantity of quartz grains present, the identification and quantification of vermicular intergrowth of quartz in plagioclase (like myrmekites) and the presence of minerals able to contribute with alkalis, such as sodium and potassium feldspars or micas.

Chemical analysis of aggregates

The chemical analysis of the three granites consisted on determining the aggregates silica content, total alkali content and water soluble alkali content. The total silica and alkali contents were determined according to standard EN 196-2 “Method of testing cement - Chemical analysis of cement” [9] and by fusing the sample with lithium tetraborate. The determination of the water soluble alkali content was made according to the Portuguese standard NP 1382 “Aggregates for mortars and concretes - Determination of soluble alkali content - Flame spectrophotometry process” [10].

Assessment of alkali-silica potential reactivity

The expansion tests, conducted to assess the sands potential alkali-silica reactivity, were performed according to the accelerated mortar-bar test, AMBT defined in ASTM C1260 [11], while those used to evaluate the granitic aggregates ACG, PB and CB were done on concrete prisms according to RILEM AAR-3 [12] and RILEM AAR-4.1 [13] test methods.

Evaluation of mitigation measures

The feasibility of using fly ash and of replacing granitic sand by non-reactive limestone sand to mitigate the deleterious development of ASR, was evaluated with modified RILEM AAR-3 [12] and AAR-4.1 [13] tests methods. The modifications consisted of adapting them to the use of fly ash, using the same principle as that defined in ASTM C1293 [6], and of incorporating an alkali boost, to account for the aggregates specificities (i.e. slowly reactive granites having minerals capable of supplying alkalis to the concrete pore solution) and the eventual existence of other alkalis sources.

Scanning electron microscopy with energy dispersive X-ray analysis (SEM/EDX)

The SEM/EDX characterization was made according to LNEC Specification E 402 [14] on mortar and concrete samples, after the expansion test, with the aim of determining the extension, localization and chemical composition of eventual expansive reaction compounds. The analysis was carried out on a SEM JEOL JSM-6400 coupled with an EDX OXFORD Inca X-Sight, using an electronic beam tension of 15 keV. The observations were done using a backscattered electron mode for polished sections and with a secondary electron image mode for broken surfaces.

3 RESULTS AND DISCUSSION

Petrographic analysis

The rocks are grey varieties of granites with biotite. The grain size is diverse and includes fine (PB, CB) but also medium to coarse grained varieties (ACG). The main composition is very similar and includes quartz, plagioclase and alkaline feldspars. Anhedral crystals quartz grain show different sizes and the undulatory extinction is weak (less than 15 degrees). Myrmekitic textures are present in all the varieties, although in different amounts quantified in modal analysis. Feldspar component include large euhedral crystals of plagioclase, in particular in medium-coarse variety (included in ACG sample) and anhedral potassic feldspars (Figure 1). Biotite (sometimes partially transformed in chlorite) and muscovite are the main accessory components although sillimanite is also identified in one of the varieties (in ACG). Caulinitic alteration and chloritization are also characteristics of these rocks. Some illustrative examples of this igneous paragenesis are presented in Figure 1. The modal results are summarized in Table 3.

Chemical analysis of aggregates

The results of the chemical analysis performed to the aggregates are presented in Table 4. The values obtained for the total silica and total alkali contents are typical of this type of rocks. The silica content values, ranging between 70.30 % and 72.30 %, indicate that the granites are classified as acid rocks; which is consistent with the petrographic examination. The values obtained for the water soluble alkali content are also compatible with the petrographic examination, in which it was observed that the granites contain minerals that can release alkalis into the concrete pore solution.

Assessment of alkali-silica potential reactivity – AAR-4.1 and AAR-3

From the AAR-4.1 tests conducted to assess the ASR reactivity of the three granitic aggregates (Figure 2), it was observed that at 13 weeks of testing all samples exhibited an expansion below 0.02 %; at 15 weeks, only granite ACG showed an expansion higher than 0.02 %; and at 20 weeks of testing, PB and ACG granites had an expansion reaching or even surpassing 0.03 %, respectively. Granite CB showed an expansion above 0.02 % only after 28 weeks of testing; from that period onwards, the expansion appears to be stabilized for specimens CB, whilst specimens ACG and PB continued to exhibit an increasing expansion trend.

From the results obtained in the AAR-3 tests (Figure 2), it was observed that at 12 months of testing all samples exhibited an expansion below 0.03 % and that at 24 months all samples had an expansion below 0.05 %. After that period, specimens CB appear to have the expansion stabilized, whilst samples ACG and PB continued to exhibit an increasing expansion curve.

According to current recommendations on ASR, the above results would allow to consider the aggregates as being ASR nonreactive. However, having in mind the results from the petrographic analysis and the long-term expansion behaviour observed in the above expansion tests, it was decided to consider them as being potentially alkali-reactive and thus mitigation measures, which minimize or impede the deleterious development of ASR in a concrete using the above granitic aggregates, should be assessed.

Scanning electron microscopy with energy dispersive x-ray analysis (SEM/EDX)

The SEM/EDX analysis confirmed that the expansions attained in the AAR-4.1 and AAR-3 tests were due to ASR development, as ASR gel was observed in the samples, filling voids and surrounding cement/aggregate interfaces.

Evaluation of mitigation measures - modified expansion tests

The test campaign carried out to evaluate the mitigation measures efficacy only used aggregates ACG and PB, because they were the ones more likely to be used in the structure and they exhibited the highest expansion in the abovementioned concrete prism tests. The results obtained in the modified expansion tests are presented in Figures 3 to 7.

The artificial increase of the concrete alkali content, by 3 kg/m^3 and 6 kg/m^3, beyond the amounts defined in the AAR-3.1 and AAR-4.1 concrete prism tests, had a pronounced effect on the ASR expansive behaviour of samples PB and ACG (Figure 3). The results confirm the slow reactivity of this type of aggregates and allow obtaining information concerning the long-term potential reactivity of the aggregate mixture in a relatively shorter test period. For instance, for specimens ACG the alkali boosting resulted in an expansion at 12 weeks of the same magnitude as that obtained at 28 weeks without the alkali boost; in the case of specimens PB, a similar trend was observed. Although, the two boost levels produce an enhanced expansion, the magnitude of the effect varies with the aggregate and is more pronounced at longer test periods.

In spite of the alkali boost, the fly ashes were able to mitigate ASR in a relevant extent for both aggregates, PB and ACG (Figure 4). For the same boost level, the increase of the fly ash dosage resulted in an increased mitigation effect. However, even with the highest fly ash dosage it was observed that they were not able to completely supress ASR, as expansion continued to evolve throughout the test period. Considering the same aggregate and the same boost level, fly ash CTC appeared to produce a slightly lower level of expansion than fly ash CTP. The PB specimens incorporating fly ashes, at a 30 % cement replacement level and with different alkali loadings, presented an expansion below 0.02 % at 15 weeks and below 0.03 % at 20 weeks, which is indicative of ASR non-deleteriously reactive aggregate combinations. The ACG specimens incorporating fly ash CTC, also at a 30 % cement replacement level and with different alkali loadings, showed a similar behaviour, although with expansion values closer to the above mentioned limits. The composition with fly ash CTP and a cement replacement dosage of 30 % was not able to fulfil the above limits, as it happened for aggregate PB. The increase of the fly ash dosage produced, has expected, a decrease in the observed expansion; this decrease was more relevant for fly ash CTP.

The effect of replacing the granitic sand with non-reactive limestone sand (Figure 5) did not produce a reduction of the expansion values; in fact, it actually increased the observed expansion for both aggregates, with the increase in expansion being higher for larger sand replacement levels. An explanation for the observed behaviour could lie in the existence of a composition related pessimum effect, which may induce a variation in the attained expansion as a function of the reactive silica content of the concrete mixture, so that to a higher content of reactive silica does not correspond a higher expansion level. The test carried out with both fly ash and non-reactive sand (Figure 6) showed that their combined use also produces an enhanced expansion.

Overall, the results obtained with the AAR-3 modified tests (Figure 7) are similar to those obtained in the aforementioned modified AAR-4.1 tests. All the evaluated combinations using the alkali boost and fly ashes presented expansion below 0.03 % at 1 year and 0.04 % at 2 years of testing. Moreover, the AAR-3 tests allowed to observe that the sand replacement made to mixtures containing the highest fly ash content did not led to a pronounced increase in the expansion as that verified in the AAR-4.1 modified tests.

Assessment of alkali-silica potential reactivity – ASTM C1260

The results from the potential alkali-silica reactivity tests, carried out with the limestone sand and the alternative sands – P13 (sand obtained from a granitic coarse aggregate), C52 (sand obtained from a siliceous coarse aggregate), C53 (sand obtained from a siliceous coarse aggregate), ZP12 and ZP13 (natural siliceous sand), to test the ability of the latter to replace the granitic sands ACG, PB and CB, are presented in Figure 8. Although, not required by ASTM C1260, the tests were prolonged up to 28 days, in order to explicit the behaviour observed in the normal test period (i.e. 14 days). In the case of the alternative sands the test was prolonged up to 1 year. As it can be seen from the results obtained, the aggregates can be considered, according to ASTM C1260, as being alkali-silica non-deleteriously reactive. However, the expansion behaviour of the alternative sands raises doubts on their ASR reactivity and, therefore, it was considered that their aptitude to replace the sands ACG, PB and CB ought to be verified through a modified concrete prism test.

4 CONCLUSIONS

The results from the petrographic examination showed that the granitic aggregates are potential alkali-silica reactive and that they contain minerals that can also release alkalis into the concrete pore solution.

According to current recommendations on ASR, the results from the RILEM AAR-3 and AAR-4.1 CPTs performed to the three granitic varieties (ACG, PB and CB) indicated that they could be considered has ASR non-reactive. However, taking into account the extended expansive behaviour and the results from the petrographic and chemical analysis they were considered as being potentially ASR deleteriously reactive. Specimens PB and ACG were the ones that, under the conditions of CPTs, exhibited the highest ASR potential. These two aggregates also registered the higher silica and soluble alkali contents. The adopted alkali boosts (3 kg/m^3 and 6 kg/m^3), which aimed at simulating an eventual long-term release of alkalis into the concrete pore solution, showed that it results in an increase of the expansion attained in the reactivity test. This is in line with the assumption of considering the aggregates as being of the slowly reactive type, i.e. an aggregate which when used in a concrete will originate an expansion initiated at a later stage and that progresses at a slower rate than regular aggregates.

Therefore, as the aggregate is to be used in a dam, a special structure with a very long service life, the use of mitigation measures was deemed necessary. The recently published RILEM document [4] concerning the prevention of damage by alkali-aggregate, produced under the scope of RILEM TCs 106, 191-ARP and 219-ACS, proposes that in the case of dams and other structures having a very high service life, the concrete produced with ASR reactive aggregates shall have an alkali content below 2.5-3.0 kg/m^3 (this value corresponds to the total releasable alkalis from all mix constituents, including cement, any SCMs, admixtures, mix water and all aggregates) and a fly ash content of at least 40 % by mass of total cementitious material (assuming that the fly ash has a CaO and $Na_2O_{eq.}$ content below 8 % and 5 %, respectively). LNEC Specification E 461 [3] prescribes, for class II and III aggregates, which is the case for the three assessed granites, a concrete having a soluble alkali content limit of 2,5 kg/m^3 and 3,0 kg/m^3, respectively, and incorporating siliceous fly ashes in a minimum proportion of 30 %.

The results of the tests performed to assess the efficacy of the fly ashes in mitigating the ASR showed that they were able to reduce significantly the ASR induced expansion; nevertheless, they were not able to supress it completely.

Concerning the second approach studied to mitigate ASR, i.e. the replacement of granitic sand by a non-reactive limestone sand, no improvement was found in terms of reduction of ASR induced expansion.

Considering all the results obtained in the present study, the ASR reactivity potential observed for the granitic aggregates, the possibility of the aggregate to contribute with alkalis to ASR, the uncertainty existing in the scientific community in respect to the expansion limits that must be fulfilled by this type of aggregates, the extended expansion profile observed in the reactivity tests, it was recommended that the concrete to be produced with the above aggregates shall contain at least 50 % of fly ashes (either fly ash CTC or another with an equivalent ASR mitigation capacity) in the concrete binder.

Furthermore, the scientific community has still some concerns that some concrete compositions containing supplementary cementitious materials may actually suffer the same ultimate expansion level as the compositions without the SCMs, but they do so in a delayed and slowly progressive way, so that the final effect on the concrete would be similar to that observed in compositions without SCMs, although at a much later age of the structure.

Consequently, in addition to the above recommendations, it advisable that expansion tests with the concrete mixture to be used in the structure are performed both with and without the alkali boost (to simulate aggregates alkalis release and to assess the very long-term effect of the mitigation measures), and that large scale concrete specimens (of at least 1 m dimensions) are produced and maintained in-situ to allow confirming the prescribed performance and the evolution of any ASR induced expansion.

5 REFERENCES

[1] CEN (2013): EN 206:2013 Concrete. Specification, performance, production and conformity. European Committee for Standardization (CEN), Brussels.

[2] CEN (2008): EN 12620:2002+A1:2008 Aggregates for concrete. European Committee for Standardization (CEN), Brussels.

[3] LNEC (2007): Especificação LNEC E 461:2007 Betões. Metodologias para prevenir reacções expansivas internas. Especificações LNEC relacionadas com a NP EN 206-1:2007. Betão.

Parte 1: Especificação, desempenho, produção e conformidade, Laboratório Nacional de Engenharia Civil, I. P. (LNEC), Lisboa.
[4] Nixon, P. J. & Sims, I., Eds (2016): RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures (State-of-the-Art Report of the RILEM Technical Committee 219-ACS). RILEM State-of-the-Art Reports. Dordrecht: Springer.
[5] Custódio, J., Ribeiro, A. B. & Santos Silva, A. (2015): Alkali-Aggregate Reaction, AAR - Dealing with AAR in large concrete structures. In 2nd International Dam World Conference - DW 2015, Lisbon, Portugal.
[6] ASTM (2015): ASTM C1293-08b(2015) Standard Test Method for determination of length change of concrete due to alkali-silica reaction. ASTM International, West Conshohocken, PA.
[7] CEN (2011): EN 197-1:2011 Cement. Composition, specifications and conformity criteria for common cements. European Committee for Standardization (CEN), Brussels.
[8] LNEC (1993): Especificação LNEC E 415:1993 Inertes para argamassas e betões. Determinação da reatividade potencial com os álcalis. Análise petrográfica, LNEC - Laboratório Nacional de Engenharia Civil, I.P. (LNEC), Lisboa, Portugal.
[9] CEN (2013): EN 196-2:2013 Method of testing cement. Chemical analysis of cement. European Committee for Standardization (CEN), Brussels.
[10] IPQ (1976): NP 1382:1976 Inertes para argamassas e betões; Determinação do teor de álcalis solúveis. Processo por espectrofotometria de chama. Instituto Português da Qualidade, I.P. (IPQ), Caparica.
[11] ASTM (2014): ASTM C1260-14 Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method). ASTM International, West Conshohocken, PA.
[12] RILEM (2014): Alkali-silica reactions in Concrete Structures. RILEM Recommended Test Method AAR-3.1 Detection of potential alkali-reactivity - 38 ºC test method for aggregate combinations using concrete prisms (Unpublished Draft), RILEM-TC219-ACS.
[13] RILEM (2014): Alkali-silica reactions in Concrete Structures. RILEM Recommended Test Method AAR-4.1 Detection of potential alkali-reactivity - 60 ºC test method for aggregate combinations using concrete prisms (Unpublished Draft), RILEM-TC219-ACS.
[14] LNEC (1993): Especificação LNEC E 402:1993 Materiais de matriz cimentícia. Microanálise de raios X por dispersão de energia associada ao microscópio electrónico de varrimento, Laboratório Nacional de Engenharia Civil, I. P. (LNEC), Lisboa.

TABLE 1: TEST CAMPAIGN.

Tests	Aggregates			
	ACG	***PB***	***CB***	***P13, C52, C53, ZP12, ZP13, NRL***
Petrography	✓	✓	✓	-
AAR-4.1	✓	✓	✓	-
AAR-3	✓	✓	✓	-
AAR-4.1 + Alkali boost 3 kg/m^3	✓	✓	-	-
AAR-4.1 + Alkali boost 6 kg/m^3	✓	✓	-	-
AAR-4.1 + Alkali boost 3 kg/m^3 + 30 % fly ash CTC	✓	✓	-	-
AR-4.1 + Alkali boost 6 kg/m^3 + 30 % fly ash CTC	✓	-	-	-
AR-4.1 + Alkali boost 6 kg/m^3 + 30 % fly ash CTP	✓	✓	-	-
AAR-3 + Alkali boost 6 kg/m^3 + 30 % fly ash CTP	✓	✓	-	-
AAR-3 + Alkali boost 3 kg/m^3 + 50 % fly ash CTC	✓	✓	-	-
AAR-4.1 + Alkali boost 6 kg/m^3 + 50 % fly ash CTC	✓	-	-	-
AAR-4.1 + Alkali boost 6 kg/m^3 + 50 % fly ash CTP	✓	-	-	-
AAR-4.1 + 20 % sand replacement	✓	-	-	-
AAR-4.1 + 50 % sand replacement	✓	✓	-	-
AAR-4.1 + 100 % sand replacement	✓	-	-	-
AAR-4.1 + Alkali boost 6 kg/m^3 + 50 % sand replacement + 30 % fly ash CTC	✓	-	-	-
AAR-4.1 + Alkali boost 6 kg/m^3 + 100 % sand replacement + 50 % fly ash CTC	✓	-	-	-
AAR-3 + Alkali boost 6 kg/m^3 + 100 % sand replacement + 50 % fly ash CTC	✓	-	-	-
Alkali content of aggregate	✓	✓	✓	-
Silica content of aggregate	✓	✓	✓	-
ASTM C1260	-	-	-	✓

NOTE: NRL – ASR non-reactive limestone sand.

TABLE 2: Characteristics of the cement and fly ashes.

Cement		**Fly ash CTC**		**Fly ash CTP**	
Property	***Value (%)***	***Property***	***Value (%)***	***Property***	***Value (%)***
SiO_2	18.87	SiO_2+ Al_2O_3+ Fe_2O_3	92.72	SiO_2+ Al_2O_3+ Fe_2O_3	n/a
Al_2O_3	5.50	$SiO_{2,reactive}$	41.65	$SiO_{2,reactive}$	n/a
Fe_2O_3	3.32	CaO_{free}	0.02	CaO_{free}	0.86
CaO	62.61	$CaO_{reactive}$	2.80	$CaO_{reactive}$	5.1
MgO	1.73	MgO	2.09	MgO	n/a
SO_3	2.82	SO_3	0.27	SO_3	0.50
K_2O	1.08	$Na_2O_{eq.}$	0.25	$Na_2O_{eq.}$	n/a
Na_2O	0.18	Cl^-	< 0.01	Cl^-	< 0.01
$Na_2O_{eq.}$	0.89	P_2O_5	3.8 mg/kg	P_2O_5	n/a
TiO_2	0.29	L. I.	3.30	L. I.	4.15
P_2O_5	0.11	Fineness	Category N	Fineness	Category N
MnO	0.05	Density	2474 kg/m^3	Density	2340 kg/m^3
SrO	0.06	A.I. at 28 days	85	A.I. at 28 days	82
L. I.	2.95	A.I. at 90 days	104	A.I. at 90 days	98
Data provided by CIMPOR.		Data provided by ENDESA.		Data provided by ENDESA.	

NOTE: L.I. – loss on ignition; A.I. - activity index; n/a – not available.

TABLE 3: Results of the petrographic examination.

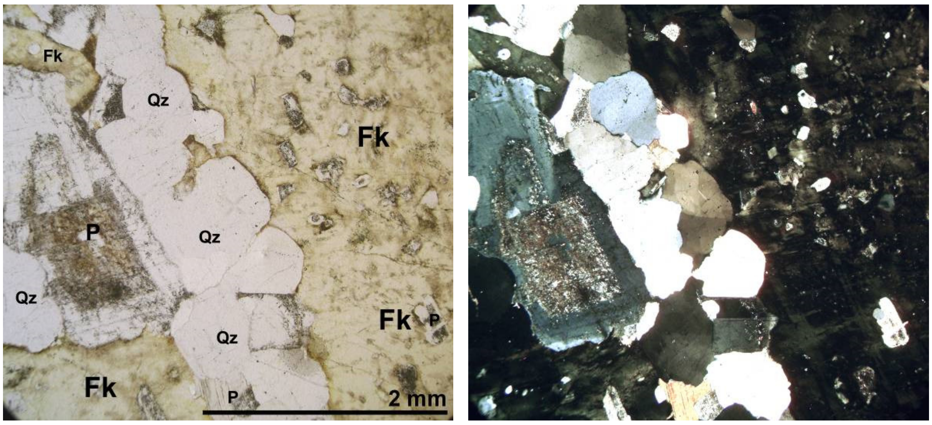
Modal analysis		***Aggregate ACG***	***Aggregate PB***	***Aggregate CB***
Alkali reactive constituents	Quartz (weak undulatory extinction - less than 15 degrees)	29	33	35
	Intergrowth of quartz in feldspars; myrmekite (droplets and vermicular) *	<1 (≈0.5)	3	<1 (≈0.2)
Constituents that may release alkalis	Plagioclase	25	10	27
	Alkaline feldspars (undifferentiated and potassic feldspars)	36 (6, 30)	34 (16, 27)	30 (2, 28)
	Biotite	5	3	5
	Muscovite	3	2	2
Others	Chlorite	2	4	-
	Others (e.g. epidote, sphene sillimanite)	<1 (≈0.3)	2	1

NOTE: * Not considered in E 415 as potentially alkali reactive, but qualified as such according to [4].

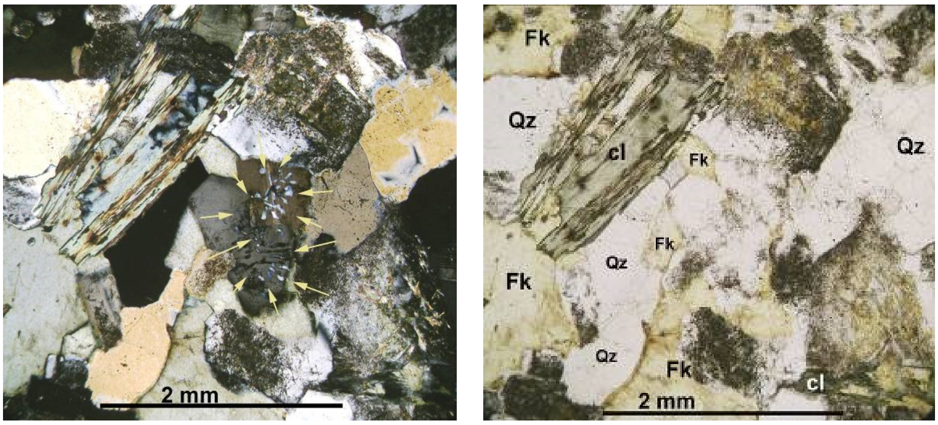
TABLE 4: Results of the aggregates chemical analysis.

Property	***Aggregate ACG***	***Aggregate PB***	***Aggregate CB***
SiO_2 (%)	72.3	71.83	70.30
Na_2O (%)	2.89	2.99	2.84
K_2O (%)	4.77	4.47	5.13
$Na_2O_{eq.}$ (%)	6.03	5.93	6.21
Na_2O_{shw} (%)	0.018	0.017	0.015
K_2O_{shw} (%)	0.030	0.019	0.012
$Na_2O_{eq.,shw}$ (%)	0.038	0.030	0.023

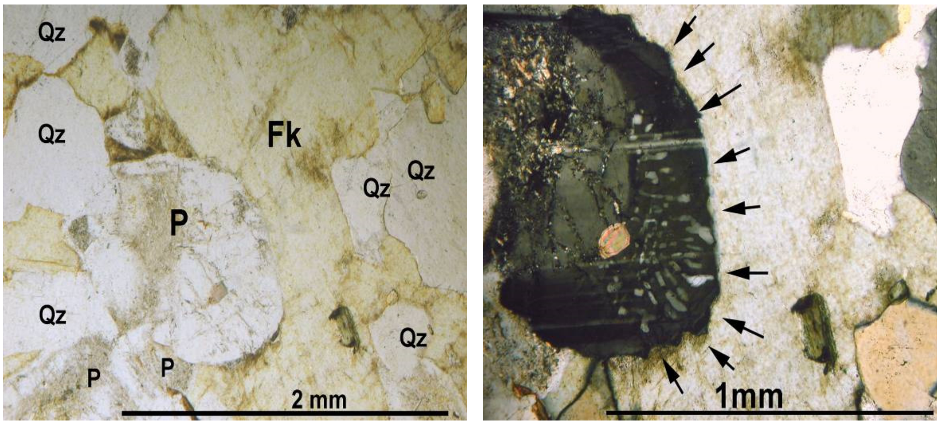
NOTE: shw – soluble in hot water.



Mineralogical composition and texture of granite ACG; crystal of plagioclase affected by kaolinite alteration (P), quartz (Qz) and potassic feldspar (Fk), (*parallel and crossed nicols, on the left and on right*)



Mineralogical composition, texture and alteration of granite PB; besides quartz (Qz) and potassic feldspars (Fk), biotite transformed in chlorite (cl) is observed. Note the intense alteration of feldspars. The presence of myrmekites can be identified and indicated by the arrows, (in *parallel and crossed nicols, on the left and on right respectively).*



Mineralogical composition, texture and alteration of granite CB; quartz (Qz), plagioclase (P) and potassic feldspars (Fk). Note the presence of myrmekites in the rim of a plagioclase crystal, as indicated by the arrows, (in *parallel and crossed nicols, on the left and on right respectively).*

FIGURE 1: Results from the petrographic examination.

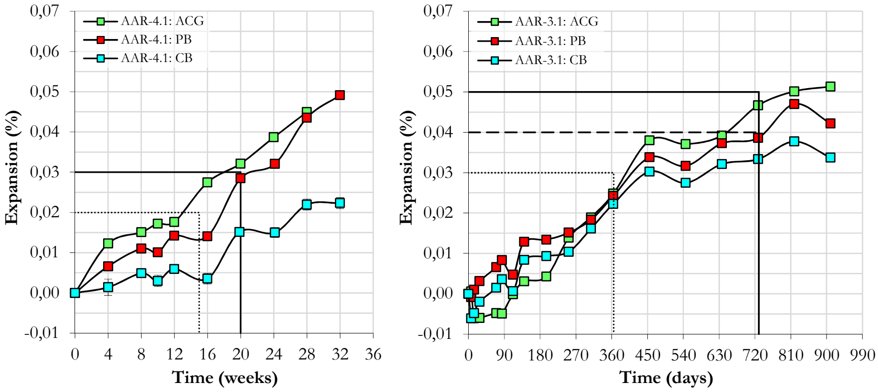


FIGURE 2: Results obtained in the RILEM AAR-4.1 and AAR-3 tests carried out to assess the potential alkali-silica reactivity of the aggregates.

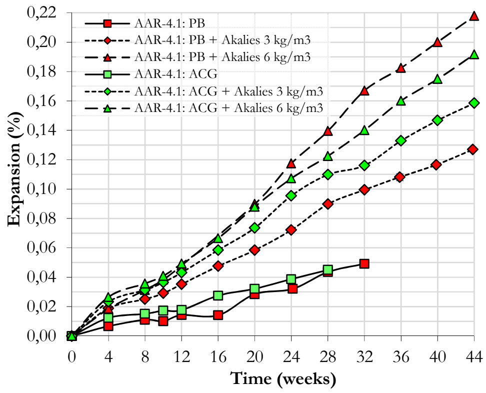


FIGURE 3: Effect of the alkali boosting on ASR expansion (RILEM AAR-4.1 tests).

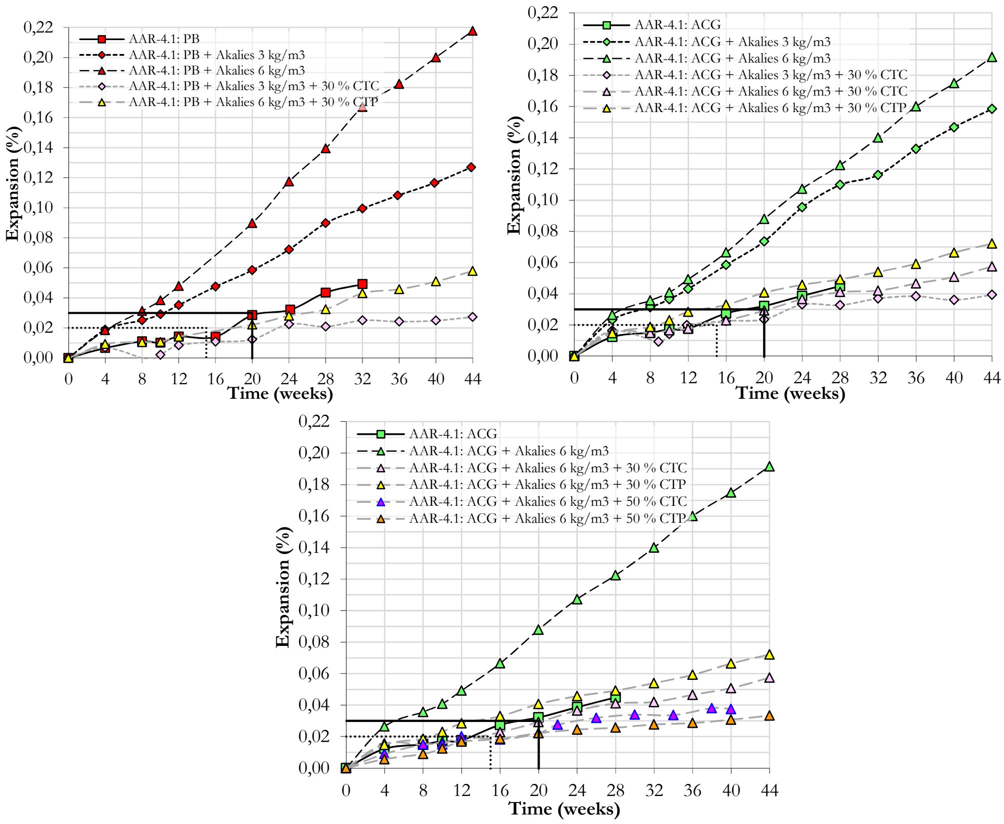


FIGURE 4: Effect of the alkali boosting and fly ash replacement level on ASR expansion.

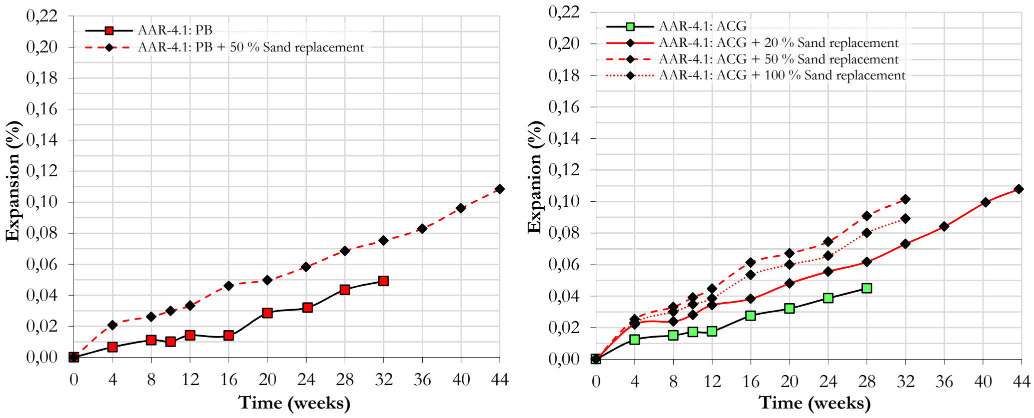


FIGURE 5: Effect of the sand replacement on the ASR expansion.

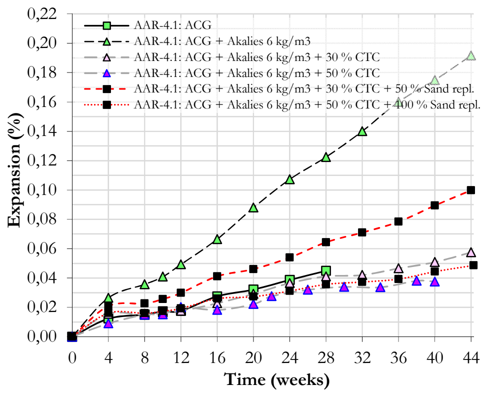


FIGURE 6: Effect of fly ash and sand replacement on the ASR expansion.

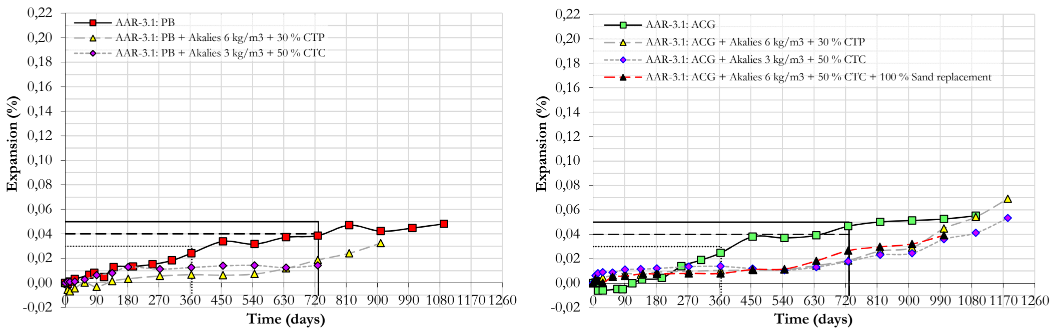


FIGURE 7: Results obtained in the AAR-3 tests.

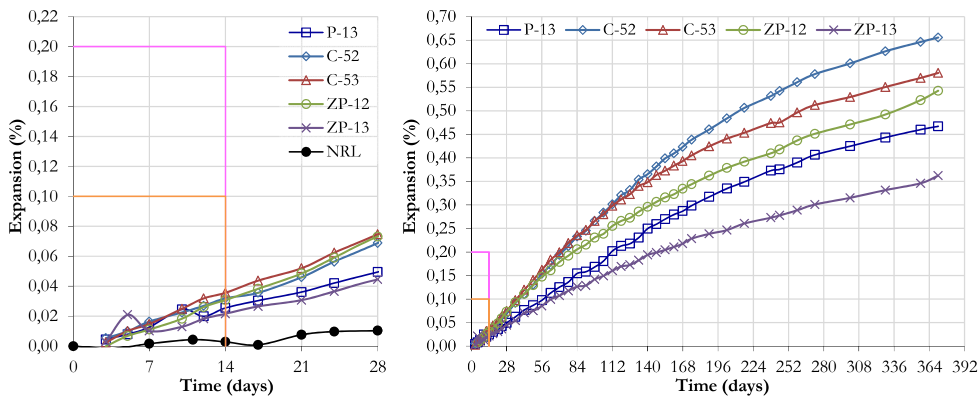


FIGURE 8: Results obtained in the ASTM C1260 test performed to alternative sands.