ALKALI REACTIVITY OF GRANITIC ROCKS IN PORTUGAL: A CASE STUDY

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Abstract

This paper discusses the relationship between the age and the degree of deformation of Portuguese granites used as aggregates and the occurrence of alkali-aggregate reactions in concrete. Granitic rocks are an important source of crushed aggregates for concrete in Portugal. The existing quarries are situated in a variety of granite types, most of them emplaced during the Hercynian orogeny. Field experience shows that in Portugal some granitic rocks behave innocuously when applied in concrete, whereas others react deleteriously. A better knowledge of the properties that control the potential alkali-reactivity of granitic rocks in Portugal is therefore essential to improve the quality of new structures.

Five granites with different Hercynian ages were studied in order to correlate their geological history with the mineral composition and texture. Especial focus was given to the deformation features of the silica minerals. Laboratory tests for the determination of the potential alkali reactivity were also performed. Additionally, the expected performance of the granites as aggregates, based on laboratory test methods, was compared to their behaviour when applied in real structures. Three concrete structures, two dams and one bridge, were inspected in order to detect signs of deterioration. In places where deterioration was found samples of reaction products and samples of concrete were collected for further characterisation in laboratory.

Through the evaluation of the petrographic characteristics of the granites and the assessment of their behaviour in real concrete structures it was verified that, as a general rule, in Portugal the older granites are more likely potentially alkali reactive than the younger granites. Nevertheless, the geologic history of the rock cannot be neglected since regional tectonic episodes can have a great influence in the deformation features of the rocks.

Keywords: alkali-silica reaction, granitic aggregates, age, deformation, concrete structures

Introduction

This paper presents the main results of the work developed by Nélia Castro during her Master thesis (Castro, 2008) under supervision of Isabel Fernandes and co-supervision of António Santos Silva. The aim of the project was to investigate the relationship between the age and the deformation degree of Portuguese granites and the occurrence of alkali-aggregate reactions (AAR) in concrete.

Granitic rocks are considered as non-reactive in many countries (RILEM AAR-1, 2003). However, under certain circumstances they may react with the alkalis in the presence of humidity causing a deleterious reaction on the concrete structures characterised by very slow rate (Cortelezzi *et al.*, 1990). The reactivity of granitic rocks has been attributed to different factors and a number of methods to predict reactivity have been proposed. Grattan-Bellew (1986) defended that the presence of microcrystalline quartz in granitic rocks that contain strained quartz is the key factor that makes granitic rocks susceptible to alkalis. Thomson and Grattan-Bellew (1993) and Thomson *et al.* (1994) showed that the most reactive constituent appeared to be the microcrystalline quartz that has undergone significant subgrain development, but not complete recrystallization. Michel *et al.* (2003) considered that the presence of microcrystalline grains increases the surface contacts between quartz and interstitial solution, enhancing the possibility of alkali-silica reaction (ASR). Kerrick and Hooton (1992) work on granitic rocks from Eastern United States shows that not only the microcrystalline quartz, which was formed by a recrystallization process, but also texture properties of the rocks influence the alkali sensivity. Shayan (1993) obtained identical results with granitic rocks from Western Australia. Wigum (1995) proposed a new and more accurate petrographic method to evaluate the alkali-reactivity of aggregates containing quartz based on the measurement of the grain size and the quartz content of the rock. Wigum *et al.* (2000) demonstrated that the grain size reduction of quartz enhances reactivity by increasing the total surface area of grain boundaries available for reaction.

Granitic rocks are a major source of crushed aggregate for concrete in Portugal due to the frequency of outcrops, especially in the Northern and Central regions of the country. The genesis and setting of this enormous volume of granitic rocks is related with the Hercynian orogeny, especially with the third tectonic phase (Noronha *et al*., 1981). In the last years, some concrete structures in Portugal (mainly dams) have been reported to show evident signs of ASR related to the use of granitic rocks as aggregates. However, some other structures also built with concrete manufactured with granitic aggregates do not show any signs of deterioration related to ASR. It is therefore evident that a better knowledge of the properties that control the potential alkali-reactivity of granitic rocks in Portugal is necessary to improve the quality of new concrete structures. Important studies about the reactivity of granitic rocks were developed in the department of Geology of Faculty of Sciences of University of Porto in the last years (Fernandes, 2005; Fernandes *et al*., 2004, 2007; Castro, 2008), however, the topic is complex and many questions remain unanswered.

Materials and methods

The experimental work on this project was focused both on the study of granitic aggregates and on concrete samples from structures built with granitic aggregates. Granite samples were used to evaluate the performance by laboratory tests of those rock types when applied as aggregate for concrete. Additionally, concrete samples of structures in which the granites were applied as aggregates were also studied to confirm or refute the laboratory tests.

Granitic aggregates

Five granites with different ages were sampled from a number of working and inactive quarries as well as from outcrops throughout the Portuguese territory (Figure 1). Granites with different ages were selected in order to represent different emplacement periods in relation to the Hercynian orogeny.

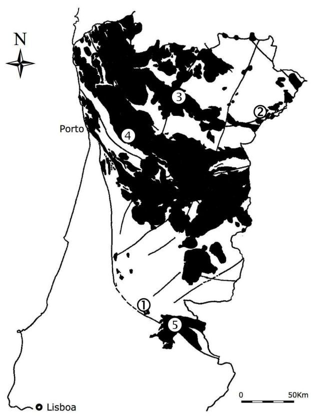

Figure 1: Simplified map of pre-mesozoic Portuguese granitic outcrops showing the location of sampling stations: ① Belver; ② Bemposta; ③ S. Tomé de Castelo; ④ Alpendurada; and ⑤ Vila Flor. The sampling sites were numbered according to the age of the granite collected from the older to the younger. The samples were labelled with the name of the town situated at the closest proximity from the sampling sites.

Belver aggregate is composed of fine-grained two-mica granite collected from a small outcrop a few kilometres north of Belver town. The outcrop is very small in length and present abundant fractures. The rock is strongly weathered, especially at the surface, exhibiting yellowish coloration. The sampling site is located in a pluton, Pre-orogenic in age, that intruded low-grade metamorphic rocks during the Cambrian (Ferreira *et al.*, 1987).

Bemposta aggregate is composed of medium-grained, two-mica granite collected from an inactive quarry near the Bemposta Dam. The granite collected in the quarry is highly strained with large crystals of feldspar and preferential orientation of minerals. The quarry was exploited for the Bemposta Dam construction and is inactive since the dam conclusion in 1964. It was excavated in three fronts. Abundant discontinuities both sub-vertical and sub-horizontal are visible. The rock is slightly weathered or fresh in most of the area but there are also zones of weathered rock. The quarry is located at the anatectic Tormes Dome, Syn-orogenic, Syn-D3 in age (Ferreira *et al.*, 1987). The Tormes Dome is heterogeneous in structure and close to the contact with the host rock the granite can exhibit an oriented texture.

S. Tomé de Castelo aggregate is composed of fine-grained two-mica granite collected from a working quarry. Aggregates from this quarry were used to build a concrete bridge over Douro river. The quarry is located in a granitic pluton, part of the Monção – Vila Real – Moncorvo lineament, Syn-orogenic, Late-D3 in age (Ferreira *et al.*, 1987). The quarry shows a fresh, medium to dark grey granite, explored in a large circular excavation.

Alpendurada aggregate is composed of coarse-grained two-mica granite, mainly biotitic, collected from a working quarry. This granite has porphyritic texture with preferential orientation of K-feldspar megacrystals (Medeiros, 1964). The quarry is being explored both for ornamental stone and crushed rock for aggregate material. Discontinuities sub-vertical and sub-horizontal with moderate distribution are visible. At the surface, where the fractures are more intense, the rock can be yellowish in appearance. The quarry is located in a batholith of large dimension, Syn-orogenic, Late-D3 in age (Ferreira *et al.*, 1987). At south and southwest the batholith is in contact with schists and greywackes, referred as schist-greywacke complex, while at North and Northeast it is in contact with other granitic batholith, Syn-orogenic, Late- to Post-D3 in age.

Vila Flor aggregate is composed of two-mica granite, mainly biotitic, collected from a quarry that was exploited for the Fratel Dam construction and is currently inactive. The granite is coarse-grained and has porphyritic texture with large crystals of feldspar (Ribeiro *et al.*, 1965). The quarry was excavated in three fronts. Several joints both sub-vertical and sub-horizontal are visible. The characteristics of the granite vary along the quarry. In zones where the joints are closer the granite is more weathered while in zones less fractured the granite is fresh or slightly weathered. The quarry is located in a batholith Late- to Post-orogenic in age (Ferreira *et al.*, 1987).

Concrete structures

Samples of three concrete structures in which the granitic aggregates were applied, one bridge and two dams, were studied in order to identify ASR manifestations (Figure 2). Considering that granitic aggregates produce a slow/late reaction, structures with ages between 11 and 44 years old were selected.

Figure 2: Simplified map of Portuguese rivers showing the location of the concrete structures: ① Bemposta Dam; ③ Fratel Dam (adapted from http://www.igeo.pt). The exact location of the structure ② Bridge over Douro river cannot be revealed. The structures were numbered according to the age of the granite used in the manufacture of the concrete, from the older to the younger.

Bemposta power plant is the third of the Portuguese power plants built in the International Douro branch of the river. In operation since December 1964, it consists of a dam, with a spillway at the central overflow zone, an underground power station and, near the right abutment, a control and a reception building and a substation. The dam is a concrete structure of symmetrical gravity arch type,

87 m high above the foundation and with a total crest length of 297 m. The foundations lie mainly on a zone of metamorphic rocks consisting essentially of migmatite and granite (PNCOLD, 1992). The aggregates applied in the manufacturing of the concrete of this dam are dominantly of granitic composition and were exploited in the same quarry where Bemposta aggregate was sampled. The quarry was opened to the construction of the dam and abandoned after conclusion.
The Bridge over Douro river was completed in 1997. It is a segmental bridge made with pre-stressed concrete. The deck is supported by piers, two of which are in contact with the water. The bottom of each pier is composed by a concrete pile cap. The foundations lie on a zone of typical low-grade metamorphism (schist-greywacke complex), Cambrian to late Precambrian in age. The aggregates applied in the manufacturing of the bridge are dominantly of granitic composition. Part of the aggregates used in the construction was exploited in the same quarry where S. Tomé de Castelo aggregate was sampled.
Fratel power plant is situated on Tagus river between Portas de Ródão town and the mouth of the Ocreza river. It consists of a dam and an adjacent powerhouse. The construction was finished in 1973. Fratel Dam is a concrete gravity dam, 43 m high above the foundation. The foundation lies on a series of schists and greywackes probably Cambrian to late Precambrian in age (PNCOLD, 1992). The aggregates applied in the manufacturing of the concrete of this dam are dominantly of granitic composition. They were obtained from the crushing of the rock exploited in the same quarry where Vila Flor aggregate was sampled. The quarry was exploited for the construction of the dam and abandoned after conclusion.

Experimental

The five granitic aggregates selected were studied in order to correlate their geological history with the mineral composition and texture. During the petrographic examination special focus was given to the deformation features of the silica minerals. Two laboratory tests for the determination of the potential alkali reactivity, the ASTM C 1260 accelerated mortar bar test and the ASTM C 289 chemical method, were also performed. Additionally, the expected performance of the granites as aggregates, based on laboratory test methods, was compared to their behaviour when applied in real structures. The three concrete structures selected were site inspected in order to detect signs of deterioration. In places where deterioration was found samples of reaction products and samples of concrete were collected for further characterisation in laboratory.

Granitic aggregates

Petrographic examination

Thin-sections of the five granitic aggregates were investigated with a Zeiss Stemi SV11 stereo-microscope (with Plan Apochromat S1.0X and magnification in a range between 0.6 and 6.6X) and a Nikon Eclipse E 400 POL polarising microscope (with transmission and reflection light, and objectives LU Plan 5x/0.15 POL ∞/0 EPI, 10x/0.30 POL ∞/0 EPI, 20x/0.45 POL ∞/0 EPI and 50x/0.80 POL ∞/0 EPI), both available at Department of Geology of Faculty of Sciences of University of Porto. The RILEM AAR-1 (2003) and the national standards Especificação LNEC E 415 (1993) and Especificação LNEC E 461 (2004) were used as a guideline to identify the presence of significant amounts of aggregate constituents capable of alkali reaction in concrete. However, further observations were made with special focus on the deformation features of the silica minerals within the granitic aggregates.

Expansion test

Accelerated mortar bar tests, according to the ASTM C 1260 (2007), of all the aggregate samples were performed at Materials Department of Laboratório Nacional de Engenharia Civil (LNEC). The aggregate samples were crushed down to sand size and graded according to the requirements of the standard. The mortar was produced with a cement CEM I 42.5R with 0.19% Na_2O, 1.02% K_2O, 0.86% Na_2O_{eq} and an cement/aggregate ratio of 0.44 and a water/cement ratio of 0.47. Three bars with 25x25x285 mm for each sample were produced. After the cure, storage during 24 hours in a moist cabinet at 23 ºC and 95% HR, the bars were stored over water at 80±2 ºC for 24 hours, then placed in containers with a 1M NaOH solution and again stored at 80±2 ºC for the subsequent time of the test.

Length measurements were taken periodically enabling to monitor the expansion. After 14 days of measurements the combination cement-aggregate was classified as non-reactive for expansion less than 0.10 percent; potentially reactive for expansion between 0.10 and 0.20 percent; and reactive for expansion greater than 0.20 percent.

Chemical method

The chemical method was performed at the Laboratory of Inorganic Chemistry of the Department of Geology of Faculty of Sciences of University of Porto (DG-FCUP) according to the ASTM C 289 (2007) standard and the Especificação LNEC E 159 (1964). The test samples were prepared from a representative portion of each granite by crushing so as to pass a 300 µm sieve and be retained on a 150 µm sieve. To ensure that all material finer than the 150 µm sieve has been removed, the samples were washed over a 150 µm sieve and dried at 105±5 ºC for 20±4 h. After cooling the samples were sieved again on the 150 µm sieve, mixed with a solution of 1N sodium hydroxide and stored at 80 ºC. After 24 hours the amount of reaction between the 1N sodium hydroxide solution and the aggregate was measured. The results were plotted on a logarithmic graphic of dissolved silica versus reduction in alkalinity that classifies the aggregates in innocuous, potentially deleterious and deleterious.

Concrete structures

In situ investigation and sampling

The three concrete structures were carefully inspected in order to identify signs of ASR in the concrete. In places were pop-outs, exudations, efflorescence or other signs of deterioration were found, samples of reaction products were collected, labelled and kept in plastic airtight containers in order to preserve them for examination and analysis. Additionally, places in the structures were selected to drilling cores in order to perform the petrographic examination of the concrete. After extraction, the concrete cores were labelled, wrapped in cling-film, stored in polythene bags and sent to the laboratory.

Petrographic examination

The petrographic examination of the samples collected in the structures was performed according to the ASTM C 856 (2007). Once in the laboratory, the products of the pop-outs, exudations and efflorescence were glued with araldite to metallic cylinders and sealed again in airtight containers in order to preserve them for examination and analysis. The concrete cores were sawed in half-length and observed by naked eye in order to detect signs of deterioration of concrete and to select places to produce thin sections. The thin-sections were investigated with the same stereomicroscope and polarizing microscope used for the granitic aggregates thin-sections. Complementary analyses by scanning electron microscope with energy dispersive X-ray spectrometer (SEM/EDS) were performed to characterize the morphology and composition of the reaction products. For observation and analysis by SEM/EDS both the thin-sections and the products of pop-outs, exudations and efflorescence were submitted to vacuum and coated, with carbon in the first case and with gold in the second with an JEOL JFC 1100 equipment, available at the Centre of Study of Materials of University of Porto (CEMUP). The samples were then examined under a JEOL JSM-6301F SEM, equipped with an OXFORD INCA ENERGY 350 EDS. The accelerated voltage used was a 15 kV with a working distance of 15 mm.

Results

Granitic aggregates

Petrographic examination

Belver aggregate is composed of a fine-grained, two mica granite with inequigranular texture, Pre-orogenic in age (Ferreira *et al.*, 1987). The petrographic examination of this granite showed some particular characteristics related to deformation features that might indicate potential reactivity. The deformation is revealed mainly in the quartz crystals and in the orientation of the phyllossilicate minerals. The quartz crystals show extensive sub-granulation at grain boundaries of strained quartz

(Figure 3A). Strain has caused the quartz crystal to deform into domains with high undulatory extinction angles.
Bemposta aggregate is composed of a medium-grained, two-mica granite with porphyritic texture, Syn-orogenic, Syn-D3 in age (Ferreira *et al.*, 1987). Some characteristics that might indicate potential alkali reactivity were observed in this granite. The petrographic examination showed some particular deformation features mostly in the quartz crystals. The quartz exhibits strong signs of deformation. Undulatory extinction in strained boundaries, sub-granulation and microcrystalline quartz was observed (Figure 3B). It was verified that the phyllossilicate minerals are oriented. Deformation is also visible in feldspars and in the cleavage plans of muscovite and biotite crystals.
S. Tomé de Castelo aggregate is composed of a fine grained two mica granite with anisotropic texture, Syn-orogenic, Late-D3 in age (Ferreira *et al.*, 1987). The petrographic examination of this granite shows that the quartz crystals are frequently strained, exhibiting undulatory extinction. Areas with sub-granulation and recrystallisation of quartz with goticular shape in strained quartz and plagioclase crystals were also observed (Figure 3C).
Alpendurada aggregate is composed of a medium grained two mica granite, mainly biotitic, with porphyritic texture. The granite is Syn-orogenic, Late-D3 in age (Ferreira *et al.*, 1987). The petrographic examination of this granite shows strained quartz crystals with undulatory extinction. Sub-granulated quartz can also be found in small areas in the limits of some strained quartz crystals.
Vila Flor aggregate is composed of a coarse grained two mica granite, mainly biotitic, with porphyritic texture, Late- to Post-orogenic in age (Ferreira *et al.*, 1987). The quartz crystals exhibit undulatory extinction but no other signs of deformation were found.

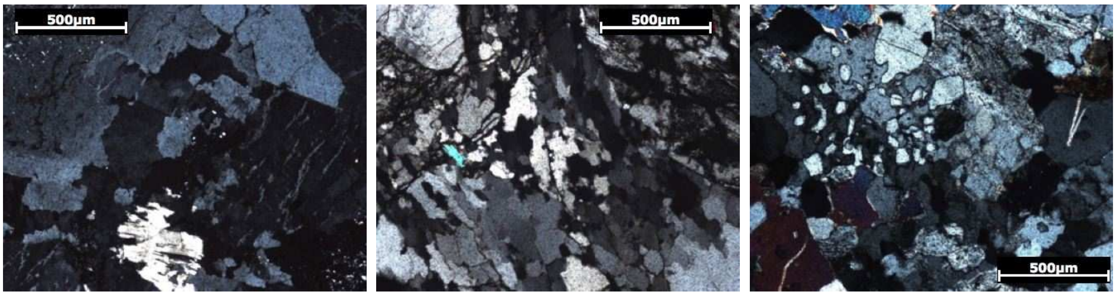

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Figure 3: Deformation features observed on the quartz grains of the granitic aggregates during petrographic examination. A: sub-granulation at grain boundaries of strained quartz of Belver granite. Cross-polarized light. B: undulatory extinction in strained boundaries, sub-granulation and microcrystalline quartz in Bemposta granite. Cross-polarized light. C: recrystallisation of quartz with goticular shape in strained quartz and plagioclase crystals in S. Tomé de Castelo granite. Cross-polarized light.

Expansion tests

As shown in Figure 4, mortar bars expansion of these aggregates varies between 0.01 and 0.08 percent after 14 days of exposure to the NaOH solution. All aggregates were classified as innocuous to concrete since the expansion is less than 0.10 percent after 14 days of exposure to the NaOH solution (RILEM TC 106-2 AAR, 2000; ASTM C 1260, 2007).
In order to confirm the results the test was extended to 28 days. The results of expansion of S. Tomé de Castelo, Alpendurada and Vila Flor aggregates remained low. The mortar bars expansion made with Belver granite show a high rate of expansion as well as a larger final expansion (0.10%) at the completion of the test. Bemposta granite aggregate revealed an anomalous behaviour. The expansion decreased from 0.10 to 0.09 percent from the 21st to the 28th day.

Chemical method

The quantity of dissolved silica of the studied aggregates varies between 29 mmol/l and 95 mmol/l while the reduction in alkalinity varies between 455 mmol/l and 680 mmol/l after 24 hours at 80 ºC in a 1N sodium hydroxide solution. Belver is the aggregate with the lowest value of dissolved silica and reduction of alkalinity. On the other hand, Vila Flor aggregate has the highest values for both the dissolved silica and the reduction of alkalinity. However, all aggregates are classified as innocuous by this method since all the results are in the left hand side of the line that represents the critical limit value between innocuous and reactive aggregates (Figure 5).

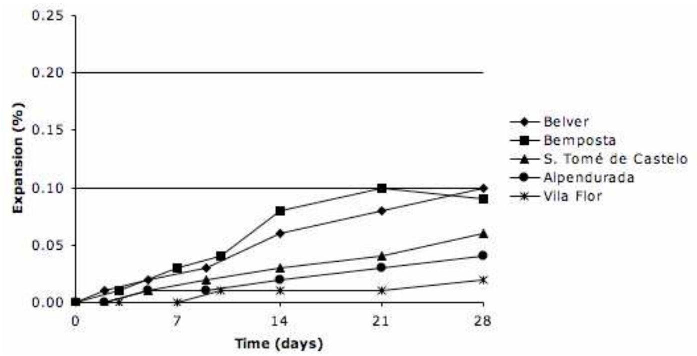

Figure 4: Expansion curves for mortar bars made with each of the five aggregates. All aggregates were classified as innocuous to concrete since the expansion is less than 0.10 percent after 14 days of exposure to the NaOH solution.

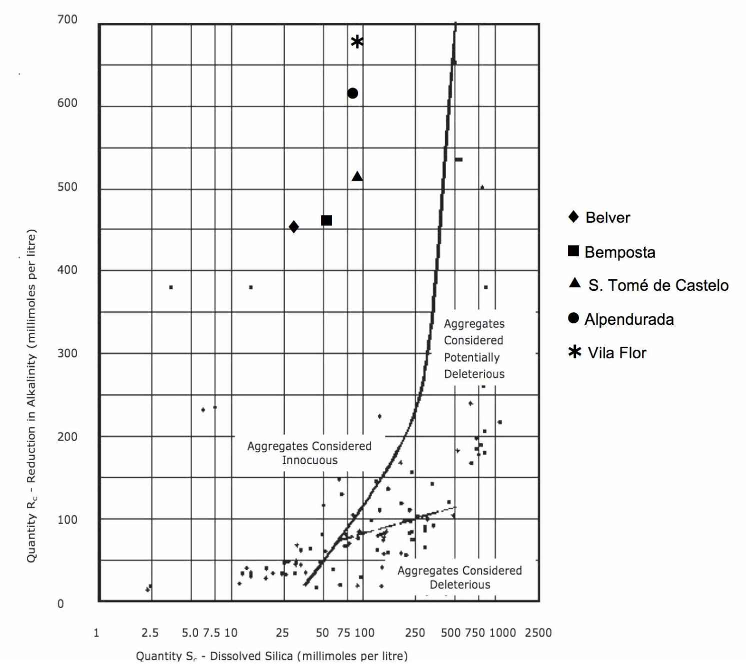

Figure 5: Results for the chemical method performed to each of the five granitic aggregates plotted in a logarithmic graphic of dissolved silica versus reduction in alkalinity. All aggregates are classified as innocuous.

Concrete Structures

In situ investigation

In the site investigation of Bemposta Dam different manifestations of ASR were detected. In the exterior of the structure map cracking and exudations were observed. The site investigation of the galleries inside the dam allowed the recognition of map cracking, pop-outs, efflorescence, exudations and spalling. The main signs of deterioration were observed in the top level gallery.

In the site investigation of the Bridge over Douro river two piers and respective concrete pile caps were inspected to detect signs of deterioration related to ASR. Map cracking was found in the piers and concrete pile caps investigated.

In the site investigation of Fratel Dam different manifestations of ASR were detected. In the exterior of the structure it was verified that map cracking and exudations occur in two of the spillways. Inside the dam map cracking, two pop-outs and exudations of calcium carbonate were observed. No alkali-silica gel exudations were found.

Petrographic examination

Through petrographic examination of the concrete samples from Bemposta dam alkali-silica gel was observed in three of the six cores drilled. Inside the concrete, alkali-silica gel was found replacing fine aggregate particles and filling cracks. Its occurrence is more abundant in the core collected close to the place where the gel exudations were observed. The other cores are related to spalling of concrete and wide pop-outs. In places were alkali-silica gel was identified replacing particles of fine aggregate, needle shaped ettringite formed rims in the interface with the cement paste (Figure 6A). The cracks where ASR gel was found start inside the monomineralic quartz particles of the fine aggregate, in places where there were sub-grains, and then extend to the cement past, sometimes crossing fine aggregate particle (Figure 6B). A pattern was observed in which the cracks are parallel to each other and also to the exterior concrete face. The alkali-silica gel detected replacing particles of fine aggregate has a composition in which calcium exists with a higher content than that of potassium and sodium and there is also some aluminium. On the other hand, in alkali-silica gel detected in cracks besides silicon, calcium, potassium and sodium, there are also aluminium and some magnesium. The study by SEM/EDS of the reaction products revealed that only one of the observed and sampled exudations corresponds to alkali-silica gel. This gel is composed of silicon, some potassium and little sodium. No calcium was detected. No alkali-silica gel was found in the samples collected from the exposed surfaces where spalling of concrete and pop-outs were observed.

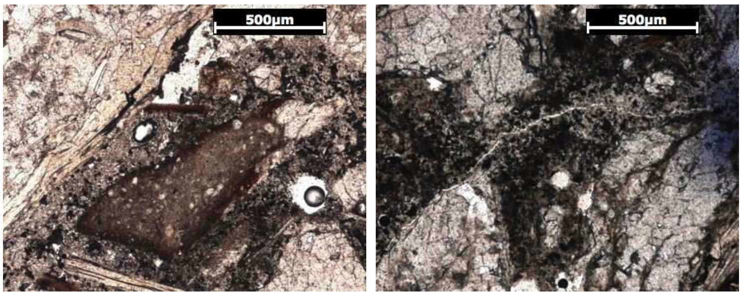

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Figure 6: Reaction features observed at Bemposta dam through petrographic examination. A: alkali-silica gel is replacing a particle of fine aggregate. Plane-polarized light. B: Crack filled wit gel crossing fine aggregate particles and then extended to the cement paste. Plane-polarized light.

The macroscopic inspection of the cores extracted from the bridge over Douro river shows that distinct rocks were used as aggregates in the manufacturing of the concrete of the piers and of the concrete pile caps. The granite used as aggregate in the piers is a medium to coarse grained biotite granite. The granite used in the concrete pile caps is a fine grained two mica granite studied in this project under the designation of S. Tomé de Castelo aggregate. Through petrographic examination of thin sections from the piers, a large number of microcracks were observed in the cement paste and around fine and coarse aggregates. Needle shaped ettringite was found in a number of voids. However, its distribution is not homogeneous in the same core or even in the same thin-section. No alkali-silica gel was found. Several microcracks were observed in the cement paste and around fine and coarse aggregates in all thin-sections from the concrete pile cap. Needle shaped ettringite was found filling partially some voids, but its distribution is not homogeneous in the structure. ASR gel with different colours was observed replacing particles of fine aggregate in five of the six cores (Figure 7 A, B and C). It was verified that alkali-silica gel is more abundant in the two cores collected from the south face, the face more exposed to temperature variation. Alkali-silica gel was also observed in other three cores, one from the north face and two from the west face. The higher abundance of alkali-silica gel in the two cores collected in the south face can result from the variations of temperature.

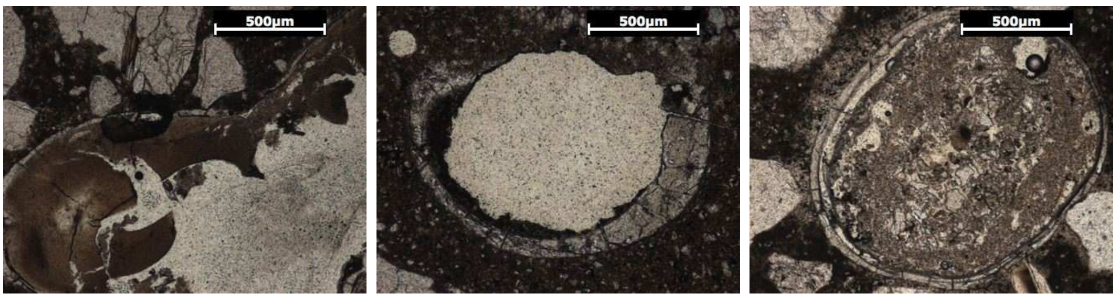

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Figure 7: Alkali-silica gel replacing particles of the fine aggregate was observed in thin-sections from the concrete pile cap of the Bridge over Douro river. A: The alkali-silica gel presents a brown coloration. Plane-polarized light. B: A grey coloration of the alkali-silica gel was observed in this case. Plane-polarized light. C: Alkali-silica gel showing a whitish coloration. Plane-polarized light.

The petrographic examination of the samples collected at Fratel dam did not allow the unequivocal identification of ASR. Through the examination of thin-sections of concrete rare microcracks were found in the cement paste and in the interface between coarse and fine aggregate particles and the cement paste. In some thin-sections a number of voids are partially filled with ettringite. No alkali-silica gel was found under the polarising microscope.

Discussion

The granites from Belver, Bemposta, S. Tomé de Castelo, and Alpendurada aggregates were classified as reactive by petrographic examination, while the granite from Vila Flor aggregate was classified as non-reactive. The potential reactivity of the Belver granite is indicated by the presence of extensive sub-granulation at grain boundaries of strained quartz (Thomson and Grattan-Bellew, 1993; Thomson *et al.*, 1994). Bemposta granite potential reactivity was indicated by the presence of sub-granulation at grain boundaries of strained quartz, microcrystalline quartz and deformation in feldspars and in cleavage plans of mica crystals. According to several authors (e.g. Grattan-Bellew, 1986; Wigum *et al.*, 2000; Broekmans, 2002; RILEM AAR-1, 2003) the presence of microcrystalline quartz in granitic rocks that contain strained quartz enhances the susceptibility to alkalis, since the presence of microcrystalline grains increases the surface contacts between quartz and interstitial solution (Michel *et al.*, 2003). The susceptibility to alkalis of granitic rocks may also be increased by the presence of deformation in the feldspars and in the cleavage plans of muscovite and biotite crystals (Kerrick and Hooton, 1992). The petrographic examination of S. Tomé de Castelo granite shows strained quartz crystals and areas with sub-granulation and recrystallisation of quartz with goticular shape in strained quartz and plagioclase crystals. Thomson and Grattan-Bellew (1993) and Thomson *et al.* (1994) defend that subgrain development of quartz is even more reactive than its complete recrystallisation. Nevertheless, recrystallisation process is related to the reactivity of granitic rocks by some authors (e.g. Kerrick and Hooton, 1992; Shayan, 1993). In Alpendurada granite, sub-granulation of quartz was found only in small areas in the limits of some strained quartz crystals. Its presence, even scarce, may indicate potential reactivity of this rock (Thomson and Grattan-Bellew, 1993; Thomson *et al.*, 1994). However, this granite is expected to be much less reactive than the ones described before. The quartz crystals of Vila Flor granite exhibit undulatory extinction but no other signs of deformation assumed to cause ASR were found. According to West (1994), undulatory extinction of quartz should be used as possible indicator rather then a diagnostic feature of potential alkali-silica reactivity in concrete aggregates. Thus this rock was classified as non-reactive.

The petrographic characteristics of these granites indicated that, as a general rule, the older granites present more deformation features often described in the literature associated to the reactivity of the granitic rocks. Nevertheless, despite the fact that the oldest granite studied was the Pre-orogenic granite from Belver it is the Syn-orogenic, Syn-D3 granite from Bemposta that shows the stronger signs of deformation and, in consequence potential reactivity. A progressive decrease in the proportion of reactive quartz is found from the oldest granites to the youngest. The youngest granite studied, the Late- to Post-orogenic granite from Vila Flor aggregate, was classified as non-reactive.

The chemical method and the accelerated mortar bar test classified all the granites as non-reactives. The discrepancies found between petrographic examination and the other two test methods can be explain by the unsuitability of those methods to evaluate the reactivity of slow/late reactive aggregates. The chemical method has the advantage of be a rapid way to evaluate the potential alkali-reactivity of aggregates. However, it is not suitable to use with all types of aggregates and it does not give an estimation of the potential expansion of the aggregate (ASTM C 289, 2007). Concerning the accelerated mortar bar test, the discrepancy between the expansive behaviour and the known reactivity of the aggregates may be explained by the use of inadequate limits (Shayan, 1993, 2007; Wigum, 1995; Silva and Gonçalves, 2006; Silva *et al.*, 2008). The results from several studies performed by Laboratory National of Civil Engineering lead to the conclusion that these tests were considered inappropriate to evaluate the alkali reactivity of the aggregates in Portugal and their use is no longer recommended by the new normative documents (Silva and Gonçalves, 2006; Silva *et al.*, 2008).

The deductions made by the petrographic examination of the aggregates were confirmed by the performance of those aggregates in concrete structures. The manifestations of ASR are more frequent and serious for Bemposta Dam. Besides the macroscopic signs of deterioration, concrete from Bemposta Dam contains alkali-silica gel replacing fine aggregate particles and gel filling cracks associated to the aggregate particles. Signs of ASR were also found in the bridge concrete pile cap. Despite the fact that only map cracking was found in the site inspection, gel replacing fine aggregate particles and intense cracking was found in the petrographic examination of the concrete. The manifestations of ASR observed in Fratel Dam are, according these results, scarce and inconclusive.

Conclusion

From this study it can be concluded that, as general rule, the older Portuguese granites are more likely potential reactive to alkalis of concrete than the younger granites. However, there is no rule without some exception as was proved by the results from Bemposta aggregate. Being the deformation features a driver factor in the potential reactivity of the granites, the regional tectonic events that affected the rock should always be investigated and taken into account. Thus, despite the fact that the age of the granite can be used as indicator of it reactivity, the geologic history of the rock cannot be neglected.

Aknowledgements

The authors are particularly indebted to Electricidade de Portugal (EDP) for allowing access to Bemposta and Fratel Dams and for permission to publish these results. The authors wish to acknowledge the Fundação para a Ciência e Tecnologia (FCT) the financial support of project GRANMAT POCTI/CTA/45936/2002 and of the project EXREACT PTDC/CTM/65243/2006.

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