

Role of granitic aggregates in the deterioration of a concrete dam

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Abstract A concrete dam was built on the early 1970s in the Douro River about 70 km from the estuary in the Atlantic Ocean, at Porto city. According to other studies developed in Portugal and some reports in the literature, granitic aggregates can be potentially reactive in concrete. The study of the concrete was, therefore, focused on the assessment of the deterioration of concrete by alkali-silica reactions and also on the influence of the conditions of exposure on concrete deterioration processes. The site inspection permitted the identification of signs of deterioration in those structural elements of the dam which were more exposed to the environmental conditions, but not on the dam body. Concrete cores were obtained by drilling and petrographic analysis was performed in order to identify possible products resultant from internal reactions. Products of alkali-silica reaction and sulfate attack were detected on thin-sections of the concrete collected from the thinner structural elements exposed to the external environmental conditions. Their qualitative composition was assessed under a scanning electron microscope and by energy dispersive spectrometry. The study confirmed the occurrence of alkali-silica reactions with granitic aggregates in which very scarce microcrystalline silica was identified. The deterioration was influenced by the environmental conditions of exposition.

Keywords Granitic aggregates · Slow reactive aggregates · Deterioration reactions · Concrete petrography

Introduction

Alkali-silica reactions (ASRs) are delayed mechanisms of deterioration of concrete that generally occur five, ten or even 20 years after construction of the structures. The present work is part of an investigation programme developed in order to evaluate the potential reactivity of some of the most common Portuguese rocks as aggregates for concrete. It is based on the study of a number of large dams built some decades ago, mainly with granitic aggregates.

The discussion about the occurrence of ASR in concrete containing granitic rocks is far from being consensual and the components of the rocks involved in the reaction are not yet well understood. In fact, although granites are classified in many countries as not potentially reactive, there are indications of reactivity in some regions both in concrete structures and in laboratory experiments (e.g., India, Chile, Portugal, Spain, Australia and UK). Chilean granites were studied by DeHills and Corvalán (1964) who found a correlation between the value of the undulatory extinction angle of quartz crystals and the intensity of deformation processes in the rocks. Gogte (1973) reported on the importance of the petrographic characterization of aggregates and concluded that rocks with more than 35–40 % of quartz with strong undulatory extinction, cracked or with sub-grains were potentially reactive to alkalis. Dolar-Mantuani (1981) proposed the quantification of the undulatory extinction angle in rocks such as granites as a measure of the potential reactivity but also highlighted the limitations of the method. Mullick (1987) studied granitic rocks with different degrees of deformation and found a correlation between strain features and the expansion of mortar bars. The extinction angle and the presence of strained quartz were debated in Buck (1983),

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Concrete Society (1987) and ICOLD (1991). However, soon the undulatory extinction was found not to be an adequate parameter to evaluate the potential reactivity, as presented by West (1991, 1994) who concluded the texture and the size of quartz crystals were far more important than the undulatory extinction.

Shayan and Quick (1991/1992) identified ASRs associated with microcrystalline quartz in a granitic rock and Shayan (1993) highlighted the importance of the presence of microcrystalline quartz and noted that the more highly deformed granite is far more prone to ASR than the less deformed rock, and causes significant expansion and cracking of concrete in which it is used. In an important paper Grattan-Bellew (1992) referred to the solubility of quartz increase for crystal sizes smaller than 100 μm and concluded that microcrystalline quartz should be the cause of reactivity in rocks such as quartzites, granites, gneisses, mylonites and greywackes. Kerrick and Hooton (1992) analysed granitic rocks from a fault zone and concluded that not only the microcrystalline quartz, but also the texture properties of the rocks influenced the susceptibility to ASR, and Thomson et al. (1994) showed that the most reactive constituent in rocks appeared to be the microcrystalline quartz that has undergone significant sub-grain development, but not complete recrystallization.

Attempts to quantify the features related to the potential reactivity of this type of aggregates have followed. Monteiro et al. (2001) studied rocks of granitic composition from a mylonite zone in order to investigate the effect of aggregate deformation on the alkali-silica reaction in concrete. The authors concluded that there was a strong development of preferred orientation in biotite as those rocks became progressively deformed. The correlation between the expansion of mortar bars, the development of foliation and the reduction in grain size was attributed to the pathways created by foliation which aided in the migration of chemical species involved in ASR. The authors emphasized that undulatory extinction was not a good feature to quantify the degree of deformation of a rock as it tends to disappear in quartz when subjected to large deformation and concluded there was a strong dependence of ASR from preferred orientation of biotite rather than from quartz. More recently, Wenk et al. (2008) quantified the dislocation density of rocks of granitic composition with increasing degree of deformation. It was observed that expansion of mortar bars increased with the dislocation density in quartz as dislocations provided favourable sites for dissolution and precipitation to occur. In their paper, the authors stated that dislocations might play a major role in determining the reactivity of quartz bearing rocks with respect to ASR and referred again the linear relationship of the texture of biotite with reactivity. Locati et al. (2010) also

studied rocks with increasing degree of deformation and observed that the reactivity of quartz-bearing rocks depended mainly on their textural and microstructural characteristics and, therefore, on the geological processes generating them.

Alaejos and Lanza (2012) discussed the effect of different crystal sizes of quartz on the reactivity of aggregates and proposed the Equivalent Reactive Quartz for the evaluation of the reactivity of aggregates in which there are simultaneously different forms of reactive quartz.

In a research which involved optical microscopy and SEM-EDS, Hagelia and Fernandes (2012) identified ASR in rocks in which quartz occurred in medium-grained strain free crystals, where no microcrystalline quartz was present, raising the question of the possible contribution of the silicates to ASR. In her study, Šachlová (2013) also found a positive correlation between expansion values of mortar bars and the mica content of rocks, but not with feldspar content.

Materials and methods

The concrete dam is located about 70 km from the mouth of the Douro River, in Porto city. It is a gravity type 57 m height dam for which construction was finished in 1972. A total volume of 190.000 m^3 of concrete was applied. The rock mass foundation is composed of two mica, mainly biotite granite. Crushed granitic fragments larger than 5 mm and reaching 200 mm were used in the concrete manufacture, originated from a quarry located close to the dam site and no longer accessible. The sand fraction was also composed of the same crushed granite. Different compositions of concrete were used during the construction and in some places a chemical admixture (*pozzolith*) was added to the mixture (pozzolanic additions are finely divided material used in concrete to improve certain characteristics or to achieve special properties—EN 206-1 (2007)- and are also used to prevent ASR). The cement content varied from 224 to 300 kg m^{-3} .

A site inspection was carried out in order to assess the conditions of the concrete and to detect possible manifestations of deterioration. A concrete drilling campaign was performed to collect samples for the petrographic analysis of the concrete. The products resulting from deterioration were characterized both by petrographic methods and by qualitative chemical analysis.

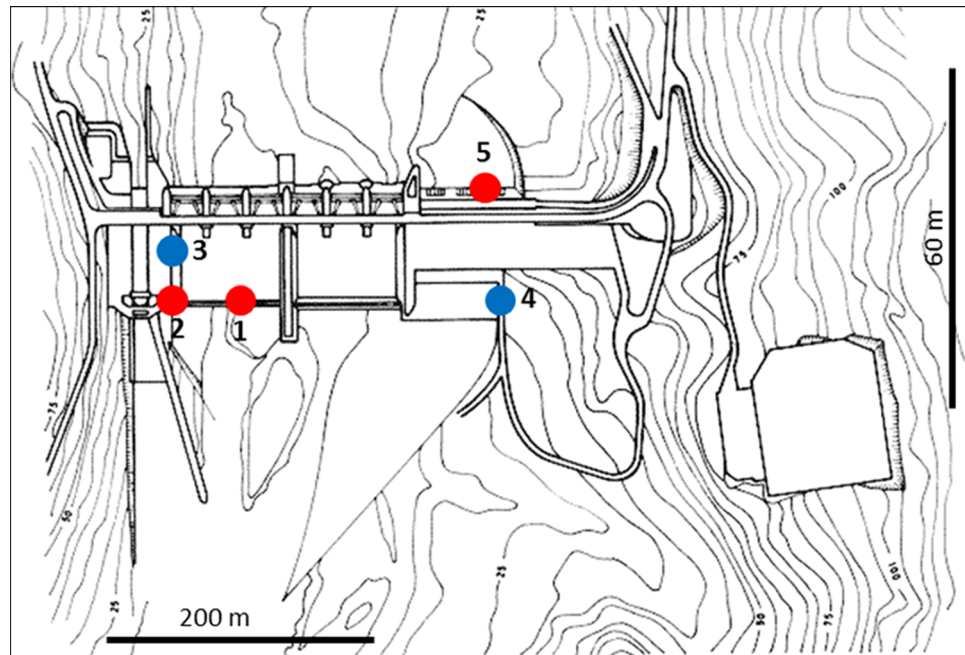
Regarding the environmental conditions, the exposure conditions of the structural elements were variable: there were submerged parts of the structure, interior concrete with no direct contact with water and walls exposed to rain and splashes. The methodology expressed on the document BCA (1992) was followed:

Table 1 Places selected for drilling of concrete (numbers also plotted in Fig. 1)

Concrete samples	Location	Drilling direction
1	Wall of the dissipation basin (downstream)	Vertical
2	Wall between the dissipation basins (downstream)	Horizontal
3	Gallery at level 3.20 (interior)	Horizontal
4	Gallery at level 3.20 (interior)	Horizontal
5	Pavement above the water intake (upstream)	Vertical

- Site inspection of the external walls and interior galleries of the dam body;
- Site inspection of the walls of the annex structures (power plant, navigation sluice, energy dissipation basin);
- Selection of the places for drilling (cracked concrete and discoloration). As a reference for comparison, a place with no signs of cracking was also selected;
- Core drilling (94 mm diameter);
- Production of thin-sections;
- Petrographic analysis with identification of the aggregates, cracks and secondary reaction products;
- Characterization of the reaction products by scanning electron microscopy (SEM) and energy dispersive spectrometry (EDS);

A total of five concrete samples were collected from different sectors of the structure as presented in Table 1 and Fig. 1.

Fig. 1 Location of the drill cores. 1, 2 and 5: surface elements (*red*). 3 and 4: interior wall in galleries (*blue*)

The concrete cores were labeled with a reference number and the sample's orientation indicated with waterproof ink. To avoid desiccation, cores were wrapped in cling-film and sealed in polyethylene bags. They were immediately taken to the laboratory. The cores were cut in half lengthwise in order to observe the concrete. This visual observation led to the selection of the sites for the production of thin-sections, namely where reaction rims, filled air voids and cracks were detected during the macroscopic analysis by the naked eye with the use of a hand lens. Several thin-sections were produced from each core in order to be representative of the concrete in the respective core.

Slices of the concrete were cut and glued with araldite to a glass slide to produce polished thin-sections measuring 25×45 mm using procedures as described in Humphries (1992). Specimen were impregnated with non-fluorescent epoxy and hardened under near-ambient conditions. Thin-sections of 30 μm thickness were produced by hand methods using several stages of grinding and lapping with powdered silicon carbide until final polishing with diamond grit.

The polished thin-sections were observed under a Nikon Eclipse E400POL petrographic microscope under plane polarized light (PPL) and crossed polarized light (XPL). The description of thin-sections included the characterization of the aggregates (petrography of coarse and fine aggregate) and the identification of the features related to the occurrence of ASR such as cracks and gel. Locations of alkali-silica gel were identified with ink on the thin-section surface. The thin-sections were then sputter-coated with carbon under vacuum in a VG MICROTECH E6700/T800 instrument for analysis by a scanning electron microscope, JEOL JSM-6301F, equipped with a field-emission gun (FEG), and a NORAN-VOYAGER energy dispersive spectrometer (EDS).

Results

Site inspection

The access to the external walls of the dam body was very limited and, therefore, sampling was performed just where possible. The interior galleries were inspected as well as the structural elements related to the annex structures of the dam, namely:

- The slab above the water intake (upstream)
- The interior walls of the power plant
- The exterior walls of the navigation sluice and of the energy dissipation basin (downstream).

In the main body of the dam and in the power plant, the concrete was found to be sound with very scarce manifestations of deterioration. The interior galleries were mainly dry with rare exudations and pop-outs. Calcium carbonate stalactites were observed in some joints. Small exudations were observed in the ceiling and walls of the galleries corresponding to individualized droplets of white to yellowish, mainly solid material. In some of the exudations, a wet and viscous material could still be found (Fig. 2).



Fig. 2 Exudation material sampled from the gallery of the bottom sluice (level 0.00)

Fig. 3 In situ manifestations of deterioration: **a** map-cracking and intense discoloration in the slab overlying the water intake; **b** cracking and irregular surface of concrete with aggregate particles protruding from the cement paste on the wall of the energy dissipation basin



On the contrary, the thinner elements of the annex structures exposed to the weather conditions exhibited manifestations of deterioration. Intense map-cracking and discoloration were observed in the upper face of the slab overlying the water intake (Fig. 3a) and in the upper part of the wall of the energy dissipation basin (Fig. 3b). Also, the surface of this wall and the lower level of the wall between the navigation sluice and the dissipation basin showed an irregular concrete surface and in some places the aggregate particles were protruding from the surrounding excavated cement paste.

Drill cores

The observation of the drill cores allowed the first identification of the aggregates and the characteristics of the concrete.

The coarse fraction of the aggregate was composed of crushed granite, the same that formed the foundation rock mass of the dam. Some of the particles showed yellow to brownish, altered granite (Fig. 4). The particles were angular and of sizes >100 mm, although the dimension was not uniform in all places sampled, being larger in the dam body concrete.

In the drill core taken from the slab overlying the water intake there was a lengthwise crack that reached 100 mm deep indicating that it extended into the interior of the slab (Fig. 4a). In the other drill cores no cracks were observed and the aggregate particles-cement paste interfaces were closed at this scale. The cores did not show other evidence of deterioration of the concrete.

Concrete petrography

Characterization of the aggregate

Thin-sections were observed by a polarizing microscope with the aim of characterizing the aggregates and detecting microscopic manifestations of ASRs.

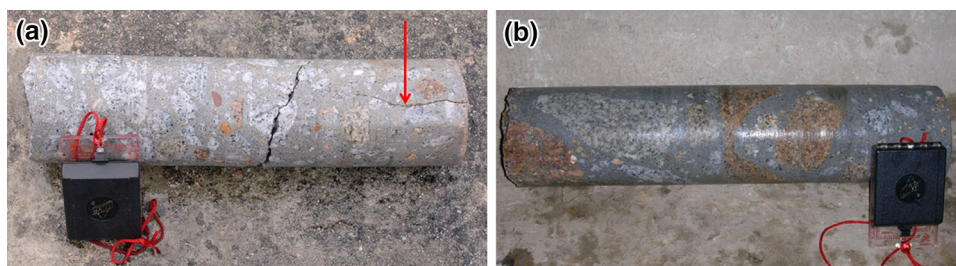
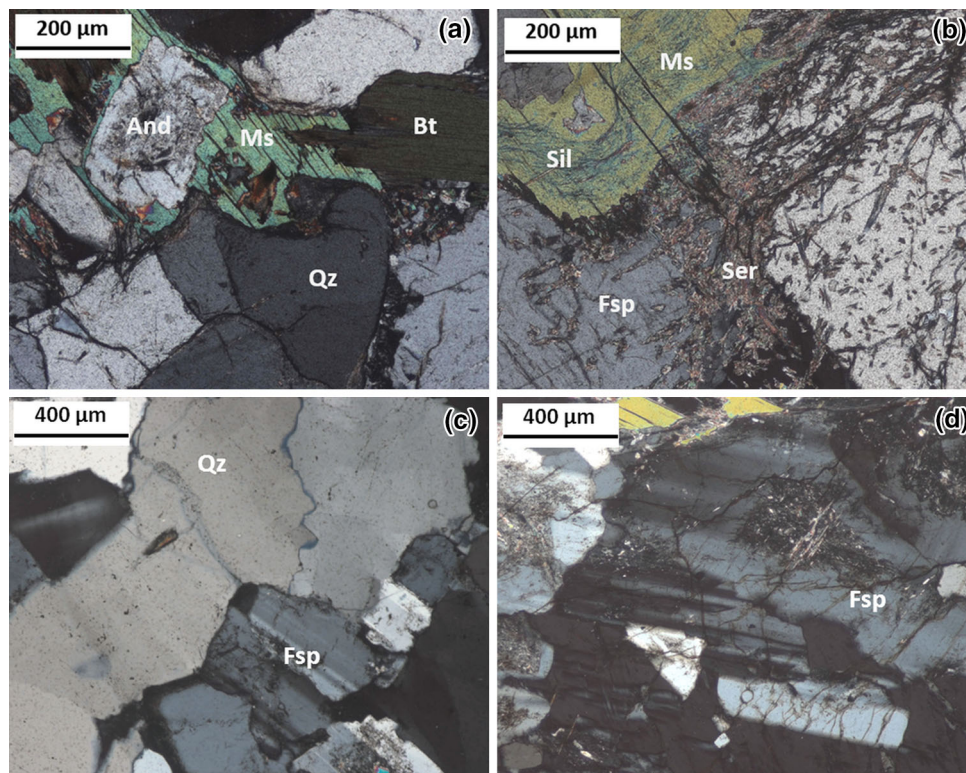


Fig. 4 Drill cores: **a** dried core from the slab overlying the water intake (the red arrow points to the superficial crack); **b** wet core from the gallery at level (0.00). The dimensions of the aggregate fragments depend on the type of structural elements, being much larger in the dam's body

Fig. 5 Photomicrographs of the granite used as coarse aggregate (XPL). **a** quartz (Qz) in crystals with linear boundaries, muscovite (Ms), biotite (Bt), and andalusite (Ad); **b** numerous cracks in the crystals of the feldspar (Fsp) with abundant sericite (Ser). Sillimanite (Sil) is associated with muscovite (Ms); **c** crystals of quartz (Qz) with undulatory extinction and indented boundaries; **d** crystals of plagioclase (Fsp) with numerous cracks and stronger alteration in the Ca-rich cores

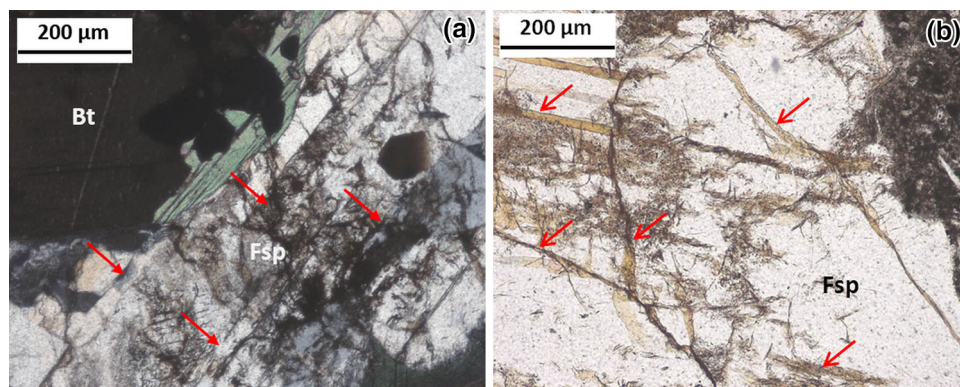


The coarse and fine aggregate components were very similar in all the cores: the coarse aggregate is composed of granitic fragments. The sand fraction was composed of particles with high angularity that resulted from the crushing of the same rock. The most abundant grains were formed by monocrystalline quartz, microcline, plagioclase, biotite and muscovite. There were also fragments of granite.

The study of the aggregate particles confirmed that it was composed of medium-grained granite containing perthitic microcline, sub-euhedral and zoned plagioclase (albite-oligoclase), quartz, biotite and muscovite. As accessory minerals there were sphene-leucoxene, rutile, apatite, zircon, andalusite, chlorite, epidote and fibrolitic sillimanite. The crystals were predominantly sub-euhedral to anhedral, defining a hypidiomorphic texture (Fig. 5).

The accessory minerals were associated with biotite (sphene-leucoxene, apatite, zircon, chlorite, epidote and rutile) and with muscovite (andalusite and sillimanite). Muscovite was mainly secondary and occurred as a late mineral frequently replacing biotite. Symplectic intergrowths were often observed. The plagioclase crystals were zoned and showed stronger alteration in the Ca-rich nucleus. Microcline was dominantly well preserved but in some grains it was moderately altered to clay minerals. The rock was slightly or moderately altered with formation of microcrystalline muscovite on the plagioclase crystals and chlorite and epidote resultant from biotite. Microcrystalline muscovite (sericite) formed along the cleavage planes and the cracks of the minerals, in especially the feldspars. There were also sericite crystals developing in the intergranular spaces, forming a cluster of fibrous crystals. Very

Fig. 6 Photomicrographs of the aggregate particles showing the micro-fractures (pointed out with red arrows): **a** thin cracks cross the large crystals of feldspar (Fsp) producing more intense alteration and/or weathering of the aggregate (brownish deposits in the cracks) (XPL); **b** cracks and alteration of plagioclase (Fsp) crystals highlighted by iron oxides and hydroxides (PPL)



rare opaque minerals were observed in some of the aggregate particles.

Abundant opened cracks crossed the quartz and feldspar larger crystals. These cracks were highlighted by the presence of clay minerals and sericite in the feldspars and by iron oxides and hydroxides (Fig. 6). The same products were found in the intergranular spaces and in the boundary of the larger crystals, namely the feldspars.

The assessment of the potential reactivity of the aggregate was based on the Portuguese guidance Especificação LNEC E 415 (1993) and Especificação LNEC E 461 (2007) and on the RILEM Recommended Test Method AAR-1 (2003). Attention was focused on the study of the crystals of quartz and the signs of deformation of the rock. Quartz was medium-grained, larger than 100 µm (up to 1.5 mm), showed dominantly straight and seldom indented boundaries. According to the Portuguese standards, undulatory extinction was quantified. Usually the crystals of quartz exhibited undulatory extinction, with angles of 13° more frequent (classified as weak when <15°), and in some crystals reaching 17° (classified as moderate for 15°–25°). Some of the larger crystals exhibited deformation lamellae. In some sectors of the rock agglomerates of smaller quartz crystals were observed showing indented boundaries. These agglomerates were scarce in the aggregate particles observed in the thin-sections. The aggregate was classified in a conservative way as class II (potentially reactive) in what concerned the AAR-1 although the presence of microcrystalline quartz was rare (<2 %vol). According to the Portuguese standards, granitic rocks are immediately classified as Class II (potentially reactive), and it is mandatory that the petrographic analysis is complemented by laboratory expansivity tests in case there is no experience in the use of the aggregate in existing structures.

Products of deterioration

The study of the concrete thin-sections showed that there were microscopic manifestations of deterioration due to

ASRs as well as of sulfate attack in some of the structural elements. No manifestations of deterioration were found in the concrete of the dam body, as was expected by the observation of the walls and the concrete cores.

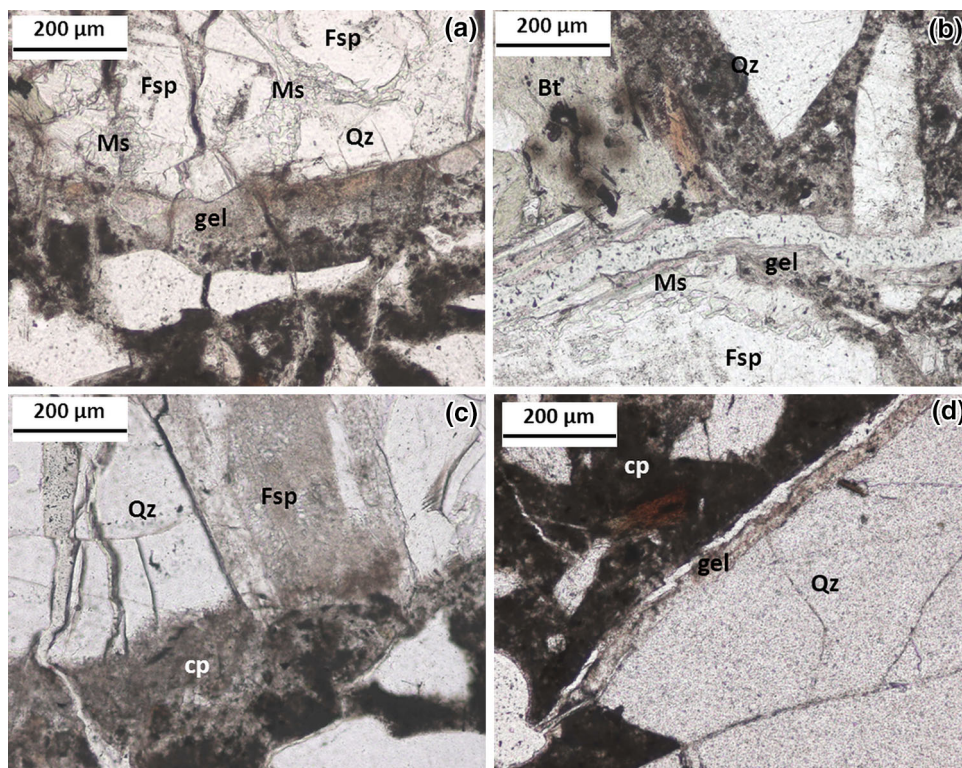
The concrete samples from the slab over the water intake, from the wall of the navigation sluice and from the dissipation basin confirmed the deterioration detected during the site inspection.

In the thin-sections from the slab over the water intake there were micro-cracks in the interfaces between the cement paste and the aggregate particles (de-bonding) and also cracks within the coarse aggregate pieces which extended to the cement paste. Alkali-silica gel was identified filling the cracks inside the coarse particle cracks and scarcely inside the cracks crossing the cement paste. A rim of brownish gel was also observed in the interface of a coarse particle with the cement paste, associated with cracks perpendicular to the interface (Fig. 7). It could be observed that the gel exhibited different characteristics in different locations in the cracks. In some of the cracks that crossed the aggregate particles, gel showed a brownish color without an identifiable structure. In other locations, closer to the cement paste, it was crystalline and exhibited colorless crystals in the interfaces and in the cracks crossing the cement paste.

Close to the interfaces the alkali-silica gel showed a fibrous/rod habit with crystals not very well defined but which grow parallel to the wall of the cracks. Gel was also crystalline inside some voids where it developed with acicular habit perpendicular to the voids' limits. In order to confirm that it was in fact alkali-silica gel, semi-quantitative composition was obtained by SEM-EDS. The analyses were performed in different locations along the cracks in order to assess the possible connection between the composition and the optical properties under a polarizing microscope.

The alkali-silica gel was composed mainly of Si with variable content of Ca and low content of K, Na, Al and Mg (Fig. 8). The Ca content increased from the interior of

Fig. 7 Photomicrographs showing cracks and alkali-silica gel: **a** amorphous brownish gel in an interface between a granitic particle and the cement paste; **b** colourless crystalline gel filling a crack inside the aggregate particle close to biotite (Bt), muscovite (Ms) and feldspar (Fsp); **c** cracks crossing the granitic particle and extending to the cement paste (cp); **d** crack with crystalline gel in the interface and crossing the cement paste (PPL)



the aggregate particles to the contact with the cement paste. This Ca-richer composition corresponded to the lighter grey tonality crystalline structure of the gel under SEM.

The examination of the thin-sections of the concrete from the wall of the energy dissipation basin revealed different microscopic characteristics although the macroscopic map-cracking had a similar pattern than the one of the water intake. In these thin-sections, ettringite was dominant when compared with the alkali-silica gel (Fig. 9). Ettringite crystals were also identified inside the voids. Ettringite was present as acicular/fibrous crystals which developed perpendicular to the voids and crack walls. Sometimes ettringite formed clusters of crystals in the cement paste. Semi-quantitative analyses by EDS were carried out, and it was observed that besides Ca, Al and S, there was Si, Mg, Na and K (Fig. 10). This composition might be due to the simultaneous presence of alkali-silica gel and ettringite.

Discussion

Thin-sections in which more intense deterioration occurred were produced from the concrete cores collected from the places where the map-cracking and the discoloration were more evident by site inspection. These places, namely the pavement above the water intake and the wall of the dissipation basin, were also those in which the concrete was

more exposed to the environmental conditions. In the area the atmosphere temperature in the last 30 years varied from -3.3°C to 38.7°C with a maximum rainfall of 84.4 mm in winter months and the temperature of the river water varied from 6.0 to 27.0°C , with an average of 16.1°C .

As is well known in the petrographic assessment of concrete aggregates, the identification of the mineral composition of a rock or its designation is not sufficient to identify the aggregate as potentially reactive. The performance of aggregates is conditioned by local and regional factors, which have moulded the structure of the rock and strained the minerals during the geological history of the rock. The features generally considered diagnostic in aggregate petrography contributing for ASR include, besides certain silica polymorphs, a large accessible surface area (small grain size preferably with sutured limits) and poor crystallinity (Marinoni and Broekmans 2013).

In the present structure the petrographic analysis proved to be crucial for the diagnosis of the deterioration of the concrete, although it gave unexpected results in what concerns the occurrence of ASRs with granitic aggregates showing scarce deformation features. The aggregate were classified as potentially reactive according to Portuguese standard Especificação LNEC E 461 (2007) and also to the RILEM Recommended Test Method AAR-1 (2003) recommendation because of the occurrence of some (scarce) microcrystalline quartz. According to Portuguese standard Especificação LNEC E 415 (1993), the occurrence of

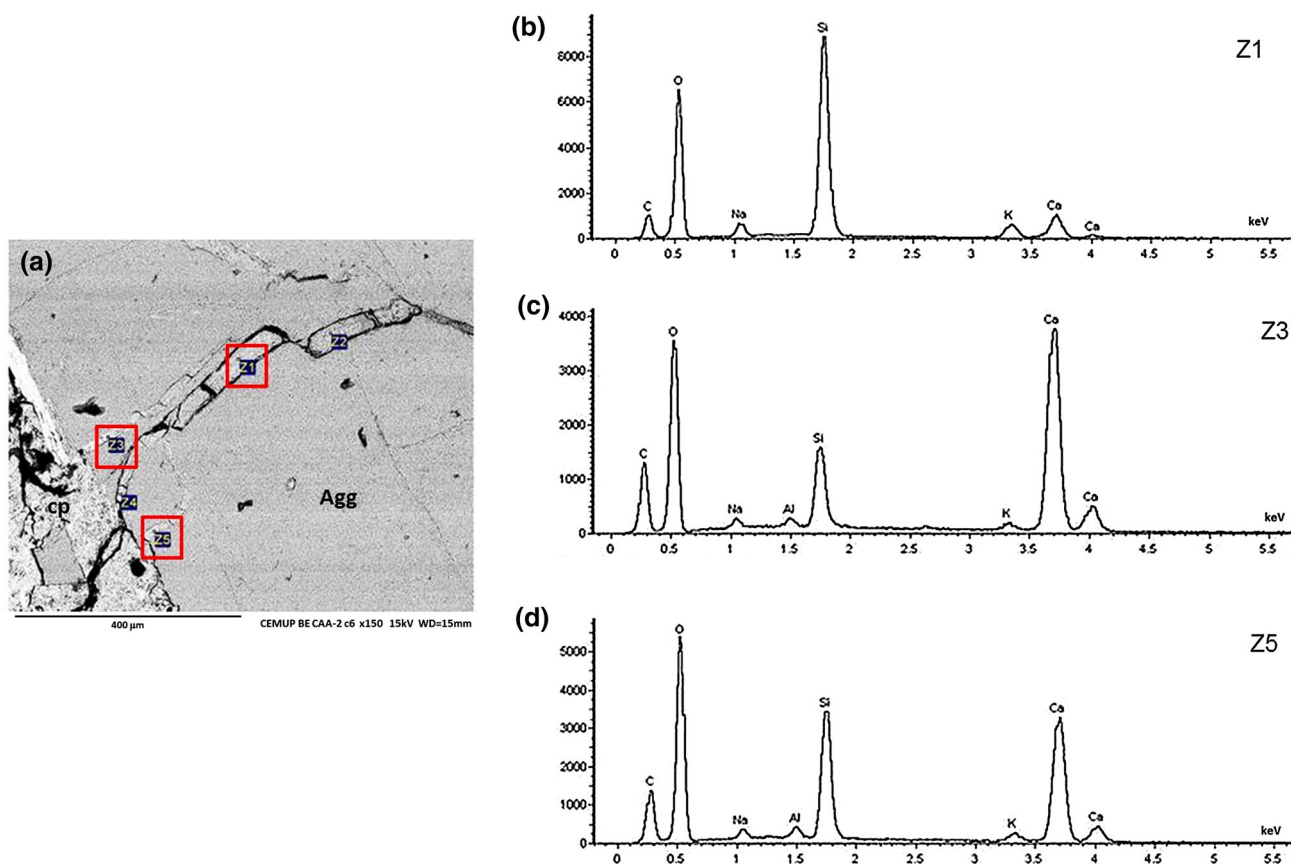
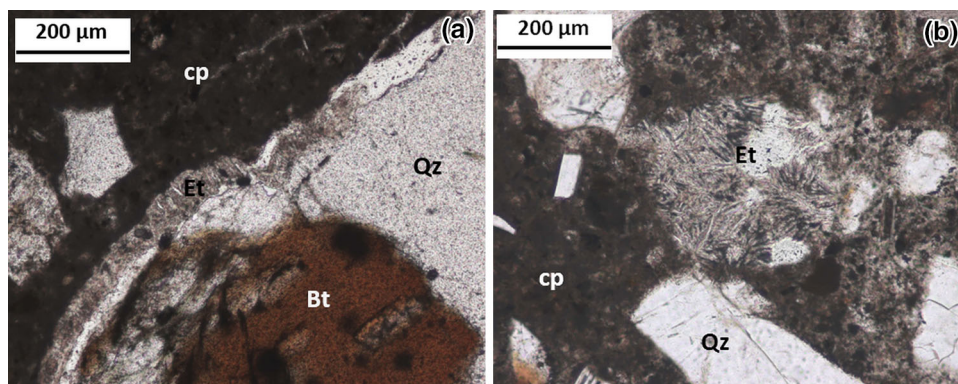


Fig. 8 Alkali-silica gel in cracks inside a coarse aggregate particle (images obtained by SEM using back-scattered electrons and spectra by EDS): **a** image by SEM. Labelled as Z1, Z2, Z3, Z4 and Z5 are the locations where the EDS analyses were performed; **b** EDS spectrum Z1 of gel in the crack inside the aggregate particle (Agg); **c** EDS

spectrum Z3 obtained closer to the interface with the cement paste (cp) showing higher content in Ca; **d** EDS spectrum Z5 also close to the interface with cement paste and with slightly lower content of Ca and higher of Si

Fig. 9 Photomicrograph showing ettringite (Et) acicular crystals: **a** inside a crack in the aggregate-cement paste (cp) interface; **b** filling voids (PPL)



undulatory extinction and deformation lamellae in quartz crystals were also considered to classify the aggregate as potentially reactive. However, many authors claim that the undulatory extinction angle of quartz grains might be a possible indicator of the presence of microcrystalline quartz but could not be used as a diagnostic feature of alkali-silica reactivity (Grattan-Bellew 1992; Thomson et al. 1994; West 1994; Wigum 1995; Wenk et al. 2008).

Thomson et al. (1994) studied metamorphic deformed rocks and concluded that the most reactive components were the microcrystalline quartz, which has undergone subgrain development and also that areas with strong undulatory extinction were not much more reactive than the undeformed ones. Wigum (1995) referred in his work to the grain interstices that are preferable pathways for the infiltration of solution from the surrounding cement paste.

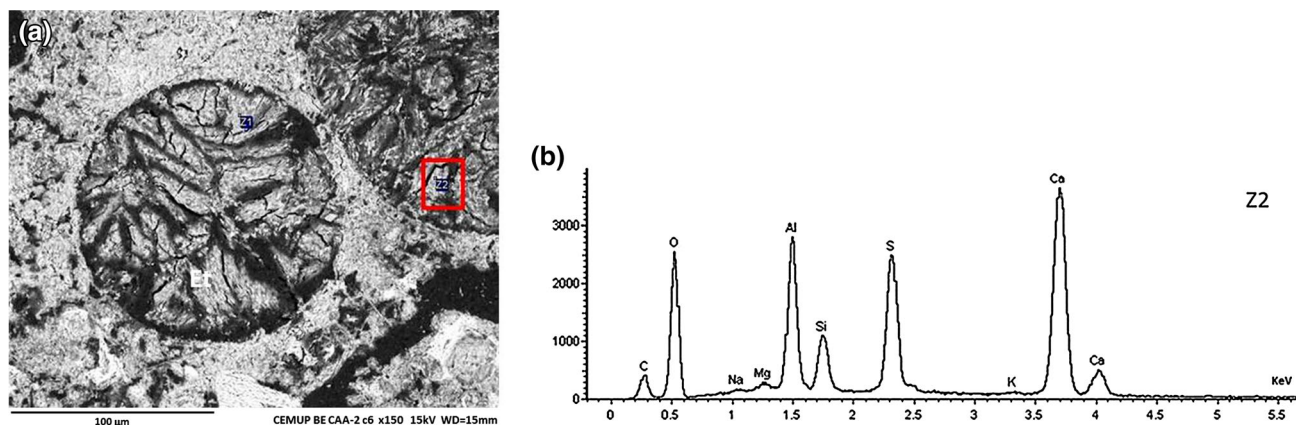


Fig. 10 **a** SEM image (back-scattered electron); **b** EDS spectrum of ettringite crystals filling the voids. The presence of Si shows the co-existence with alkali-silica gel

The author measured the total grain area of quartz as a way to supply the results from petrographic examination, and concluded that the content of subgrains could promote the ability of the alkali-rich fluid to permeate to the reaction site. Šachlová (2013) studied the microstructure parameters affecting the potential reactivity of aggregates in various metamorphic rocks and assessed deformation and recrystallization characteristics such as undulatory extinction, patchy extinction, serrated boundaries, bulging, subgrain rotation and grain boundary migration recrystallization mechanisms. The author concluded that grain size showed a negative correlation with the expansion results from tests, and that this correlation was higher for the specific area. Also, the degree of deformation and recrystallization was suggested to be responsible for ASR due to its effect on grain size and grain shape. Marinoni and Broekmans (2013) studied some sedimentary rocks by petrography, XRD and expansion tests and concluded that microstrain seems to be a more sensitive marker to ASR-reactivity of quartz than crystallite size.

Although granitic rocks are not universally considered as alkali reactive, as referred above, there are examples in the literature about the occurrence of ASR both in structures and in laboratory tests (Kerrick and Hooton 1992; West 1991, 1994; Fernandes et al. 2004, 2007; Yan et al. 2004; Batic and Sota 2004). Shayan (1993) referred to deformed granite for which reactivity is due to the presence of microcrystalline quartz and strained grains, and Shayan and Grimstad (2006) found out that in concrete with some medium-grained to coarse-grained rocks, such as deformed granitic rock, the ASR products can form within the intracrystalline spaces in the aggregate. Fatt and Beng (2007) studied granitic rocks with variable degrees of deformation and weathering, including mylonitic granite and cataclastic granite and considered strained quartz as the quartz with undulatory extinction larger than 15° as well as quartz with

deformation bands and lamellae. For these researchers, the microcrystalline quartz is fine grained ($<60 \mu\text{m}$) and includes re-crystallized quartz grains and sub-grains. The authors found out that, in the mylonitic granite, the quartz and mica deformed plastically causing polygonisation and dynamic re-crystallization. The cataclastic granites were mainly deformed in the brittle domain and presented cracks that affected all the minerals in the rock, with minor polygonization and re-crystallization. The performance in accelerated mortar bar tests classified these rocks as marginally deleterious to deleterious. There was a relationship between total strained and microcrystalline quartz (over 12 %) and expansion values. The cataclastic granite, with microcrystalline quartz in the matrix, showed the larger expansion.

The study of two granitic aggregates used in Spanish dams showed that the main mechanism of formation and storage of gel was associated to micro-cracks rather than to sub-grain boundaries of quartz (Velasco-Torres et al. 2010). The importance of cracks has also been pointed out earlier by Spry (1976) who stated that the diffusion through polycrystalline aggregates was facilitated by the presence of cleavages and cracks while Sprunt and Brace (1974) observed cavities which occupied up to 90 % of grain boundaries in some granites, therefore, explaining features of porosity not visible under a polarizing microscope.

In the present structure, alkali-silica gel was identified inside cracks that cross the coarse aggregate pieces, in interface rims and in voids. This granitic rock shows weak signs of deformation, rare microcrystalline quartz, is altered, and exhibits a large number of cracks highlighted by iron oxides and hydroxides, which might have been a privileged path for concrete fluids. This possibility was also discussed by Velasco-Torres et al. (2010) who concluded that granite can develop a rapid or slow ASR and that the main mechanism of formation and storage of gel was

associated with micro-cracks rather than to sub-grain boundaries. Other cases of deteriorated field structures with apparently innocuous granitic rocks are in the origin of the procedures in the Portuguese standards. Although petrographic analysis is the first step in the characterization of new aggregates regarding potential reactivity, petrographic analysis alone is considered not to be sufficient for granitic rocks and these are immediately classified as Class II and submitted to laboratory expansion tests.

The alkali-silica gel is darker in the cracks inside the aggregate particles and less visible in the cracks that extend into the cement paste. Sometimes it shows rods and rosette like crystals in cracks inside the aggregate particles. The morphology of the gel is identical to that found by other workers such as Stievenard-Gireaud (1987) and Shayan and Quick (1989). Also Regourd-Moranville (1989) referred in her work to having gels that can be grainy, spongy, foliated and massive.

The semi-quantitative composition obtained by SEM-EDS agrees with the results that have been published by a number of authors. However, it can be verified that the composition varies with a number of factors, namely with the location in the concrete and the age of the gel. Ca is always present in the gel inside the concrete and more in the textured gel than in the massive gel. Crystals occur as roses, lamellas, fibers, needles and filaments. Compared to massive gels, they can contain Al, Fe and Na. Silica surfaces are sites of cation exchanges and Na or K previously adsorbed on the gel can be easily replaced by Ca. With time, lime amorphous and massive gels transform into textured silicates. According to Thaulow et al. (1996), the gel has a high and variable content in Si, a low and variable content of Ca and very small contents of alkalis (K and Na). Other authors (Knudsen and Thaulow 1975; Regourd and Hornain 1986; Regourd-Moranville 1989; Helmuth and Stark 1992; Thaulow et al. 1996; Kawamura et al. 1998; Thomas 1998; Diamond 2000; Peterson et al. 2006) also found very variable compositions of gel. The present analyses revealed the existence of Al, as published by Brouxel (1993) and Yan et al. (2004). The fact that most analyses in the literature are semi-quantitative and normalized to 100 % leads to some uncertainties regarding the stoichiometric composition of gel, which is not yet well known.

Concerning the presence of Si in the analyses of ettringite, some authors discussed the co-existence of ettringite and alkali-silica gel. Pettifer and Nixon (1980) referred to the frequent observation of the occurrence of ettringite and isotropic gel from AAR as indicative of a possible connection between sulphate attack and ASR. However, Johansen et al. (1993) discussed the formation of alkali-silica gel and of ettringite, and the authors concluded

that there is no evidence of any mutual interference of both phenomena although the authors have identified alkali-silica gel and ettringite recrystallized in air voids, micro-cracks and cement-paste interfaces. According to Shayan and Quick (1991/1992) the cracks could have originated by ASRs and the space created was then filled with secondary ettringite.

Ettringite occurred in the wall of the energy dissipation basin in consequence of delayed ettringite formation. No relationship was found with the aggregate composition. The wall of the energy dissipation basin and the wall between this one and the navigation sluice presented an irregular surface of the concrete indicating some dissolution of the cement paste probably with the contribution of mechanical forces from the movement of the water caused by the high energy of the water falls when the gates are open. This mechanical effect might originate cracks and facilitate the access of water to the inner concrete and promote further deterioration.

Conclusions

The present study showed that the deterioration of concrete is restricted to the thinner structural elements exposed to the exterior environmental conditions. Petrography was shown to be an important method both in the characterization of the aggregates and in the identification of the features related to chemical reactions. Optical microscopy led to the identification of cracks partially filled with alkali-silica gel and also with ettringite. There were cracks with gel crossing the granitic aggregate particles being a clear evidence of ASR with this slow reactive rock. In the wall of the dissipation basin, there was abundant ettringite denoting the existence of sulphate attack. In this wall also mechanical action from the water fall seemed to affect the concrete elements durability. Sulphate attack seems to occur along with the ASR and ettringite might be replacing the ASR gel.

The body of the dam did not show any manifestation of deterioration which indicates that the occurrence of ASR is facilitated by the exposure conditions.

As found out before and published by other authors, this case testifies to the occurrence of ASRs in concrete manufactured with granitic aggregates. In the cases reported elsewhere, there are microscopic characteristics identified by petrographic methods such as microcrystalline quartz or sub-grains that permit the classification of the aggregate as potentially reactive. In the present case, the texture observed in the granitic particles indicates that the aggregate has scarce features that might suggest potential reactivity, and, therefore, it was classified as potentially reactive, following a conservative approach.

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