



Assessment of the potential reactivity of granitic rocks – Petrography and expansion tests



Violeta Ramos^{a,*}, Isabel Fernandes^{a,b}, António Santos Silva^c, Dora Soares^c, Benoit Fournier^d, Sara Leal^{a,e}, Fernando Noronha^{a,e}

^a ICT, Institute of Earth Sciences, Porto Pole, Rua do Campo Alegre, 4169-007 Porto, Portugal

^b Department of Geology, Faculty of Sciences, University of Lisbon, Edifício C6, Campo Grande, 1749-016 Lisbon, Portugal

^c LNEC, National Laboratory for Civil Engineering, Av. do Brasil, 101, 1700-066 Lisbon, Portugal

^d Centre de Recherche sur les Infrastructures en Béton (CRIB), Université Laval, 1065 ave de la Médecine, Québec, QC G1V 0A6, Canada

^e Department of Geosciences, Environment and Spatial Planning, Faculty of Sciences, University of Porto, Rua do Campo Alegre, 4169-007 Porto, Portugal

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ABSTRACT

Granite is one of the most commonly employed materials in the production of aggregates for concrete, and represents 40% of the total volume of aggregates produced in Portugal. This type of rock is traditionally considered as slowly/late reactive or even non-reactive to alkalis. However, a number of cases of damaged concrete structures in Portugal, due to alkali–silica reaction, have been related to granitic aggregates. A research program has been developed in order to define the best test method for evaluating the potential alkali-reactivity of granitic rocks. The present study involved thirteen granites collected from different quarries. The tests carried out included: petrographic examination of the aggregate, as well as mortar and concrete expansion tests. It was concluded that the content of microcrystalline quartz correlates better with the results of concrete prism expansion tests than with the mortar-bar expansion test.

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1. Introduction

1.1. Textural features and the potential reactivity of slowly reactive rocks to alkalis

Although granitic aggregates are commonly considered as being innocuous or unlikely to be reactive to alkalis in concrete (e.g. [1]), a number of reports have been published worldwide showing that, under some circumstances, such rock types may react with alkalis causing a slow deleterious reaction in concrete structures [2,3]. These rocks are considered, among other quartz bearing rocks, as slowly reactive according to the classification in Lindgård et al. [4]. French and Howarth [5] state that granite is mostly stable but might be reactive due to the presence of cataclasite or strained quartz. Several factors were pointed out as being responsible for the reactivity of granitic rocks and a number of methods to predict the behavior of this type of rock have been proposed.

The first statements suggesting that alkali-aggregate reactions (AAR) in quartz bearing rocks were a consequence of their mineral's

defective crystal lattice are dated from the middle of the last century (e.g. [6]). Till then, little importance was given to textural features of those rocks used as aggregates. Taking into account the work of DeHills and Corvalán [7] in Chilean granitic rocks, who found that it was possible to correlate the value of the undulatory extinction angle of quartz crystals, the degree of deformation in their lattices and the intensity of deformation processes, Gogte [8] showed that the potential alkali-reactivity of some crystalline rocks was related to the content and straining effects in quartz. According to the author, the increased number of dislocations in quartz in response to strain caused greater reactivity due to the weakening of the silicon-oxygen bond. It created regions of small misorientation within an individual grain, known as sub-grains, which optically appeared as extinction differences [9]. As so, when deformed quartz was observed under crossed polarizers, a dark extinction band began to form which moved across the crystal as the stage was rotated from the bright position. The rotation angle between the first and the last appearance of the extinction band, as it moved across the crystal, was called undulatory extinction angle (UEA) [10]. Gogte [8] also concluded that rocks containing 35% to 40% of micro-cracked and sub-granulated quartz, and crystals with UEA between 18° to 27°, performed as reactive in expansion tests. Further researches using the measurement of the UEA as a parameter for evaluating the potential alkali-reactivity of aggregates have followed [11,12]. The threshold value of UEA of 25° was proposed for considering a rock as reactive [12]. On the other hand, a value below 15° pointed out a non-reactive

* Corresponding author.

E-mail addresses: violetaramos@fc.up.pt (V. Ramos), mifernandes@fc.ul.pt (I. Fernandes), ssilva@lnec.pt (A. Santos Silva), dsoares@lnec.pt (D. Soares), benoit.fournier@ggl.ulaval.ca (B. Fournier), sara.m.leal89@gmail.com (S. Leal), fmnoronha@fc.up.pt (F. Noronha).

behavior. In 1983, Buck [13] also suggested that, in an aggregate containing more than 20% of quartz, a value of UEA above 15° was indicative of potential reactivity. Furthermore, the Concrete Society [14] recommended that an aggregate presenting more than 30% of highly deformed quartz, i.e. with a mean UEA of 25° after, at least, twenty grain measurements, should be considered as potentially reactive. Meanwhile, the usefulness of the UEA was questioned (e.g. [15–19]) and it was pointed out as being a possible indicator rather than a diagnostic feature for alkali–silica reactivity [20,21], since quartz showing high UEA was usually associated with the presence of microcrystalline quartz [10,22]. However, the evaluation of the UEA in quartz crystals as an identifying parameter of potential ASR has not been totally dropped out and recently Tiecher and co-workers [23], after the examination of quartz-rich strained Brazilian aggregates, proposed different quartz deformation degrees taking into account the presence and the intensity of undulatory extinction. The same authors also concluded that rocks predominantly formed by quartz grains with a marked undulatory extinction and featuring deformation bands were highly prone to developing alkali–silica reaction (ASR). Other studies showed that there is a positive correlation between the amount of microcrystalline quartz, resulting from the conversion of a mineral grain which previously showed undulatory extinction into an agglomeration of smaller new grains in response to deformation, and mortar and/or concrete expansion tests (e.g. [16,18,19,24,25]). Kerrick and Hooton [24] and Shayan [25] attributed ASR to the presence of microcrystalline quartz in replacement of deformed quartz, and stated that the reaction took place at grain boundaries and zones containing finely divided quartz which present a larger surface area. According to the work of Grattan-Bellew [16], the solubility of quartz is highly increased by grain sizes less than 100 µm due to the increased surface area, while Joyce [26] considered 10 µm as the threshold for reactivity. An approach proposed by Wigum [27] in the study of cataclastic rocks was the estimation of the alkali-reactivity by determining the total grain boundary area of quartz, which was strongly influenced by sub-grain development. In order to study the reactivity of aggregates containing different quartz crystal sizes, Alaejos and Lanza [28] tested quartzites, quartzarenites and limestone. The authors set four classes of potential reactivity according to the following crystal sizes: >130 µm – innocuous quartz; 60–130 µm – doubtful quartz; 10–60 µm – reactive quartz; and <10 µm – highly reactive quartz. Both reactive and highly reactive quartz were combined in the equivalent reactive quartz (ERQ), which had a standard limit of 2 vol.% for the classification of the aggregate as reactive.

Also, according to Kerrick and Hooton [24] and Shayan [25], the presence of foliations could provide an enhanced penetration of alkali solutions. Taking those facts into account, the recrystallization of the quartz could explain the decrease in the reactivity of strongly mylonitized rocks [29], since the amalgamation of smaller grains into larger ones, which occurs when the geothermal gradient increases, leads to a smaller total grain boundary area of quartz [30]. The presence of myrmekites, defined as a vermicular intergrowth of quartz and sodic plagioclase formed by replacement of K-feldspar, typically in deformed granitic rocks [9], was also considered by Wigum [27] as a preferential site for ASR.

Wenk et al. [19] demonstrated that there is a positive correlation between ASR and dislocation density, and also that dislocations, accompanied by grain size reduction, play a major role in the process. The same authors corroborated the work of Monteiro and co-workers [31] by showing that there was a linear relationship between biotite preferred orientation and quartz susceptibility to ASR. In addition, the comparison of two granitic aggregates from Spanish dams led Velasco-Torres et al. [32] to conclude that the ASR is slower when the reactive component involved is strained and micro-cracked quartz, and faster when it contains microcrystalline quartz. In the first case, the main mechanism of formation and storage of gel was associated to micro-cracks rather than to sub-grain boundaries.

In spite of microcrystalline quartz being pointed out as the major mineral form responsible for ASR in slowly reactive aggregates, other

minerals such as micas and feldspars have been suggested to also unleash this deleterious reaction (e.g. [33,34]). In their experiments, Velasco-Torres et al. [32] observed a large amount of gel where the quartz crystals were in contact with plagioclase or K-feldspar, especially when myrmekites or perthitic structures were present. Hagelia and Fernandes [34] suggested that, under some circumstances, the role played by the size of quartz grains might not be enough to explain the existence of ASR and other mechanisms were needed in order to supply Si to the formation of ASR reaction products. Fernandes et al. [35] also presented cathodoluminescence images showing rims of gel close to feldspar crystals in concrete prisms with granitic aggregates, subjected to laboratory expansion tests. Both feldspars and micas (namely biotite and muscovite) were proved to have increased dissolution rates at very high pH values (e.g. [36–38]) releasing Si and Al to the system. Furthermore, geological alteration and/or weathering of minerals, such as feldspars into secondary clay minerals, can greatly contribute to alkali release. Despite that most of the alkalis are safely chemically bound within stable minerals and thus not releasable, given that the aggregate makes up a high proportion (~75% by weight) of the concrete, even a small proportion of these minerals have the potential to contribute with significant amounts of alkalis to the pore solution, providing an extra source for further ASR expansion [39].

1.2. Portuguese granites and granitic aggregates

In Portugal, large amounts of granitic aggregates are produced every day. The huge abundance of this material, especially in the north and center of the country, has contributed to the construction of major structures such as dams, mainly during the 1960s and 1970s.

Portuguese granitic rocks have diverse geological histories, which generated different degrees of strain that are directly responsible for some granites' main characteristics (e.g. texture and mineralogy). Particularly, in the NW of the Central Iberian Zone (CIZ), a significant volume of granitic rocks (60%–70% of the outcropping rocks) occurs, corresponding to successive magmatic pulses that mainly took place after the Variscan syn-collisional thickening stage [40]. The granites, sometimes in association with basic to intermediate composition rocks, define alignments in close relation to Variscan structures [41]. These rocks are characterized by a strong compositional variability and diverse typology, varying from strongly peraluminous to slightly metaluminous [40,42].

In 1987, Ferreira and co-workers [41], essentially based on structural, petrographic, mineralogical, textural and geochemical characteristics, classified the granitic rocks in agreement with their emplacement period using the last ductile Variscan deformation phase (D3 – Westfalian in age) as referential and together with the prevailing mica observed in the rock (biotite granites: biotite >> muscovite; and two-mica granites: muscovite > biotite).

Since granitoids emplaced predominantly during and after D3, nowadays these are considered as syn-tectonic, late-tectonic and post-tectonic in terms of installation period [40,43]. As so, the granitoids are distributed in four groups [40,41]:

- syn-D3 granitoids – biotitic granites and granodiorites weakly to moderately peraluminous and two-mica granites strongly peraluminous (312–321 Ma);
- late-D3 granitoids – weakly to moderately peraluminous biotitic granites and granodiorites sometimes associated with basic to intermediate rocks (305–312 Ma);
- late- to post-D3 granitoids – two-mica leucogranites and weakly peraluminous biotitic granites (300 Ma);
- post-D3 granitoids – slightly metaluminous biotitic granites (290–299 Ma).

According to Camelo [44], there are 65 concrete and masonry dams in Portugal. Among these, 25 are more than 50 years-old. The same

Table 1

Codification, lithology and age of the studied granitic rocks according to Dias et al. [40] and Ferreira et al. [41]. The relative density of the aggregates is also provided.

Aggregate	Lithology	Age	Relative density
GR1	Granite	Late- to post-D3	2.64
GR2	Granite	Syn-D3	2.58
GR3	Granite	Late- to post-D3	2.63
GR4	Tonalite	Late- to post-D3	2.75
GR5	Granite	Late- to post-D3	2.60
GR6	Granite	Late- to post-D3	2.63
GR7	Granite	Late- to post-D3	2.59
GR9	Granite	Late- to post-D3	2.56
GR11	Granite	Late- to post-D3	2.55
GR17	Granite	Late-D3	2.65
GR18	Granite	Syn-D3	2.63
GR19	Granite	Syn-D3	2.64
GR20	Granite	Syn-D3	2.64

author states that in 2050, 36 dams will be more than 75 years and 9 will be more than 100 years. This clearly suggests that an increasing number of ASR-affected dams can be expected in the next decades, as well as the number of structures that may need to be repaired/demolished/replaced. Of the aforementioned inventory, and till now, 11 large concrete dams built using granitic aggregates have been diagnosed with ASR. Some of those cases have been investigated (e.g. [22,45–51]). The work developed so far has shown that the behavior of Portuguese granitic aggregates towards ASR is puzzling and that the currently used assessment methodologies have not proven to be totally satisfactory. For example, the aforementioned authors indicated the inefficiency of the accelerated mortar-bar test ASTM C 1260 since its testing period and limits are not adequate for the detection of the potential reactivity of these slowly reactive rocks. The inadequacy of the test period of 1 year for the concrete prism test at 38 °C RILEM AAR-3.1 [52] in the assessment of granitic aggregates was also pointed out. Its extension till 2 years using a threshold of 0.04% has been recommended [53].

2. Scope of the work

In order to contribute to the quest of understanding the behavior of Portuguese granitic aggregates in what concerns ASR, thirteen aggregates were selected. The main goal was to identify the factors that contribute to reactivity, through both the petrographic characterization and the evaluation of their performance in expansion tests when applied in mortar and concrete. The methodology precluded in RILEM AAR-0 [52] was followed, namely the petrographic characterization of the aggregates, according to RILEM AAR-1.1 [52] and the Portuguese specification LNEC E 461 [54], as well as the performance of expansion tests, namely the accelerated mortar-bar test ASTM C 1260 [55] and the concrete prism tests RILEM AAR-4.1 [52] and RILEM AAR-3.1 [52].

Table 2

Testing periods and criteria used for the expansion tests' evaluation.

Test method	Testing periods and limits/criteria		
ASTM C 1260	>0.20% at 14 days RILEM AAR-0 [52]	>0.10% at 21 days Shayan [61]	>0.20% at 14 days (100 days for granitic aggregates) Santos Silva et al. [53]
RILEM AAR-4.1	>0.020% at 12 weeks LNEC E 461 [54]	>0.030% at 15 weeks (±0.010% – uncertainty band) RILEM AAR-0 [52]	>0.030% at 20 weeks (±0.010% – uncertainty band) Lindgård et al. [4]
RILEM AAR-3.1	>0.100% at 1 year (0.050%–0.100% potentially reactive) (±0.025% – uncertainty band) RILEM AAR-0 [52]	>0.050% at 1 year LNEC E 461 [54]	

3. Materials and methods

3.1. Aggregates

In order to evaluate the possible influence of the degree of deformation on the behavior of the granitic rocks as aggregates, there was a clear intention in selecting granitic rocks with diverse emplacement ages. To keep the producers' request for confidentiality of the quarries' locations, aggregates have been codified in accordance to the nomenclature established in the Portuguese project IMPROVE – Improvement of performance of aggregates in the inhibition of alkali-aggregate reactions in concrete; the lithology and age of each granitic aggregate are displayed in Table 1, which also shows the relative densities of the investigated aggregates. For aggregates GR3 and GR17 manifestations of ASR have been identified in thin-sections of concrete cores drilled from existing structures [56,57].

3.2. Cement

A CEM I 42.5 R from CIMPOR company was used for the manufacture of mortar and concrete specimens. The cement had an alkali content ranging from 0.86 to 0.89% Na₂O_{eq}.

3.3. Petrographic characterization

Crushed aggregate materials were collected from each quarry (i.e. current production/stockpiles at the time of the visit), in a total amount of about 100 kg per quarry. Blocks of rock were sampled at each of the quarries from the specific zones that were being mined at the time of the visit. These blocks were considered to be representative of the rock being processed for producing concrete aggregates. In cases of variable degree of weathering or facies, several blocks were collected.

Geochemical analyses of portions of the collected blocks, which included major and trace elements, were performed at Activation Laboratories (ACTLABS), in Canada, by lithium metaborate/tetraborate fusion–inductively coupled plasma (ICP).

Thin-sections (thickness 30 µm) were produced from the blocks collected in the quarries. They were studied under a Leica DM750 P polarizing microscope according to the procedure named “whole rock petro” [58]. For photomicrographic record, a Leica ICC50 HD camera was used. A detailed description of the essential and accessory minerals was made. The symmetrical extinction angle method was used to assess plagioclase in respect to its composition.

For the quantification of the potential reactive features, a PELCON automatic point-counter (version 01) was attached to the polarizing microscope. For all the thin-sections, a pace of 0.05 mm was used in order to successfully evaluate the percentage of potentially reactive features present in each rock. The constituent minerals of each granitic aggregate were distributed in the following groups: quartz; K-feldspar; plagioclase; muscovite; biotite + chlorite; microcrystalline quartz

Table 3

Results of the petrographic characterization of the investigated granitic aggregates. The main components are displayed from the most to the least abundant.

Aggregate	Brief petrographic description
GR1	Medium-grained granite with hypidiomorphic porphyritic texture. Quartz, K-feldspar and plagioclase are the essential minerals. Biotite, muscovite, zircon, apatite, opaque minerals, chlorite, rutile, leucoxene, monazite, fluorite, fibrolite, epidote, calcite and sericite are the accessory minerals. Quartz inclusions; myrmekites. Some micro-cracks.
GR2	Medium to coarse-grained granite with hypidiomorphic porphyritic texture. Quartz, K-feldspar and plagioclase are the essential minerals. Muscovite, biotite, tourmaline, zircon, apatite, opaque minerals, leucoxene, chlorite, rutile and sericite are the accessory minerals. Tectonized quartz; quartz inclusions; myrmekites. Some micro-cracks.
GR3	Medium to coarse-grained granite with hypidiomorphic porphyritic texture. Quartz, K-feldspar and plagioclase are the essential minerals. Biotite, muscovite, zircon, apatite, andalusite, opaque minerals, chlorite, rutile, leucoxene, calcite and sericite are the accessory minerals. Deformation bands; quartz inclusions; myrmekites. Abundant intra- and intergranular micro-cracks filled with oxides.
GR4	Medium-grained tonalite with hypidiomorphic texture. Quartz and plagioclase are the essential minerals. Biotite, amphibole, apatite, chlorite, epidote, opaque minerals, pyroxene, clay minerals, calcite and sericite are the accessory minerals. Quartz inclusions; myrmekites. Some micro-cracks.
GR5	Medium-grained granite with hypidiomorphic texture. Quartz, K-feldspar and plagioclase are the essential minerals. Biotite, chlorite, apatite, monazite, zircon, opaque minerals and sericite are the accessory minerals. Quartz inclusions; myrmekites; locally, serrated boundaries and bulge. Rare micro-cracks.
GR6	Medium to fine-grained granite mainly composed of plagioclase, quartz and K-feldspar and seriated texture. Biotite, chlorite, muscovite, andalusite, apatite, zircon, opaque minerals and sericite are the accessory minerals. Quartz inclusions; myrmekites.
GR7	Medium to coarse-grained granite with hypidiomorphic porphyritic texture. Quartz, K-feldspar and plagioclase are the essential minerals. Biotite, muscovite, zircon, apatite, rutile, chlorite, carbonates, opaque minerals, leucoxene, fluorite, calcite and sericite are the accessory minerals. Myrmekites.
GR9	Medium to fine-grained granite with hypidiomorphic texture. Quartz, plagioclase and K-feldspar are the essential minerals. Biotite, muscovite, chlorite, apatite, zircon, opaque minerals and sericite are the accessory components. Quartz inclusions; myrmekites. Some micro-cracks.
GR11	Medium to coarse-grained granite with hypidiomorphic texture. Quartz, plagioclase and K-feldspar are the main components. Biotite, chlorite, alanite, apatite and opaque minerals are the accessory minerals. Myrmekites.
GR17	Fine to medium-grained granite with hypidiomorphic texture. Quartz, K-feldspar and plagioclase are the essential minerals. Biotite, muscovite, apatite, zircon, rutile, opaque minerals, chlorite, leucoxene and sericite are the accessory minerals. Quartz inclusions; myrmekites.
GR18	Medium-grained granite with hypidiomorphic porphyritic texture. Quartz, K-feldspar and plagioclase are the essential minerals. Biotite, muscovite, apatite, zircon, opaque minerals, chlorite, leucoxene, fibrolite, calcite and sericite are the accessory minerals. Tectonized quartz; deformation lamellae. Quartz inclusions; myrmekites. Abundant micro-cracks.
GR19	Medium-grained granite with hypidiomorphic texture. Quartz, K-feldspar and plagioclase are the essential minerals. Biotite, muscovite, andalusite, zircon, apatite, leucoxene, opaque minerals, chlorite, fibrolite and sericite are the accessory minerals. Deformation lamellae. Quartz inclusions; myrmekites. Some micro-cracks.
GR20	Fine to medium-grained granite with hypidiomorphic texture. Quartz, K-feldspar and plagioclase are the essential minerals. Biotite, muscovite, tourmaline, andalusite, apatite, zircon, opaque minerals, chlorite, rutile and sericite are the accessory minerals. Quartz inclusions; myrmekites. Some micro-cracks.

Fine-grained: <1 mm; medium-grained: 1 mm–3 mm; coarse-grained: >3 mm [60].

(<60 μm); and others. The assessment of reactivity to alkalis was based on local experience with granitic aggregates, on the ERQ ($\text{ERQ vol.\%} = \text{vol.\% HR Qz}_{(<10 \mu\text{m})} + 0.31 \text{ vol.\% R Qz}_{(10-60 \mu\text{m})}$), where reactive quartz is designated as R Qz and highly reactive quartz as HR Qz), proposed in Alaejos and Lanza [28] and according to the classes established by RILEM AAR-1.1 [52] and by the Portuguese specification LNEC E 461 [54]. These last two standards define similar classes of reactivity: Class I: very unlikely to be alkali-reactive; Class II: alkali-reactivity uncertain;

Class III: very likely to be alkali-reactive (including aggregates containing opal or opaline silica). Myrmekitic quartz was included in the microcrystalline quartz group and considered as a potentially reactive form of silica, following the work of Wigum [27]. In LNEC E 461 [54], Class I is attributed to aggregates with reactive forms of silica <2 vol.%.

Besides the dimension, deformation evidences of the crystals of quartz, including the UEA, were also taken into account in the evaluation of the potential reactivity to alkalis of the granitic aggregates.

Table 4

Values for the UEA of the crystals of quartz according to LNEC E 415 [59]: <15° – weak; 15°–24° – moderate; $\geq 25^\circ$ – strong) and identification of microcrystalline quartz. The classification is based on RILEM AAR-0 [52] (Class I: very unlikely to be alkali-reactive; Class II: alkali-reactivity uncertain; Class III: very likely to be alkali-reactive (aggregates containing opal or opaline silica)). Following LNEC E 461 [54], aggregates are classified as potentially reactive for >2.0 vol.% reactive forms of silica.

Aggregate	Undulatory extinction of quartz				Potentially reactive silica forms				
	Class	Median (°)	Standard deviation (°)	Coefficient of variation (%)	<10 μm (vol.%)	10–60 μm (vol.%)	ERQ (vol.%)	SUM (<10 μm + 10–60 μm) (vol.%)	Class
GR1	Moderate	16.0	4.54	27	1.4	0.25	1.48	1.65	Class I
GR2	Moderate	20.0	4.99	20	0.4	7.75	2.80	8.15	Class II
GR3	Moderate	18.0	3.93	21	0.15	0.35	0.26	0.5	Class I
GR4	Moderate	15.0	4.83	30	0	0.1	0.03	0.1	Class I
GR5	Moderate	15.0	2.70	17	0.6	0	0.60	0.6	Class I
GR6	Moderate	15.0	4.06	26	0	0	0.00	0	Class I
GR7	Weak	14.0	3.03	21	0.15	0	0.15	0.15	Class I
GR9	Weak	13.0	1.95	14	0.25	0.7	0.47	0.95	Class I
GR11	Weak	6.0	3.46	51	0.7	0.3	0.79	1.0	Class I
GR17	Moderate	15.0	4.03	24	0.15	1.1	0.49	1.25	Class I
GR18	Moderate	23.0	3.98	17	0.4	4.7	1.86	5.1	Class II
GR19	Moderate	20.0	3.48	18	0.65	0.8	0.90	1.45	Class I
GR20	Moderate	19.0	3.51	18	1.15	0.5	1.31	1.65	Class I

In addition to the stress level attained by the rock and the expertise of the operator, the UEA of each grain is affected by its orientation, being measured relative to its optical axes. It also depends on the size of the crystal, since small crystals yield smaller angles. These factors make reproducible undulatory results hard to obtain [10,22]. Although the UEA is not commonly used as a direct indicator of potential alkali reactivity,

its use still raises some questions that need a total and an irrevocable clarification. The method used for the determination of the UEA is described in DeHills and Corvallán [7] and was applied to thirty quartz grains of each granitic rock. The UEA was classified in respect to the most representative class in each rock in accordance to LNEC E 415 [59]: $<15^\circ$ – weak; 15° – 24° – moderate; $\geq 25^\circ$ – strong.

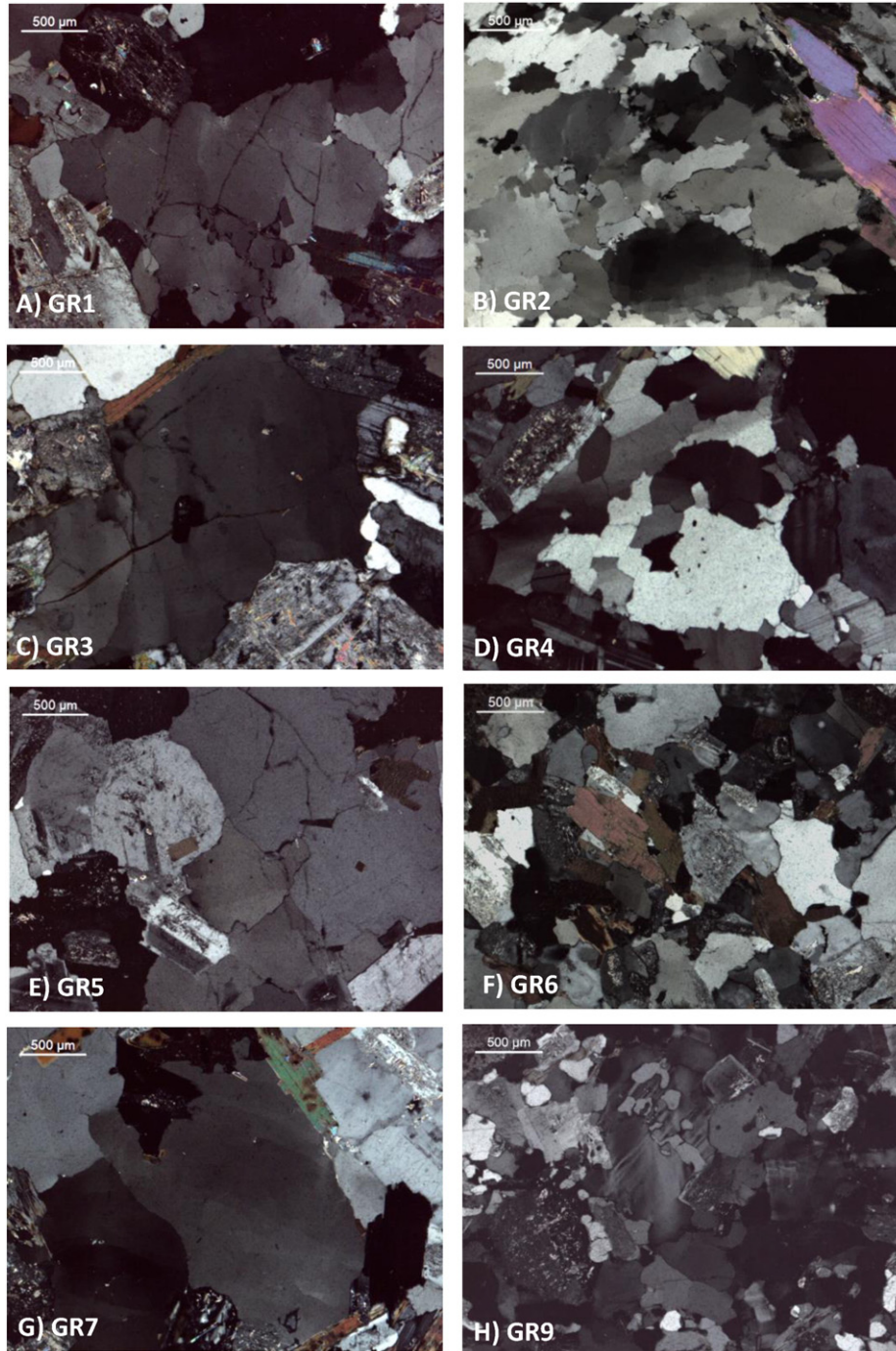


Fig. 1. Microphotographs of the investigated aggregates in cross-polarized light (XPL). The scale bar in all the images corresponds to 500 µm. A) GR1 – crystal of quartz with undulatory extinction and micro-cracks; B) GR2 – stretched crystals of quartz and chessboard extinction; C) GR3 – deformation bands and micro-cracks in a quartz crystal; D) GR4 – serrated boundaries and undulatory extinction of quartz crystals; E) GR5 – straight boundaries of quartz crystals; F) GR6 – texture of the rock reflecting smaller grain size in relation to most of the other samples (fine-grained granite); G) GR7 – undulatory extinction in the crystal of quartz; H) GR9 – quartz occurs in small crystals and in graphic-textured inclusions. I) GR11 – micro-cracks and straight contacts between quartz grains; J) GR17 – quartz in small crystals; K) GR18 – deformation lamellae and sub-grains; L) GR18 – deformation lamellae, strongly serrated boundaries, sub-graining and micro-cracks; M) GR19 – serrated boundaries, undulatory extinction and micro-cracks; N) GR20 – quartz crystals showing serrated limits.

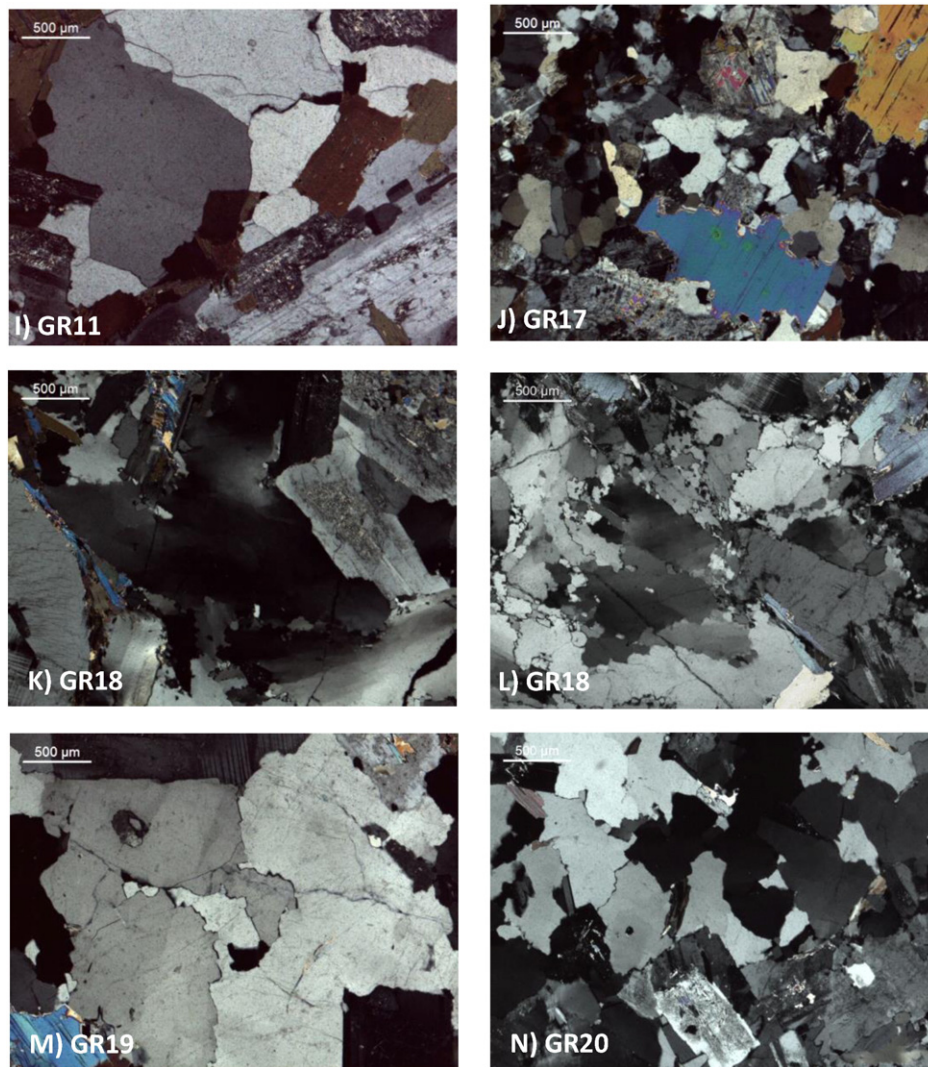


Fig. 1 (continued).

3.4. Laboratory expansion tests and mixes

The samples collected from the stock piles in the quarries were crushed/ground and/or sieved, and weighed according to the requirements of the accelerated mortar-bar test at 80 °C (ASTM C 1260) [55], the accelerated concrete prism test at 60 °C (RILEM AAR-4.1) [52] and the concrete prism test at 38 °C (RILEM AAR-3.1) [52].

Mortar-bars and concrete prisms were then manufactured and subjected to the storage conditions described in the test procedures. Concrete prisms were stored unwrapped both for RILEM AAR-4.1 and RILEM AAR-3.1 tests. Length and mass changes of the test specimens were monitored at regular intervals. Table 2 displays the various testing periods and the expansion criteria used for classifying aggregates as potentially reactive to alkalis.

4. Results

4.1. Petrographic characterization of aggregates

The results of the petrographic characterization of the aggregates are summarized in Tables 3 and 4. Fig. 1 displays mineralogical and textural features of the studied aggregates. Deformation features, namely undulatory extinction, subgrains, bulges and preferred orientation of crystals are included, as well as reference to cracks.

All the investigated rocks are classified as granites, with the exception of aggregate GR4 which is a tonalite. All samples show hypidiomorphic texture. A porphyritic character, conferred by the presence of feldspar megacrysts, is observed in GR1, GR2, GR3, GR7 and GR18. The presence of deformation is evident in GR18 and, especially, in GR2. This last granite presents a preferred orientation of minerals (namely quartz and phyllosilicates) in association to subgraining of quartz and to sutured boundaries along with bulging. GR2 also presents the least developed quartz crystals, which reach, at the maximum, 1.1 mm. The same deformation features of GR2 are observed in aggregate GR18, but to a lesser extent. All other granitoids present, overall, crystals with serrated boundaries. Late microcrystalline quartz inclusions, mainly in K-feldspars, are quite common, with exception of GR7 and GR11. Intra- and inter-crystalline micro-cracks, which can be filled with microcrystalline muscovite, quartz or oxides, are quite abundant in GR1, GR2, GR3, GR4, GR9, GR18, GR19 and GR20, crossing both the quartz and the feldspar crystals.

Undulatory extinction of the quartz crystals is clear in all samples (Table 4), being stronger in GR2, GR3, GR18, GR19 and GR20. It is also accompanied by the presence of deformation bands and lamellae (regions where the crystalline reticulate is deformed forming displacement walls). The first feature is present in aggregate GR3, while deformation lamellae can be observed in GR18 and GR19. The results of the measurement of the UEA of the quartz crystals are displayed in boxplots in Fig. 2. It is possible to observe that for each sample the mean, median,

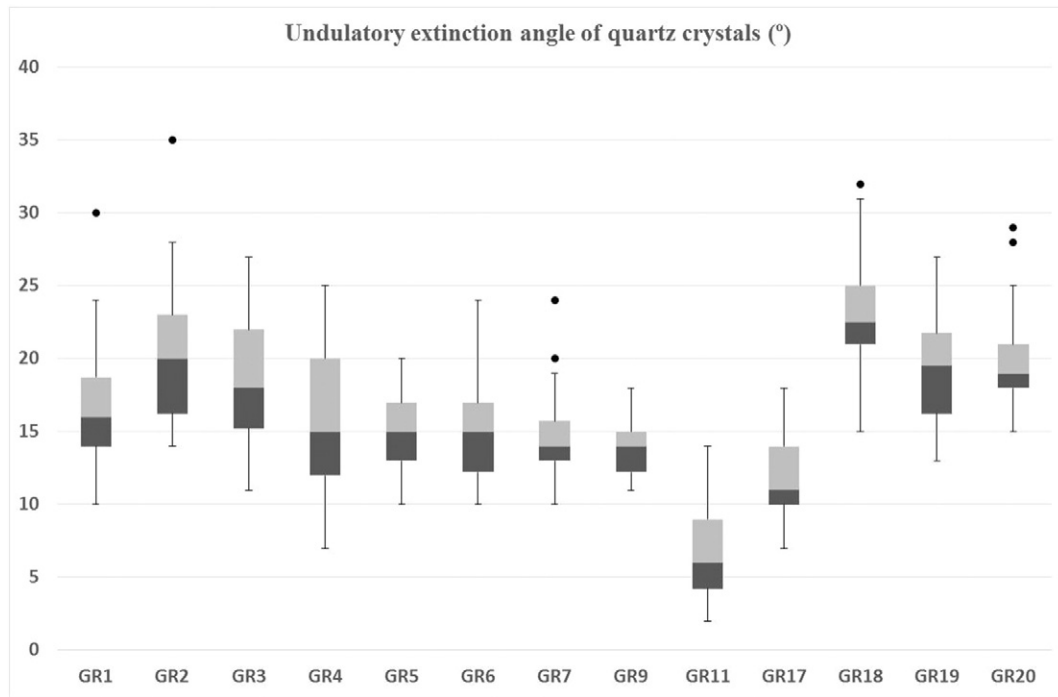


Fig. 2. Boxplots of the results of measurement of the UEA of quartz crystals. • — outliers. The values in the dark gray zone are between the lower quartile and the median while the values in the light gray zone are between the median and the upper quartile.

mode and third quartile (which indicates that 75% of the data is less than that value) of the quartz population submitted to the measurement of the extinction angle are all comprised in the UEA classes determined using LNEC E 415 [59]. Overall, the achieved standard deviation and coefficient of variation values for each rock do not indicate an important dispersion of the measurements. However, the presence of outliers should be noticed in all the samples.

Only GR2 and GR18 present over 2.0 vol.% of microcrystalline quartz (sum of <10 and 10–60 μm) (Table 4), which classify them as Class II according to RILEM AAR-1.1 [52] and LNEC E 461 [54]. The classification is, however, different for quartz <100 μm , as published elsewhere [62–65]. For all the other aggregates, the percentage of “deleterious” quartz ranges from 0 to 1.65 vol.%; they are thus classified as Class I by LNEC E 461 [54]. It can be noticed that aggregates GR1, GR18 and GR20 display microcrystalline quartz contents close to the threshold value of 2.0 vol.%. Using the ERQ, only GR2 should be considered as reactive. The most conservative criterion was used in the present work, meaning the values of the SUM in Table 4 (quartz crystals <60 μm) were applied to compare with the expansion tests.

Besides the characteristics of the crystals of quartz, namely the size and deformation manifestations, also the other main components were studied in order to define the degree of alteration, namely late deuteric alteration in each rock sample. Plagioclase crystals show, in all the samples, stronger alteration, like sericitization, than the crystals of K-feldspar. In all the studied samples, except GR7, GR17 and GR20, the plagioclase crystals exhibit compositional zoning with much stronger alteration to sericite in the nucleus than in the borders. Calcite and, in some cases, calcite + epidote are also present as a result from the alteration of plagioclase crystals in GR1, GR3, GR4, GR7 and GR18. Chlorite occurs as a product from biotite alteration. The results of this study are presented in Fig. 3. The minerals that can contribute with alkalis to the pore solution according with LNEC E 415 [59] and LNEC E 461 [54] are also listed.

4.2. Mortar and concrete expansion tests

According to Portuguese experience, LNEC E 461 [54] suggests that granitic rocks are immediately classified as Class II, which means that

the expansion tests RILEM AAR-4.1 and RILEM AAR-3.1 are the only methods to be carried out for such aggregates. However, in this study, the ASTM C 1260 test was also performed as this is the most commonly used expansion test on a worldwide basis.

The expansion results of the investigated granitic aggregates during the expansion tests and respective interpretation criteria are presented in Table 5.

4.2.1. ASTM C 1260 test results

All granitic aggregates showed expansions well below 0.10% at 14 days [52] (Table 5), thus indicative of non-reactive aggregates according to RILEM AAR-0 [52]. That non-reactive character was maintained even when the test was extended to 21 days, as suggested by Shayan [61].

In order to confirm the expansion behavior at later ages, for some aggregates the test duration was extended till 6 months (Fig. 4). As can be observed, all granites show no signs of leveling-off the expansions. Aggregates GR2 (0.30%), GR17 (0.22%), GR18 (0.28%), GR19 (0.21%) and GR20 (0.31%) present at 100 days expansions higher than 0.20%, a limit suggested by Santos Silva et al. [53] as a possible indicator of ASR reactivity for this type of rocks.

4.2.2. RILEM AAR-4.1 test results

The expansion results of the accelerated concrete prism test at 60 °C (RILEM AAR-4.1) [52] will be addressed regarding the different limit criteria identified in Table 5.

Fig. 5 presents the expansion curves obtained for the studied granitic aggregates. Besides the alkali leaching that normally occurs in this kind of test reducing the ultimate expansion value [66,67], it was observed with this type of aggregates an expansion increase after 12 weeks that is not stable at the end of 20 weeks.

According to the various expansion criteria proposed for this test (see Table 2), the proportion of aggregates producing expansion values higher than the limits (i.e. regarded as reactive) ranges from 38% (5/13; RILEM criterion) to 62% (8/13; Lindgård et al. criterion). In fact, a total of five aggregates are regarded as non-reactive (i.e. GR1, GR5, GR6, GR7, GR9) and five as reactive (GR2, GR4, GR11, GR17, GR20) by all three

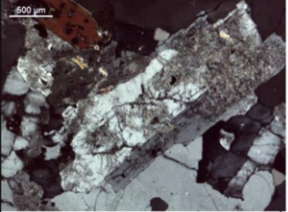
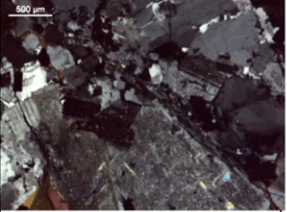
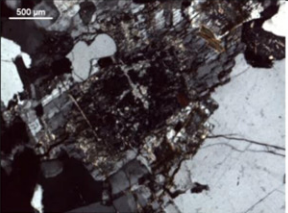
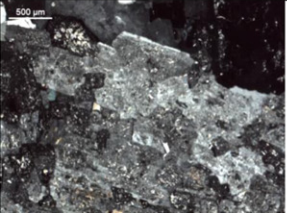
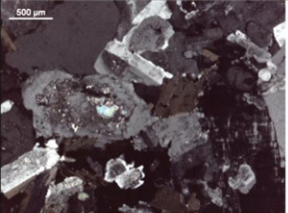
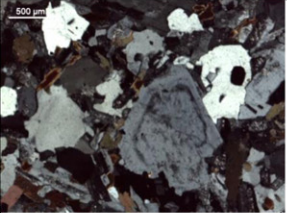
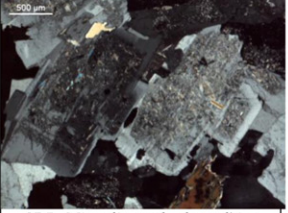
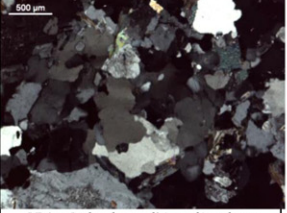

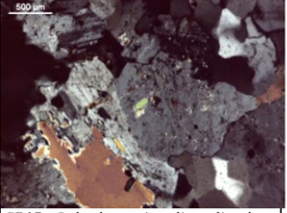
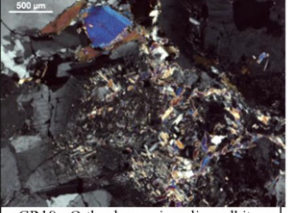
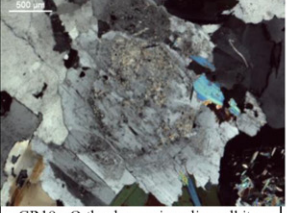
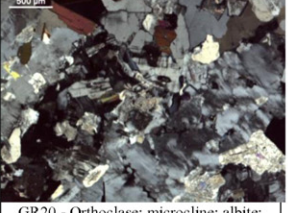
Minerals that can contribute with alkalis	Plagioclase	K-feldspar	Minerals that can contribute with alkalis	Plagioclase	K-feldspar
 GR1 - Orthoclase; microcline; albite; oligoclase; muscovite; biotite	S	-	 GR2 - Microcline; orthoclase; oligoclase; muscovite; biotite	M	L
 GR3 - Orthoclase; microcline; oligoclase; muscovite; biotite	S	M	 GR4 - Andesine; oligoclase; biotite	M	-
 GR5 - Orthoclase; microcline; albite; oligoclase; muscovite; biotite	M	-	 GR6 - Microcline; orthoclase; albite; oligoclase; biotite	M	L
 GR7 - Microcline; orthoclase; albite; oligoclase; muscovite; biotite	S	L	 GR9 - Orthoclase; albite; oligoclase; muscovite; biotite	M	-
 GR11 - Orthoclase; albite; oligoclase; biotite	M	-	 GR17 - Orthoclase; microcline; oligoclase; muscovite; biotite	M	L
 GR18 - Orthoclase; microcline; albite; oligoclase; muscovite; biotite	S	M	 GR19 - Orthoclase; microcline; albite; oligoclase; muscovite; biotite	M	L
 GR20 - Orthoclase; microcline; albite; oligoclase; muscovite; biotite	S	M			

Table 5

Expansion results of the investigated granitic aggregates during the expansion tests and respective interpretation criteria. The values in bold are those in excess of the respective limits criteria. The petrographic classification of the aggregates is also included for comparison purposes.

Aggregate	Expansion of test specimens in % at selected ages							Reactivity class LNEC E 461 [54]	Long term field performance
	ASTM C 1260			RILEM AAR-4.1			RILEM AAR 3.1		
	14 days	21 days	100 days	12 weeks	15 weeks	20 weeks	1 year		
GR1	0.02	0.03	0.20	0.017	0.023	0.027	0.018	I	N.a.
GR2	0.04	0.07	0.30	0.048	0.061	0.070	0.060	II	N.a.
GR3	0.01	0.02	0.17	0.022	0.028	0.035	0.019	I	Reactive
GR4	0.02	0.03	–	0.021	0.031	0.040	0.004	I	N.a.
GR5	0.02	0.02	0.15	0.014	0.019	0.020	0.012	I	N.a.
GR6	0.03	0.03	–	0.009	0.014	0.020	0.011	I	N.a.
GR7	0.02	0.02	0.19	0.009	0.013	0.018	0.016	I	N.a.
GR9	0.03	0.03	–	–0.005	0.000	0.011	0.003	I	N.a.
GR11	0.03	0.03	0.12	0.030	0.031	0.033	0.015	I	N.a.
GR17	0.03	0.05	0.22	0.030	0.038	0.049	0.039	I	Reactive
GR18	0.04	0.07	0.28	0.023	0.028	0.044	0.029	II	N.a.
GR19	0.03	0.05	0.21	0.019	0.025	0.032	0.027	I	N.a.
GR20	0.04	0.06	0.31	0.029	0.040	0.053	0.036	I	N.a.
Expansion criteria at that age	>0.10% RILEM AAR-0 [52]	>0.10% Shayan [61]	>0.20% Santos Silva et al. [53]	>0.020% LNEC E 461 [54]	>0.030% RILEM AAR-0 [52]	>0.030% Lindgård et al. [4]	>0.050% LNEC E 461 [54]		

N.a. – non-available.

criteria. For each “group”, several aggregates display final expansion values close to the limit criteria and can accordingly be considered in the uncertainty band of the respective test method/criteria. Aggregates GR3, GR18 and GR19 have different classifications depending on the criterion adopted. In what concerns the age of the granites, the criterion by Lindgård et al. [4] identifies all the syn-D3 granites as potentially reactive. However, it also classifies GR3, GR4, GR11 and GR17 as potentially reactive, which are late- and late- to post-D3. The criteria in LNEC E 461 and RILEM AAR-0 present an even lower correlation with the age.

4.2.3. RILEM AAR-3.1 test results

After one year of testing (Fig. 6) in the concrete prism test at 38 °C (RILEM AAR-3.1) [52], only aggregate GR2 displays a final expansion above 0.05%. Since the achieved value is also below 0.10% and a definitive interpretation guidance is not provided by RILEM AAR-0 [52] for aggregates that plot in such range (0.05%–0.10%), the national recommendation LNEC E 461 [54] must be used. The latter actually suggests that an expansion above 0.05% after 1 year of testing is enough to consider aggregate GR2 as reactive. The results show that GR4 has the second lowest value of expansion, a different result from the one obtained in RILEM AAR-4.1 [52]. There is no correlation between the results of the test and the age of the granites.

5. Discussion

5.1. Petrographic characterization

The UEA is regarded as a parameter that is highly influenced by several factors. Besides the stress level attained by the rock and the expertise of the operator, the UEA is affected by the orientation of the grain, being measured relative to its optical axes, and also by the size of the crystal, since small crystals yield smaller angles. Some of these issues were encountered when obtaining the UEA of the different granitic rocks. Also, different values were obtained in the same thin-section for large and small quartz grains. The large grains were found to be responsible for the values considered as outliers. However, the statistic tools applied here do not seem to indicate a significant dispersion of the UEA in each thin-section. For example, the performance of GR11 in

RILEM AAR-4.1 is regarded as potentially reactive. However, this aggregate presents a mean UEA of 6° for the crystals of quartz. This fact does not sustain the conclusions of several authors who stated that an UEA of, at least, 15° would be needed to classify an aggregate as potentially reactive [8,11–14].

The correlation between the median value of the UEA of the quartz crystals and the percentage of microcrystalline quartz (<60 µm) of each aggregate is presented in Fig. 7. Its use is justified since the median, contrarily to the mean, is not affected by outlier values, thus giving the more central value. It was concluded that no correlation can be established between the percentage of microcrystalline quartz and the UEA (correlation coefficient $r = 0.32$). For example, aggregate GR2 exhibits by far the highest content in microcrystalline quartz, but it is aggregate GR4 that shows the quartz grains with the highest UEA. Also, aggregates GR19 and GR20, which are rated as Class I, present very similar values of UEA to aggregate GR2, classified as Class II, but lower contents of microcrystalline quartz in comparison to the same aggregate. The above discussion is in accordance with West [20,21], who pointed out UEA as a possible indicator of potential alkali-reactivity of rocks, rather than a diagnostic feature.

However, according to Tiecher et al. [23], the presence of dislocation walls materialized by deformation bands and lamellae, along with a marked undulatory extinction, cannot be neglected, as they are pointed out to be a preferential dissolution site of the aggregates, thus contributing to expansion. These are observed in GR3, GR18 and GR19.

Regarding the time relationship of the granites with D3, it can be verified that with the exception of GR1 and GR17, the highest values in the content of microcrystalline quartz correspond to the syn-D3 granites (GR2, GR18, GR19, GR20). Also the values of undulatory extinction angle above 20° were obtained for the same granites, with a slightly lower value of 19° for GR20.

5.2. Petrography vs accelerated mortar-bar test (AMBT – ASTM C 1260)

The 14 and 21 days accelerated mortar-bar expansions were found to offer moderate correlations (i.e. r values of 0.64 and 0.83) with the percentages of microcrystalline quartz (Fig. 8A and C) and somewhat weaker correlations with the UEA of quartz crystals (Fig. 8B and

Fig. 3. Minerals that can contribute with alkalis to ASR according to the Portuguese specifications LNEC E 415 [59] and LNEC E 461 [54], listed by sample. Degree of alteration of the feldspars (S – severe; M – moderate, L – low). Photomicrographs in cross-polarized light (XPL).

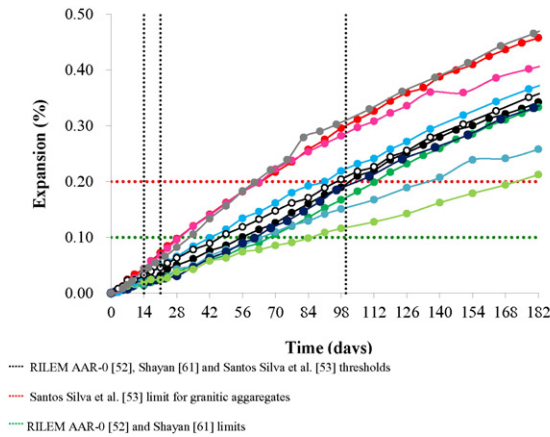


Fig. 4. Expansion curves of accelerated mortar-bar test (ASTM C 1260) extended up to 182 days.

D) measured in the granitic aggregates investigated in this study. Although the AMBT is widely used for assessing the potential alkali-reactivity of concrete aggregates, its limits often do not reflect the performance of slowly reactive aggregates, leading to their incorrect classification as non-reactive or of uncertain reactivity [61,68]; this seems to be the case of aggregate GR2. The explanation for such results might remain in the findings of Lu et al. [69,70] and Multon et al. [71], who suggested that materials processing operations (crushing) to produce fine materials for mortar bar testing can destroy the original microstructure of such coarse-grained rocks, with the risk of under-estimating their potential alkali-reactivity. The standard AMBT is actually considered inappropriate to evaluate the alkali-reactivity of Portuguese granitic aggregates [48,51]. The extension of the test period till 100 days using a threshold expansion of 0.20%, carried out by Santos Silva et al. [53] when studying aggregates GR2, GR17, GR18 and GR19, is suggested (Fig. 8E and F). A similar suggestion was made by Alaejos et al. [72] when studying slowly-reactive Spanish aggregates.

5.3. Petrography vs accelerated concrete prism test (RILEM AAR-4.1)

Mixed classifications are obtained between the results of petrographic examination and the expansions at various ages in the accelerated concrete prism test RILEM AAR-4.1. Similar classifications in what concerns the potential alkali-reactivity are obtained between both tests in the case of the Class II aggregate GR2 and the Class I aggregates GR1, GR5, GR6, GR7 and GR9. The correlation between the results

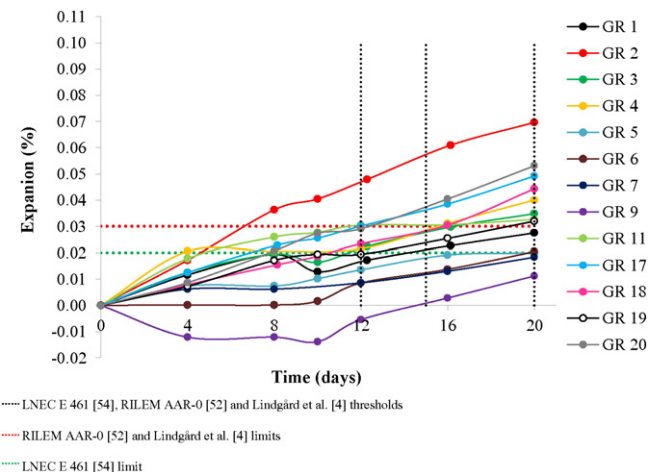


Fig. 5. Expansion curves of the accelerated concrete prism test at 60 °C (RILEM AAR-4.1).

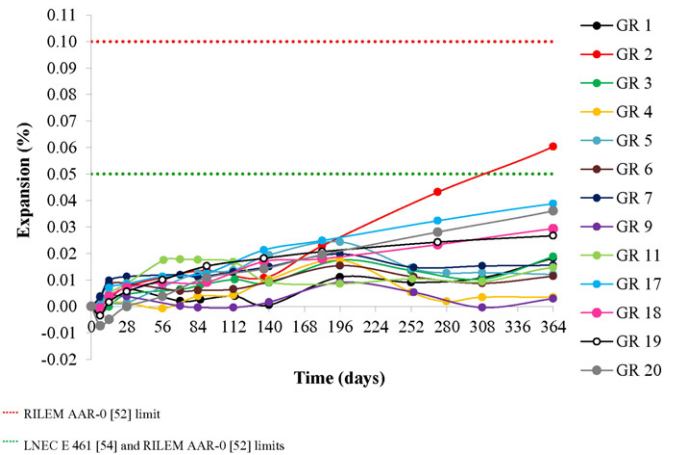


Fig. 6. Expansion curves of the concrete prism test at 38 °C (RILEM AAR-3.1).

achieved by the several interpretation criteria used in RILEM AAR-4.1 and the percentages of microcrystalline quartz and the UEA are illustrated in Fig. 8G to L. As mentioned above, the correlations vary from moderate ($r = 0.67$) to generally poor ($r = 0.26$ to 0.47).

For a correct interpretation of the aforementioned data, it is important to keep in mind that some granitic aggregates are considered as slowly reactive aggregates in terms of the development of ASR. As such, it might be appropriate to implement the most severe criterion proposed by Lindgård et al. [4], which uses a testing period of 20 weeks, for the interpretation of RILEM AAR-4.1. Actually, this is the criterion that identifies a larger number of granitic aggregates as potentially reactive.

The criterion used in RILEM AAR-0 [52] does not detect several aggregates as potentially reactive (i.e. GR3, GR18 and GR19), which can probably be considered as false negative results. Nonetheless, the final expansion values achieved by the concerned aggregates are comprised in the band of uncertainty defined in Lindgård et al. [4] and also considered in RILEM AAR-0 [52]. In contrast, aggregates GR3 and GR4 are regarded as Class I by the petrographic method. The potential reactivity detected by RILEM AAR-4.1 in all criteria for aggregates GR4, GR19 and GR20 might probably be attributed to the fact that there are a large number of micro-cracks in the aggregate. According to Velasco-Torres et al. [32], in slowly reactive aggregates, the concrete pore solution enters slowly into the aggregates mainly through the micro-cracks and to a less extent through the sub-grain boundaries, the former being

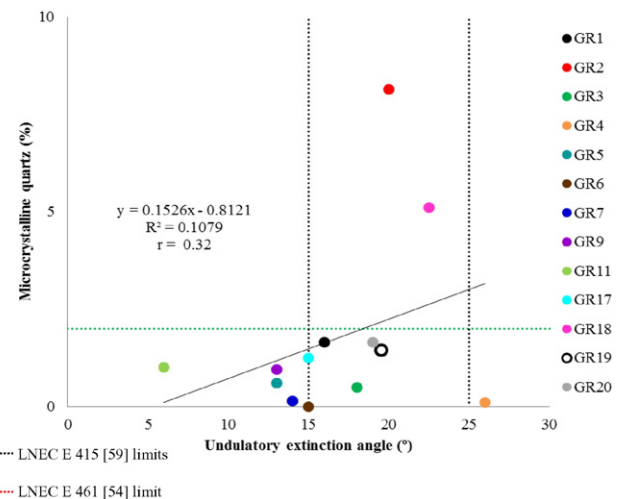


Fig. 7. Comparison between the percentages of microcrystalline quartz (<60 μm) and the UEA of the quartz crystals.

the main mechanisms of formation and storage of gel instead of sub-grain boundaries.

The assumption of the use of the petrographic characterization just as an informative tool and the immediate classification of granitic aggregates as Class II by LNEC E 461 [54] seems to be justified, since there are

expansive behaviors in RILEM AAR-4.1 that are not detected by petrographic examination. Such fact is clearly corroborated by the different performances in RILEM AAR-4.1 of aggregates GR9 and GR11, which present similar characteristics in terms of microcrystalline quartz (<60 µm) content and UEAs <15°. On the other hand, the testing

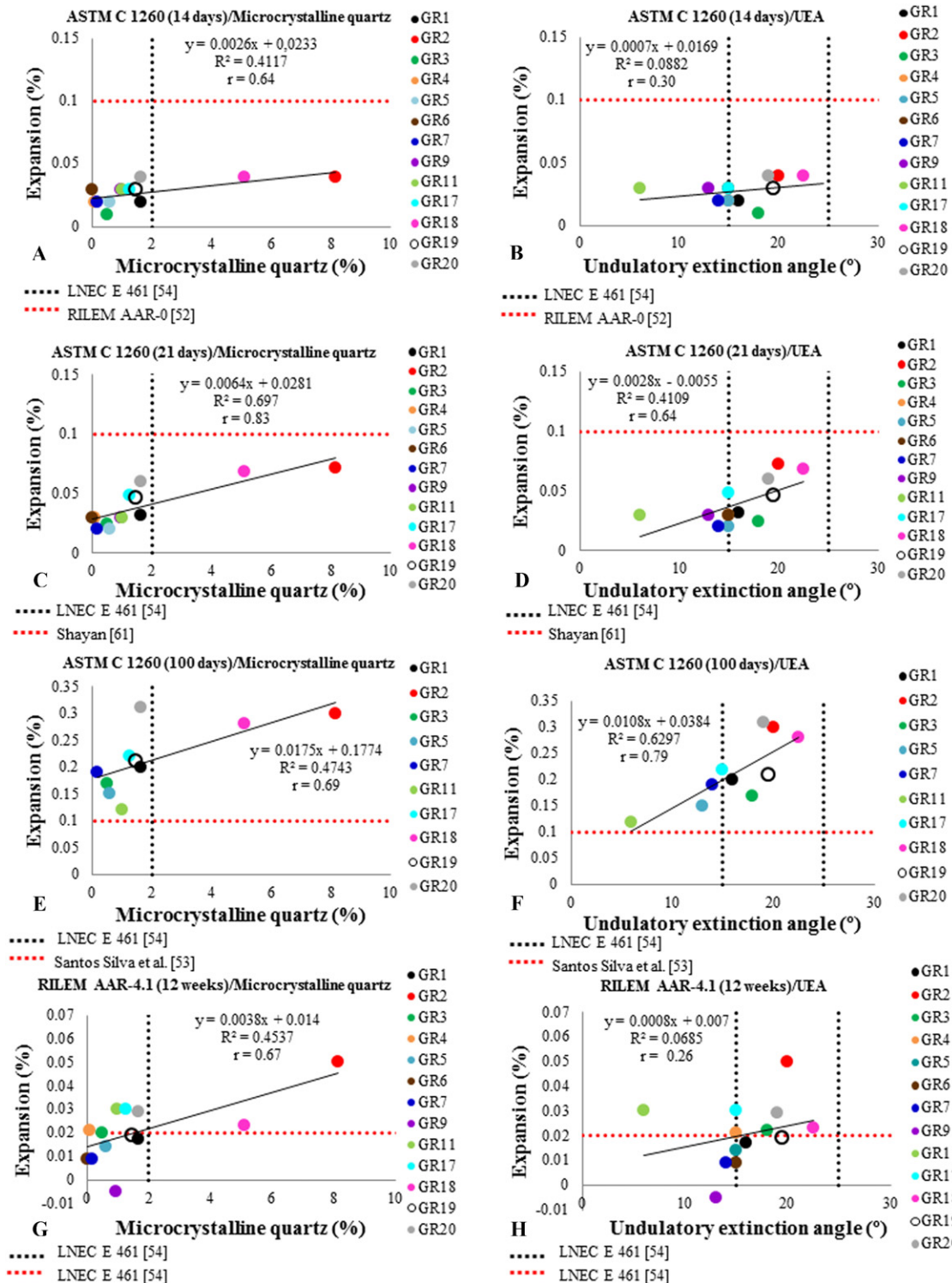


Fig. 8. Correlations between the accelerated expansion tests and respective interpretation criteria, the microcrystalline quartz (<60 µm) content and the undulatory extinction angle (UEA) of quartz crystals. A) ASTM C 1260 (14 days) vs microcrystalline quartz; B) ASTM C 1260 (14 days) vs UEA; C) ASTM C 1260 (21 days) vs microcrystalline quartz; D) ASTM C 1260 (21 days) vs UEA; E) ASTM C 1260 (100 days) vs microcrystalline quartz; F) ASTM C 1260 (100 days) vs UEA; G) RILEM AAR-4.1 (12 weeks) vs microcrystalline quartz; H) RILEM AAR-4.1 (12 weeks) vs UEA; I) RILEM AAR-4.1 (15 weeks) vs microcrystalline quartz; J) RILEM AAR-4.1 (15 weeks) vs UEA; K) RILEM AAR-4.1 (20 weeks) vs microcrystalline quartz; L) RILEM AAR-4.1 (20 weeks) vs UEA; M) RILEM AAR-3.1 vs microcrystalline quartz; N) RILEM AAR-3.1 vs UEA.

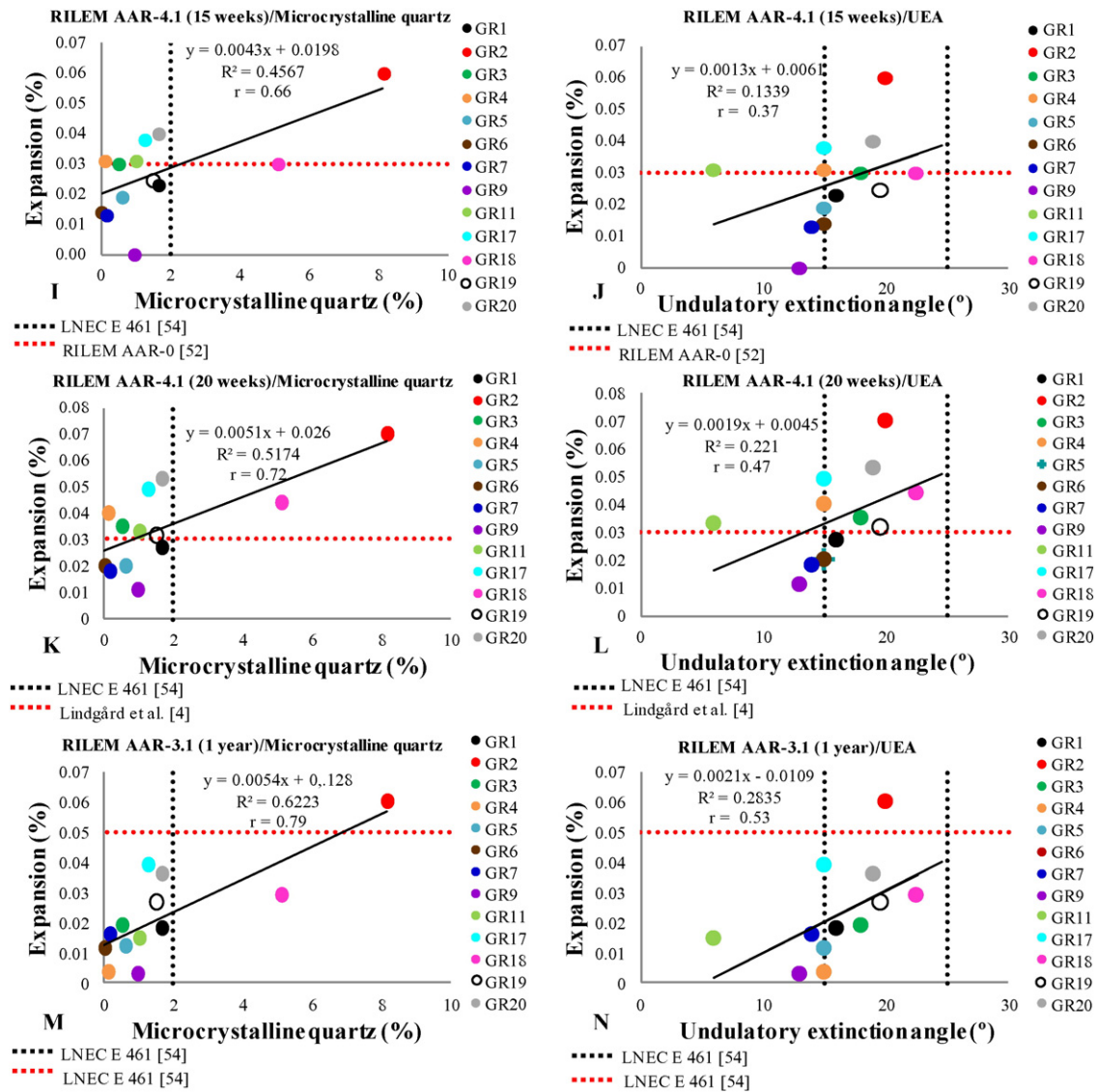


Fig. 8 (continued).

conditions used in RILEM AAR-4.1 are regarded as severe (60 °C) in comparison to the ones verified in field structures or even in the RILEM AAR-3.1 test procedure (38 °C). However, according to the present work, the behavior of aggregates GR3, GR4, GR11, GR17, GR19 and GR20 in RILEM AAR-4.1 cannot be justified exclusively by the presence of microcrystalline quartz. Other parameters, such as the presence of abundant micro-cracks, which facilitate the access of the alkali pore fluids into the grains and the variability of texture and grain size features can also be responsible for the aggregate's reactive performances. In addition to the potentially reactive silica forms, Le Roux et al. [73] believe that different factors can make minerals reactive or non-reactive, namely the degree of alteration and weathering of minerals such as feldspars. Processes of hydrolysis of feldspars lead to the release of K^+ , Na^+ and Ca^{2+} , which in the natural environment can create clay minerals, and the identification should be performed during the petrographic assessment of aggregates. The recently published NF P 18-543 standard [74] includes a table with reactivity indexes in which, besides the list of susceptible minerals under an alkaline environment (including feldspars and mica), textural features are also considered, namely opened cracks and grain boundaries.

In order to use just the content of microcrystalline quartz, a lower limit of 1% can be suggested as it will fit better the results obtained in the RILEM AAR-4.1 test.

Therefore, the question whether minerals besides microcrystalline or strained quartz may participate in ASR arises in consonance with the work of Hagelia and Fernandes [34] who defended that gel formation appears to be partly sustained by dissolution of feldspars and micas in Portuguese granitic aggregates, contributing with Si to ASR. Fig. 3 refers to the constitutive minerals of the investigated aggregates, which are regarded by LNEC E 415 [59] and LNEC E 461 [54] as possible suppliers of alkalis. The abundance of such minerals, along with alteration/weathering minerals, in the investigated aggregates may help to explain the potentially reactive behavior of some of the aggregates. Aggregates GR3, GR18 and GR20 show an intense weathering/alteration degree of plagioclase and also a moderate degree in the K-feldspars, which might be related to the expansion observed in RILEM AAR-4.1. However, GR7 shows to be an exception.

5.4. Petrography vs concrete prism test (RILEM AAR-3.1)

As can be seen in Table 5, GR2 was the only aggregate that was classified as reactive by RILEM AAR-3.1. Overall, a strong “positive” correlation is observed between RILEM AAR-3.1 and the percentage of microcrystalline quartz ($r = 0.79$; Fig. 8M), while the correlation is moderate with the UEA ($r = 0.53$; Fig. 8N). This test fails in identifying the reactivity of GR18. The test would have closer results to the RILEM

AAR-4.1 in case a lower threshold of 0.02% expansion is used for granitic rocks instead of 0.05%.

Lindgård et al. [4] questioned the suitability of the RILEM AAR-3.1 method for identifying slowly reactive aggregates of gneissic origin containing microcrystalline quartz as a reactive component. Also, the above method was pointed out as not being conclusive at the age of one year. A longer test period may be needed for identifying the potential reactivity of slowly reactive aggregates [53,61,75]. RILEM AAR-0 [52] suggests pursuing the test until expansion ceases or it has become clear whether or not the criteria will be exceeded. In the present study, this phenomenon occurs for several aggregates, with the exception of aggregates GR4, GR5 and GR6, GR7, GR9. For aggregate GR2, there is no doubt that it is potentially reactive.

Lindgård et al. [4] also mentioned that RILEM AAR-4.1 seems more effective than RILEM AAR-3.1 for assessing slowly reactive aggregates. However, the slowly reactive aggregates tested in the scope of the Partner Project are not of granitic origin, which makes it difficult to establish a true comparison with the present samples. RILEM AAR-3.1 is better at demonstrating the slowness of the reaction, due to the lowest temperatures applied. The same was verified by Shayan et al. [75] using a concrete prism test similar to RILEM AAR-3.1.

Concerning both RILEM AAR-4.1 and RILEM AAR-3 expansion tests, it must be noted that the most deformed aggregates influence the trend of the regression lines (Fig. 8) suggesting that more tests and field performance results with similar rocks might elucidate about the existence of a better correlation.

5.5. Final thoughts

Petrographic examination is considered in most international standards as the first step for assessing the potential alkali-reactivity of concrete aggregates but rated as not essential in the case of granitic rocks by the Portuguese specification LNEC E 461 [54]. In the present study, the petrographic examination revealed itself as an important informative tool by giving qualitative and quantitative information towards the presence of potentially alkali-reactive microcrystalline quartz in this work assumed to be <60 µm. For example, the scarcity of this deleterious material in aggregates GR5 and GR7 clearly suggested their performance in expansion tests as non-reactive. An opposite behavior was indicated by the great abundance of microcrystalline quartz in aggregate GR2. In this study, median UEA values ranging from 6° to 23° were obtained for the various investigated granitic aggregates. Information available in the literature suggests that an UEA of at least 15° can be indicative of potential reactivity, while lower values are indicative of a non-reactive behavior. As defended by a number of researchers in the last three decades, UEA should only be used as a possible indicator of the potential alkali-reactivity, and not as a diagnostic feature, as it was found that this characteristic occasionally correlates with the results of the other performed tests. A better, but no good correlation, seems to occur between the presence of microcrystalline quartz and the results of the concrete prism expansion tests.

In what concerns expansion tests, till the present moment, their reliability in the assessment of slowly reactive aggregates, such as granitic ones, has not proven to be totally satisfactory. The results of this study showed that the very aggressive AMBT (ASTM C 1260) was not able to detect the potential reactivity of any of the investigated granitic aggregates. This test, in the present form, should not be used for assessing the potential reactivity of this kind of slowly/late reactive materials. The suggestion in Santos Silva et al. [53] to extend the test period of ASTM C 1260 to 100 days, which still allows a shorter testing period in comparison to the one of RILEM AAR-4.1, seems to deliver more satisfactory results. However, using such test period, the ultra-accelerated aspect of the mortar-bar test, which is its main advantage, is lost and favors the use of RILEM AAR-4.1 performance test.

The accelerated concrete prism test (RILEM AAR-4.1) is the test which classifies a larger number of granitic aggregates as potentially

reactive, especially when using the criterion in Lindgård et al. [4] (20 weeks). In addition, this criterion is able to successfully identify the reactive field performance of aggregates GR3 and GR17. Therefore, it is suggested that this criterion is used for granitic aggregates. The concrete prism test (RILEM AAR-3.1) is better at demonstrating the slowness of the reaction when compared to RILEM AAR-4.1, although this test only classifies aggregate GR2 as potentially reactive.

6. Conclusions

From the above and in what regards the petrographic examination to evaluate the potential alkali-reactivity of granitic aggregates, the following can be concluded:

- it is advisable that petrographic examination precedes the expansion tests in order to identify the presence (or not) of potentially reactive mineral phases within the aggregates;
- in the case of granitic aggregates, the UEA, though usually considered as irrelevant in what concerns ASR evaluation, must not be disregarded. This parameter, eventually along with the presence of deformation bands, should always be included in the petrographic description of concrete aggregates;
- a correlation was found between the age of the granitic rocks and the results obtained by petrography regarding the content of microcrystalline quartz and the values of the UEA;
- with exceptions, the syn-D3 granites were identified as potentially reactive to alkali by RILEM AAR-4.1 (Lindgård et al. criterion);
- there is a correlation between the percentage of microcrystalline quartz (<60 µm) and the concrete expansion tests (RILEM AAR-4.1 and RILEM AAR-3.1); correlation coefficients of 0.72 and 0.79 were found between the percentage of microcrystalline quartz and the expansion in RILEM AAR-4.1 and RILEM AAR-3.1, respectively;
- the presence of micro-cracks must be considered, as an important characteristic that can explain the access of alkalis to the interior of the quartz crystals in some of the tested samples;
- the possibility of other minerals, besides microcrystalline quartz (e.g. feldspars and micas), to be responsible for ASR by contributing with Si and/or alkalis to the reaction must be regarded, since granitic rocks are rich in minerals which are considered as Si and alkali suppliers;
- in the current state of knowledge, the alteration degree is also a factor to be taken into account, and needing further investigation, as it is the main feature in some of the aggregates with low content in microcrystalline quartz that have behaved as reactive in the concrete prism tests.

In what concerns the expansion tests towards granitic aggregates, the following statements can be made:

- ASTM C 1260 should never be used solely when assessing slowly reactive aggregates similar to the ones studied; the extension of its test period till 100 days using a threshold expansion of 0.20% is suggested; however, it should be highlighted that the main advantage of the mortar-bar test is to be a quick test, and therefore the extended period of testing makes it less advantageous compared to the RILEM AAR-4.1 test method (20 weeks);
- RILEM AAR-4.1 is the expansion test which detects more potentially reactive granitic aggregates. The use of the interpretation criterion in Lindgård et al. (20 weeks) is suggested. This is the more conservative criterion among the ones used for RILEM AAR-4.1's interpretation and there is evidence of reactivity in concrete structures where GR3 and GR17 were used. Such reactivity was correctly identified by the aforementioned criterion;
- according to the results obtained and plotted in charts in Fig. 8, it can also be suggested that a lower threshold of 1% is used for the content of microcrystalline silica present in granitic rocks and that would increase the number of rocks identified as potentially reactive by petrographic method and therefore enhance the correlation with the results of the RILEM AAR-4.1 test;

- RILEM AAR-3.1 must be extended to more than one year for a more correct assessment, a duration that might be incompatible to the deadlines of the construction industry. The postulation in LNEC E 461 that granitic aggregates should be only submitted to concrete prism tests seems to be adequate. However, RILEM AAR-4.1 showed to be more conservative in the assessment of these aggregates and should be preferred also due to its short duration. Additionally, further results from field experience will indicate which test procedure and criterion is the most suited for evaluating the potential alkali-reactivity of the investigated Portuguese aggregates.

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