



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



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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 cataclase 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

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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 – Westefalian 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

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