PORTUGUESE EXPERIENCE IN ASR AGGREGATE ASSESSMENT

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Abstract

Although considerable efforts have been made worldwide regarding alkali-silica reaction (ASR) prevention and mitigation, including the approval of new national and international regulations, several concrete structures are still being diagnosed with ASR. In Portugal, the new cases of ASR pertain to concrete produced mainly with igneous aggregates, whose potential reactivity is difficult to assess, notably on granitic and basaltic rocks.

The most effective way to prevent ASR is an adequate knowledge of the alkali reactivity of the aggregate, which requires the application of appropriate tests and criteria to enable a correct classification.

In the last 4 years a research program conducted in Portugal has evaluated more than 90 aggregates of different mineralogy and/or texture. The test campaign included petrography, ASTM C1260, RILEM AAR-3 and RILEM AAR-4.1 test methods. In this paper the results of ASR reactivity evaluation obtained in a group of granitic and basaltic aggregates are presented and discussed. From the results obtained, proposals to improve the reliability of existing test-methods are presented.

Keywords: ASR, aggregates, reactivity, test-methods, granites

1 INTRODUCTION

The fast growth of the world population and increased urbanization during the last century has generated a high demand of construction of infrastructures, being concrete the building material most widely used. Since the end of the 20th century, a large number of investigations in concrete have been conducted worldwide to improve its characteristics, the quality of its constituents (with special attention on aggregates) and increase service life of concrete construction [1].

In the alkaline environment of concrete, aggregates are exposed to potential reaction with the constituents of the cement paste, which can lead to the formation of undesirable cracks and gel formation. This reaction is known as alkali-aggregate reaction (AAR) and, depending on which minerals are involved, it is subdivided into alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR) [1,2,3]. ASR is the most common form of AAR and is considered the second most important cause of concrete structures deterioration in Portugal [4].Until today, 16 large dams [5] and 14 large bridges affected by ASR [6] have been already identified in Portugal.

The experience acquired over the last decades in several countries proved that the use of some aggregates previously considered non-reactive was in the origin of degradation observed in some concrete structures. To overcome this situation, considerable efforts were made on the evaluation of the alkali reactivity of aggregates. Nowadays, this is generally done by using different test methods, which include mainly petrographic analysis and expansion tests.

In Portugal, the characterization methodology is based on the specification LNEC E 461, 2007 [7], which starts by petrographic analysis and, depending on the result obtained, is complemented by expansion tests of mortar and concrete. However, since its publication, it has been found that some types of rocks, e.g. granites, exhibit a behavior in field performance that is not consistent with the results obtained in the laboratory.

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In order to overcome those difficulties and improve the reliability of the used tests, during the last four years more than 90 samples of Portuguese aggregates were studied regarding their potential alkali reactivity. Some of these aggregates were used in the past in large constructions, such as bridges and dams, causing structural distress due to ASR and leading, in some cases, to significant and/or costly repairs. The overall goal of that research was to better know the alkali reactivity of Portuguese aggregates, and the factors that contributed to it, aiming the improvement in the reliability of the employed test-methods or to adapt the test criteria to the Portuguese reality.

In this paper, results obtained regarding the characterization of Portuguese granitic and basaltic aggregates are presented and discussed.

2 MATERIALS AND METHODS

2.1 Selected aggregates

Granitic and basaltic aggregates were directly collected in the quarries or from the aggregates producers from Portugal mainland and from Azores and Madeira Islands (Figures 1 and 2). Table 1 presents a summary of the studied aggregate, with the respective lithology, petrographic information and field performance, when available.

2.2 Petrographic characterization

The petrographic characterization was made according to LNEC Specification E415 [8] and RILEM AAR-1.1 [9].

The petrographic studies of the aggregates focused both on the identification of the main components of each rock and on the texture, in special when deformation features were observed. For the granitic rocks, the quantification of microcrystalline quartz was made by point-counting. In an attempt to define the potential reactivity, rocks containing more than 2% of microcrystalline quartz, mainly correspondent to subgraining, were classified as potentially reactive.

Regarding the volcanic rocks, for which point-counting is not feasible, the classification of potential reactive was based on the bulk chemical analysis of the rock (SiO_2>50%) and on the presence of volcanic glass. The occurrence of pure silica minerals was detected by X-ray diffraction in just one sample.

The carbonate rocks (limestone and dolostone) were rated as potentially reactive when they contained cryptocrystalline silica dispersed in the rock.

Finally, for the metamorphic rocks, the main characteristics related to potential reactivity were due to deformation features such as serrated boundaries, bulging and subgraining.

2.3 Expansion test-methods

According to the Portuguese Specification LNEC E 461 [7], the granitic rocks are classified as Class II (potentially reactive) independently of the results obtained in the petrographic assessment. The Portuguese normative also does not recommend the application of the accelerated mortar-bar test (AMBT) [10,11] in the evaluation of this type of aggregates. Nevertheless, this test was used in the present work in order to evaluate the behavior of the samples in the course of the test.

Concrete prism tests (CPT) manufacture was based on RILEM AAR-3 [12] and RILEM AAR-4.1 [13] test-methods.

Accelerated mortar-bar test at 80ºC (ASTM C1260)

The AMBT tests were made according to ASTM C1260 standard protocol [10]. According to the Portuguese experience, AMBT test limits (see Table 2) in use are not enough to detect the reactivity of some types of aggregates, namely granites. In order to evaluate if this type of aggregates show expansion with higher test durations, the AMBT were extended beyond 28 days until the expansion curve reaches the plateau.

Concrete prism test at 38ºC (RILEM AAR-3)

The RILEM AAR-3 [12] concrete prism test (CPT) is usually considered the reference test for alkali evaluation of aggregates. The concrete prims were prepared with fine and coarse aggregate of the same origin and with cement with alkali content of 0.9% Na_2O_{eq}. The specimens were stored over water at 38ºC±2ºC in closed containers for maintaining high relative humidity condition (HR> 95%). Measures were taken at periodic intervals, during 1 year, and then extended to 2 years in order to evaluate the tendency expansion curve obtained.

Since the criteria for the interpretation of the results of RILEM AAR-3 have not yet been finally agreed, the results obtained using this test were checked against different criteria's (Table 2).

There is some evidence that a lower criterion (perhaps 0.03% at 1 year or even 0.04% at 2 years) might be applicable for some slow reactive aggregates, as it has been suggested in RILEM AAR-7.3 [14] specific for concrete dams and other hydro structures [6].

Accelerated concrete prism test at 60ºC (RILEM AAR-4.1)

This CPT [13] is an accelerated version of RILEM AAR-3 for evaluating the reactivity of an aggregate combination. The concrete prisms had the same dimensions and the cement composition for both tests. The prisms were sealed in containers over water which were stored in a reactor generating constant temperature of 60±2ºC and relative humidity > 95%. Periodic measurements were made during at least 20 weeks.

The criteria for the interpretation of the results are still a matter of dispute. In this work different criteria were also considered (Table 2).

Criteria for interpretation of results of expansion tests

As mentioned above, the criteria for the interpretation of the results of mortar and concrete tests are still a matter of dispute. In this work the aggregates were classified in terms of their reactivity to alkalis based on the criteria referred to in ASTM C 1260 [10], LNEC E 461 [7], RILEM AAR-0 [15], RILEM AAR-7.3 [14] and Lindgård et al., 2010 [16], as summarized in Table 2.

3 RESULTS

The petrographic classification and the expansion results obtained for the aggregates in evaluation are presented in Tables 3 and 4.

Figure 3 presents the curves obtained in ASTM C 1260 test for granitic aggregates. As can be observed, no tendency for expansion stabilization is detected, even though with a 6 months test duration. A similar behavior was obtained for some basaltic aggregates tested.

As seen in the AMBT, also in the concrete prism tests (RILEM AAR-4.1 or RILEM AAR-3) the expansion curves did not reach a plateau value (Figures 4). This slow expansive behavior observed, which was found to be quite common with granitic aggregates, reflects the current concern about the evaluation of such igneous aggregates using short test periods.

4 DISCUSSION

One of the objectives of the research regarding ASR is to find the laboratory test method which best simulates the field concrete performance of the aggregates. All the tests applied in the present study have advantages and drawbacks and it is common to find discrepancies between the results of the petrography, AMBT and CPT [17,18].

It must be taken into account that the test conditions of the AMBT are considered very severe and not representative of those encountered by concrete in service [17,19,20]. However, AMBT has the advantage of being fast, relatively simple to carry out and a good screening test for some types of rocks [16,21].

According to the data presented in Table 3 all granitic aggregates are classified as non-reactive in AMBT. This result confirms the non-applicability of this test for granitic aggregates, as already indicated in the used Portuguese standard [7]. Shayan [21] had also shown the inability of this test to determine the reactivity of Australian slow reactive aggregates and suggested a limit of 0.08% at 14 days. However, this limit is also insufficient to fit the results of the Portuguese granites. In order to better evaluate the behavior this type of aggregates it was decided to extend the duration of AMBT (Figure 3). A similar study was carried out by Alaejos et al. [22] and these authors observed that in the case of Spanish slow reactive aggregates the limit of 0.20% at 90 days would be sufficient for a correct classification. In the case of Portuguese aggregates it seems that the application of the same limit of 0.20% at 100 days (Figure 3) best correlates with the petrographic analysis and the field performance (Table 1) [6]. Suggestions have been made in the literature for extending the testing period and/or lowering the detection limits for the AMBT [23,24,25].

One of the basic differences between AMBT and CPT tests is the size of the aggregate particles [17]. The crushing and grinding actions to obtain the required grain size curve should not affect the characteristics of the aggregate sample [26,27] and therefore the characteristics of the coarse and the fine particles should be the same. According to some authors, the grinding operations to obtain fine aggregate particles can destroy the original microstructure characteristic of the rocks, and thus can under-estimate the alkali reactivity of some rocks in AMBT [26,28]. Multon et al. [29,30] also concluded that the aggregate size causing the highest ASR expansion is dependent on the nature and composition of the aggregate.

With regard to results of CPT at 60°C (Table 3 and Figure 4a), four interpretative criteria that differ in the value of reactivity limit and test duration were taken into account. The application of the criteria of LNEC E 461 [7] and Lindgård et al. [16] lead to similar results, classifying 19 and 18 granitic aggregates, respectively, as reactive. Of this total, only 9 granitic samples (GR1, GR2, GR12, GR13, GR14, GR18, GR22, GR24 and GR29) are in line with the results of petrographic analysis (Table 3).

In the CPT at 38°C (Table 3 and Figure 4b) only 3 granites samples (GR2, GR13 and GR24) are classified as reactive according to all the criteria indicated in Table 2. The criterion of RILEM AAR-7.3 [14] is the one that best adjusts to the results of petrographic analysis. However, in some cases (such as GR17 sample), the petrographic evaluation is not able to evaluate correctly the reactivity of aggregates which are proved to be reactive in field (Table 1).

It is found that the expansion curves in slow CPT, similarly to what occurs in AMBT method, are not stabilized after two years of testing (Figure 4b). This reflects the slow expansion of such aggregates [16] and reinforces the need to define test limits that better fits this trend. According to these results, CPT tests are the ones which best represent the behavior of slowly reactive granitic aggregates. The 60ºC CPT has the advantage of enabling to obtain results in the shortest time (13 or 20 weeks), since the slow CPT (38ºC) requires the extension until at least two years and the need to decrease the expansion limits.

In what concerns the possible correlation between the results of all expansion test-methods and the petrographic evaluation of the aggregates, it could be expected that the most deformed samples [17], namely those presenting sutured boundaries of quartz crystals, bulging and subgraining, showed reactivity. However, from a petrographic point of view the reactivity of a siliceous aggregate shall not take into account only the reactive silica constituents, but also the alkali minerals present, including their alteration degree, which can release to the pore solution alkali ions [31]. This may be very important for slowly reactive aggregates that did not present significantly contents of reactive silica constituents, and possibly can justify the long-term reactivity presented by this type of aggregates in several concrete structures.

Table 4 presents the expansion results obtained for the basaltic aggregates. It is noted that the CPT at 38°C is the one to identify BS1, BS3, BS4 and BS7 samples as potentially reactive, confirming the results of petrographic analysis. On the other hand, there seems to be expansion for samples not identified as potentially reactive by petrographic examination. The representativity of samples in these rocks is difficult to guarantee due to the heterogeneity found in most of the quarries, making the petrographic analysis usually insufficient in the classification of these aggregates.

5 CONCLUSIONS

The results obtained in the present work allow drawing the following conclusions:

- The petrographic characterization of granitic aggregates should not just take into account the reactive silica forms but mainly the texture of the rocks.

- The reactivity of basaltic rocks might not be detected by petrographic analysis due to the heterogeneities of the quarries.

- The AMBT, according to the currently recommended limits, should not be applied to aggregates from igneous rocks, namely granites and basalts. However, the extension of the test duration to 100 days for granitic aggregates allows obtaining a good correlation with the results of petrographic analysis and field concrete performance.

- For granitic aggregate the test-method that best translates the reactivity of such aggregates is the accelerated CPT (RILEM AAR-4.1). It was found that the limit criteria of 0.02% at 13 weeks or 0.03% at 20 weeks lead to similar results. Also, for this type of aggregates, known to have slow reactivity, it is recommended that the duration of the slow CPT (RILEM AAR-3) should be extended at least up to 2 years and the reactivity limit be lowered to 0.04%, as recommended in RILEM AAR-7.3.

- In the case of basaltic aggregates it is recommended that their evaluation should be done preferably by applying the slow CPT, but with test extension until 2 years.

Anyway, it is proposed that in the evaluation of reactivity of such type of aggregates the shape of the expansion curves during the mortar or concrete prism tests should be taken into account in order to understand if the expansion is stabilized or if there is potential for further expansion, and depending of that, decide to extend or not the test duration.

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TABLE 1: Codification, lithology, petrographic classification and field performance of the studied aggregates.

Type of rock	Code	Lithology	Petrographic classification	Main reactive constituents	Field performance	Structure type and age
	GR1	Granite	Potentially reactive	Strained quartz	*n.a.*	
	GR2	Granite	Potentially reactive	Strained quartz	*n.a.*	
	GR3	Granite	Non-reactive	-	*Reactive*	Hydraulic struct.., 45 yrs.
	GR4	Tonalite	Non-reactive	-	*n.a.*	
	GR5	Granite	Non-reactive	-	*n.a.*	
	GR6	Granite	Non-reactive	-	*n.a.*	
	GR7	Granite	Non-reactive	-	*n.a.*	
	GR8	Granite	Non-reactive	-	*n.a.*	
	GR9	Granite	Non-reactive	-	*n.a.*	
	GR10	Granite	Non-reactive	-	*n.a.*	
	GR11	Granite	Non-reactive	-	*n.a.*	
	GR12	Granite	Potentially reactive	Strained quartz	*n.a.*	
	GR13	Granite	Potentially reactive	Strained quartz	*n.a.*	
	GR14	Granite	Potentially reactive	Strained quartz	*n.a.*	
	GR15	Granite	Potentially reactive	Strained quartz	*n.a.*	
	GR17	Granite	Non-reactive	-	Reactive	Bridge, 15 yrs.
	GR18	Granite	Potentially reactive	Strained quartz	*n.a.*	
	GR19	Granite	Non-reactive	-	*n.a.*	
	GR20	Granite	Non-reactive	-	*n.a.*	
	GR21	Granite	Potentially reactive	Strained quartz	Reactive	Dam, 50 yrs.
	GR22	Granite	Potentially reactive	Strained quartz	*n.a.*	
	GR23	Granite	Non-reactive	-	*n.a.*	
	GR24	Granite	Potentially reactive	Strained quartz	*n.a.*	
Igneous	GR25	Granite	Potentially reactive	Strained quartz	Reactive	Dam, 60 yrs.
	GR26	Granite	Non-reactive	-	Reactive	Dam, 40 yrs.
	GR27	Granite	Non-reactive	-	Reactive	Dam, 45 yrs.
	GR28	Granite	Non-reactive	-	*n.a.*	
	GR29	Granite	Potentially reactive	Strained quartz	Reactive	Pavement, 2 yrs.
	BS1	Trachybasalt	Potentially reactive	Volcanic glass	*n.a.*	
	BS2	Basanite	Non-reactive	-	*n.a.*	
	BS3	Trachyte	Potentially reactive	Volcanic glass	*n.a.*	
	BS4	Basalt	Potentially reactive	Volcanic glass	*n.a.*	
	BS5	Trachybasalt	Non-reactive	-	*n.a.*	
	BS6	Hawaiite, Basalt, Basanite	Potentially reactive	Volcanic glass	*n.a.*	
	BS7	Basanite	Potentially reactive	Volcanic glass	*n.a.*	
	BS8	Basalt	Non-reactive	-	*n.a.*	
	BS9	Basanite	Non-reactive	-	*n.a.*	
	BS10	Trachybasalt	Non-reactive	-	*n.a.*	
	BS11	Basalt	Non-reactive	-	*n.a.*	
	BS12	Trachybasalt/Basalt	Non-reactive	-	*n.a.*	
	BS13	Basalt	Non-reactive	-	*n.a.*	
	BS14	Basanite	Non-reactive	-	*n.a.*	
	BS15	Trachyandesite	Non-reactive	-	*n.a.*	
	BS16	Basaltic Trachyandesite	Non-reactive	-	*n.a.*	
	BS17	Basalt	Non-reactive	-	*n.a.*	
	CL3	Limestone	Non-reactive	-	*n.a.*	
	CL4	Limestone	Non-reactive	-	*n.a.*	
	CL-SS5	Limestone	Potentially reactive	Chert	Reactive	Bridge, 70 yrs.
Sedimentary	CL-SS7	Limestone	Potentially reactive	Chert	*n.a.*	
	DL1	Dolostone	Potentially reactive	Cryptocryst. silica	*n.a.*	
	DL2	Dolostone	Non-reactive	-	*n.a.*	
	DL3	Dolostone	Potentially reactive	Cryptocryst. silica	*n.a.*	
	QZ1	Quartzite	Potentially reactive	Microcryst. quartz	Reactive	Dam, 45 yrs.
Metamorphic	QZ2	Quartzite	Potentially reactive	Microcryst. quartz	Reactive	Dam, 65 yrs.
	QZ-SS1	Quartzite	Potentially reactive	Microcryst. quartz	Reactive	Dam, 65 yrs.
	QZ-SS2	Quartzite	Potentially reactive	Microcryst. quartz	Reactive	Dam, 70 yrs.

Legend: n.a. – results not available.

TABLE 2: Criteria for classification of alkali reactive aggregates.

Method		Limits/Criteria			
		ASTM C 1260	***RILEM AAR-0***	***LNEC E 461***	
AMBT (80º C)	*14 days*	> 0.20 % (0.10 % – 0.20 % - *Potentially reactive*) Exception: for granitoid rocks, LNEC E 461 *non applicable*			
	28 days	readings should be made until 28 days when the expansion is between 0.10 and 0.20 % at 14 days			
		RILEM AAR-0	***Lindgård et al., 2010***	***RILEM AAR-7.3***	***LNEC E 461***
CPT (60º C)	*13 weeks*	-			> 0.02 %
	15 weeks	> 0.03 % (± 0.025% - band of uncertainty)		> 0.02 %	
	20 weeks		> 0.03 %	> 0.03 %	
		RILEM AAR-0	***RILEM AAR-7.3***	***LNEC E 461***	
CPT (38º C)	*1 year*	> 0.10 % (0.05 % – 0.10 % - *Potentially reactive*) (± 0.01% - band of uncertainty)	> 0.03 %	> 0.05 %	
	2 years	-	> 0.04 %		

TABLE 3: Expansion values (%) for granitic aggregates studied (*the **bold** values indicates reactive aggregate according to the criterion applied).*

Code	Petrographic classification	Expansion (%)						
		AMBT (80º C)		***Accelerated CPT (60º C)***			***CPT (38º C)***	
		14 days (1)	***28 days (2)***	***13 weeks (3)***	***15 weeks (4,5)***	***20 weeks (6)***	***1 year (7,8)***	***2 years (9)***
GR1	**PR**	0.02	0.05	**0.02**	**0.02 (4)**	**0.03**	0.02	*n.a.*
GR2	**PR**	0.04	0.10	**0.05**	**0.06 (4,5)**	**0.07**	**0.06 (7,8)**	**0.15**
GR3	NR	0.01	0.04	**0.02**	**0.03 (4,5)**	**0.03**	0.02	*n.a.*
GR4	NR	0.02	0.04	**0.02**	**0.03 (4,5)**	**0.04**	0.00	*n.a.*
GR5	NR	0.02	0.04	0.01	**0.02 (4)**	0.02	0.01	*n.a.*
GR6	NR	0.03	0.03	0.01	0.01	0.02	0.01	*n.a.*
GR7	NR	0.02	0.03	0.01	0.01	0.02	0.02	*n.a.*
GR8	NR	*n.a.*	*n.a.*	**0.04**	**0.04 (4,5)**	**0.05**	**0.06 (7,8)**	**0.11**
GR9	NR	0.03	0.05	-0.01	0.00	0.01	0.00	*n.a.*
GR10	NR	*n.a.*	*n.a.*	**0.05**	**0.05 (4,5)**	**0.06**	0.02	**0.04**
GR11	NR	0.02	*0.04*	**0.03**	**0.03 (4,5)**	**0.03**	0.01	**0.04**
GR12	**PR**	0.02	*n.a.*	**0.03**	**0.03 (4,5)**	**0.03**	0.01	**0.05**
GR13	**PR**	*n.a.*	*n.a.*	**0.06**	**0.08 (4,5)**	**0.09**	**0.08 (7,8)**	**0.14**
GR14	**PR**	*n.a.*	*n.a.*	0.01	0.01	**0.03**	0.02	**0.04**
GR15	**PR**	*n.a.*	*n.a.*	0.01	0.00	0.02	0.02	0.03
GR17	NR	0.03	0.07	**0.03**	**0.04 (4,5)**	**0.05**	**0.04 (7)**	**0.07**
GR18	**PR**	0.04	0.10	**0.02**	**0.03 (4,5)**	**0.04**	**0.03 (7)**	**0.06**
GR19	NR	0.03	0.06	**0.02**	**0.03 (4,5)**	**0.03**	**0.03 (7)**	*n.a.*
GR20	NR	0.04	0.08	**0.03**	**0.04 (4,5)**	**0.05**	**0.04 (7)**	*n.a..*
GR21	**PR**	0.04	0.08	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
GR22	**PR**	0.02	0.04	**0.02**	**0.02 (4)**	0.02	0.02	**0.05**
GR23	NR	0.02	0.05	**0.03**	**0.03 (4,5)**	**0.03**	**0.05 (7,8)**	**0.11**
GR24	**PR**	0.04	0.08	**0.04**	**0.06 (4,5)**	**0.08**	**0.06 (7,8)**	**0.16**
GR25	**PR**	0.03	0.04	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
GR26	NR	0.02	0.03	0.01	**0.02 (4)**	0.02	*n.a.*	*n.a.*
GR27	NR	0.03	0.05	**0.02**	**0.02 (4)**	0.02	0.02	**0.06**
GR28	NR	0.03	0.04	**0.04**	**0.05 (4,5)**	**0.05**	**0.04 (7)**	**0.08**
GR29	**PR**	0.03	0.05	**0.03**	**0.03 (4,5)**	**0.04**	**0.03 (7)**	*n.a.*

Legend: (1)- criteria ASTM C 1260/LNEC E 461/RILEM AAR-0; (2)- criterion ASTM C 1260; (3)- criterion LNEC E 461; (4)- criterion RILEM AAR-7.3; (5)- criterion RILEM AAR-0; (6)- criteria RILEM AAR-7.3/Lindgård et al., 2010; (7)- criterion RILEM AAR-7.3; (8)- criteria LNEC E 461/RILEM AAR-0; (9)- criterion RILEM AAR-7.3; n.a. – results not available.

TABLE 4: Expansion values (%) basaltic aggregates studied (*the* ***bold*** *values indicates reactive aggregate according to the criterion applied).*

Code	Petrographic classification	Expansion (%)						
		AMBT (80º C)		***Accelerated CPT (60º C)***			***CPT (38º C)***	
		14 days (1)	***28 days*** (2)	***13 weeks*** (3)	***15 weeks*** (4,5)	***20 weeks*** (6)	***1 year*** (7,8)	***2 years*** (9)
BS1	**PR**	0.01	0.01	0.01	0.01	0.01	**0.03**	**0.05**
BS2	NR	0.00	0.00	0.01	0.01	0.01	0.02	*n.a.*
BS3	**PR**	**0.13**	0.17	0.00	0.00	0.01	0.02	**0.04**
BS4	**PR**	0.02	0.01	0.01	0.01	0.01	**0.03** (7)	**0.05**
BS5	NR	0.01	0.01	0.01	0.01	0.01	**0.03** (7)	*n.a.*
BS6	**PR**	0.02	0.02	0.00	0.01	0.00	0.02	0.02
BS7	**PR**	0.01	0.01	0.00	0.01	0.01	**0.03** (7)	0.03
BS8	NR	0.01	0.01	0.00	0.01	0.01	0.02	0.02
BS9	NR	0.01	0.01	**0.02**	**0.02** (4)	0.02	**0.03** (7)	0.03
BS10	NR	0.01	0.01	0.00	0.00	0.01	0.02	**0.04**
BS11	NR	0.00	0.00	0.01	0.01	0.02	**0.03** (7)	**0.06**
BS12	NR	0.02	0.03	0.00	0.01	0.00	**0.04** (7)	**0.06**
BS13	NR	0.02	0.02	0.01	0.01	0.01	0.02	*n.a.*
BS14	NR	0.01	0.01	0.00	0.00	0.00	0.02	*n.a.*
BS15	NR	0.01	0.01	0.00	0.00	0.00	0.01	*n.a.*
BS16	NR	0.01	0.01	0.00	0.00	0.00	0.01	*n.a.*
BS17	NR	0.01	0.01	0.00	0.00	0.00	**0.03** (7)	**0.05**

Legend: (1)- criteria ASTM C 1260/LNEC E 461/RILEM AAR-0; (2)- criterion ASTM C 1260; (3)- criterion LNEC E 461; (4)- criterion RILEM AAR-7.3; (5)- criterion RILEM AAR-0; (6)- criteria RILEM AAR-7.3/Lindgård et al., 2010; (7)- criterion RILEM AAR-7.3; (8)- criteria LNEC E 461/RILEM AAR-0; (9)- criterion RILEM AAR-7.3; n.a. – results not available.

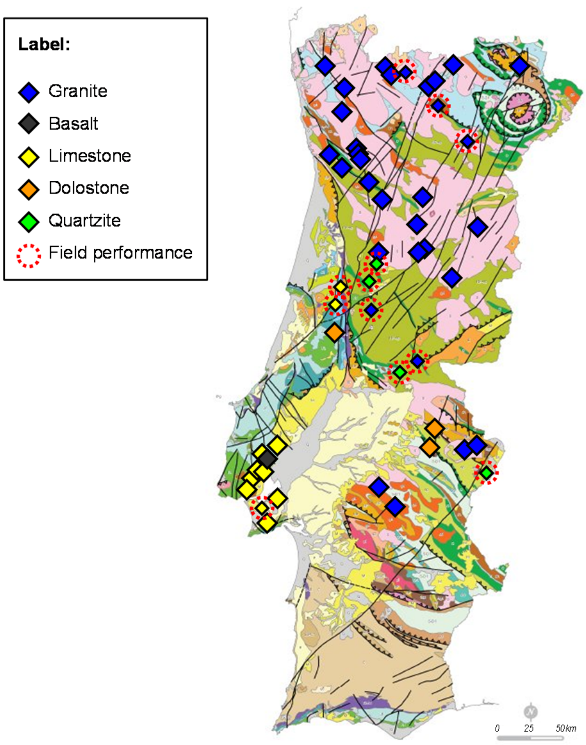

FIGURE 1: Geographical distribution of the selected aggregates quarries in mainland Portugal *(Source: IMPROVE Project).*

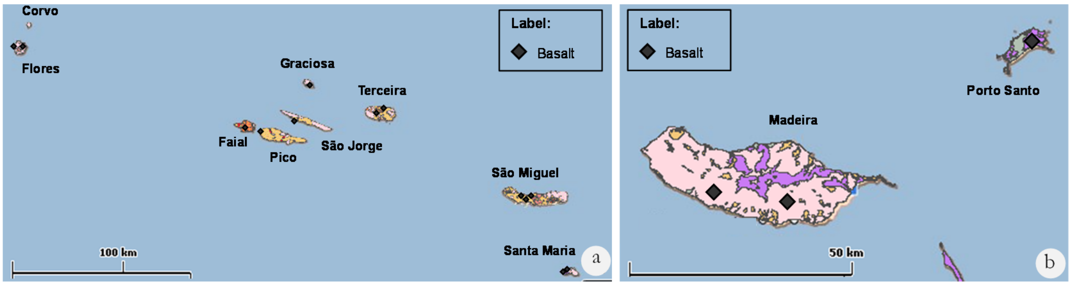

FIGURE 2: Geographical distribution of the selected aggregates quarries in Azores (a) and Madeira (b) Islands *(Source: IMPROVE Project)*.

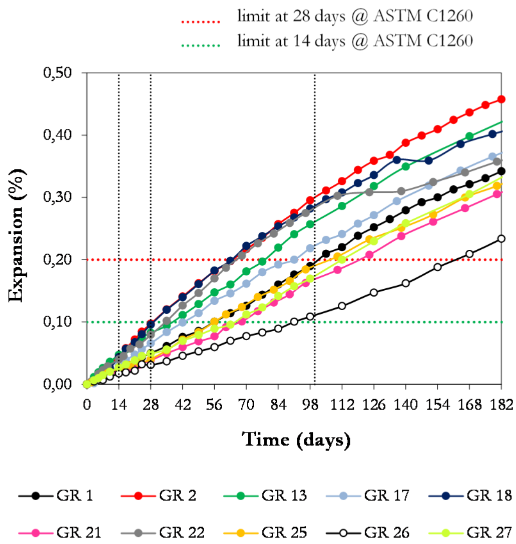

FIGURE 3: Expansion curves of AMBT for granitic aggregates with slow reactivity (the dotted lines indicate the reactivity limits allowed by different authors - see table 2).

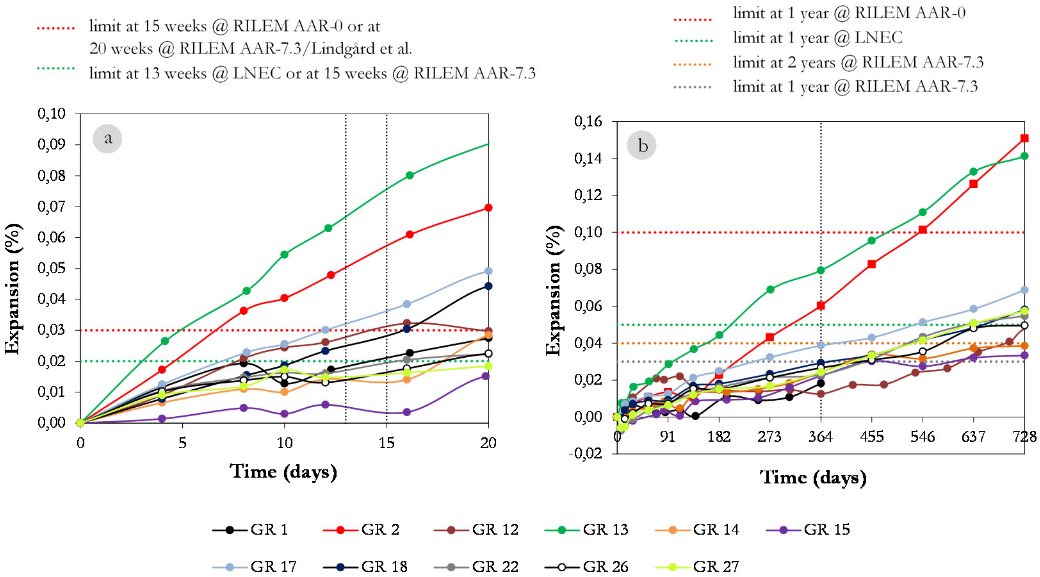

FIGURE 4: CPT expansion curves of granitic aggregates: (a) RILEM AAR-4; (b) RILEM AAR-3; (the dotted lines indicate the reactivity limits allowed by different authors - see table 2).