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Influence of equivalent reactive quartz content on expansion due to alkali silica reaction

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ABSTRACT

In this research, the effect on the reactivity of aggregates containing different quartz crystal sizes (0–10 μm; 10–60 μm, 60–130 μm) has been studied, proposing a unique limit for all of them applied to their weighted sum (Equivalent Reactive Quartz). For this aim, the expansion in mortar bars has been correlated with the content of reactive components, and values of the individual mathematic weights for different crystal sizes have been obtained: 8.3 vol.% of quartz 10–60 μm; and 2.6 vol.% of quartz <10 μm (corresponding to 0.1% expansion at 14 days). The results show that 60–130 μm crystal size of quartz has a negligible effect on the expansion.

These individual limits can be reduced to a unique one equal to 2.6 vol.% applied to the Equivalent Reactive Quartz. The use of this concept allows to evaluate the reactivity of aggregates in which there are simultaneously different reactive quartz crystal sizes.

1. Introduction

Alkali silica reaction (ASR) takes place when the alkaline pore fluid and siliceous minerals in some aggregates react to form a calcium alkali silicate gel. This gel imbibes water, producing a volume expansion that can disrupt the concrete [1,2].

Several forms of quartz are reactive. For two decades, the reactivity of quartz was attributed to imperfections and dislocations of the crystal lattice, measured by means of the undulatory extinction angle [3–5].

Afterward, Grattan Bellew [6] proved that the reactivity of rocks which had suffered stress metamorphism was associated with the presence of microcrystalline quartz formed in the deformation processes. There was a reasonable correlation between the content of microcrystalline quartz in rocks and their mortar bar expansion, because the grain size reduction enhances reactivity by increasing the surface area of quartz grain boundaries available for reaction. Then, the undulatory extinction was not an accurate method to measure the reactivity of aggregates and parameters to evaluate the surface area of quartz grains (grain boundary area and the mean grain size of quartz) became a better way to detect the reactivity of aggregates [7].

Therefore, the reactivity of some aggregates is related to the quartz crystal size, existing different criteria to classify it (Table 1) [8].

On the other hand, when the petrographic texture of a rock is studied, the term microcrystalline is applied to a texture so fine-grained that a petrographic microscope is needed to resolve individual crystals (4 μm–62 μm). The term cryptocrystalline is applied when the texture is too small to be resolvable under petrographic microscope (<4 μm) [10].

The *threshold* applied to rocks with micro and cryptocrystalline quartz texture is also different in each country, as shown in Tables 2 and 3.

The limits in Tables 2 and 3 are expressed either in weight or volume percentage, depending on the *petrographic methodology* used, existing mainly two different methods in literature [16]:

- Particle counting method (ASTM C295 [17] and BS 812-104 [18]): The result is expressed in weight percentage of reactive components.
- Point counting method: This method is nowadays used in an increasing number of countries [16] as Denmark (TI B52 [16]), Norway [19], Belgium, The Netherlands (CUR Recommendation 89 [20]) and Sweden. It is also the method described in RILEM-AAR1 [10]. The result is expressed in volume percentage of reactive components. This method, laborious to carry out, can be improved by means of image analysis.

Table 2 shows different limits for rocks with cryptocrystalline quartz, between 1% and 5%.

On the other hand, there are few references limiting microcrystalline quartz content in aggregates: 15% (US Army Corps of Engineers) and 20% (Norway) are limits for aggregate particles containing microcrystalline quartz. Indeed, 5% is the only threshold applied to the content of the reactive component itself (applied by Washington State Department of Transportation, Portland Cement Association and Ireland).

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Table 1
Quartz crystal size. Reactive threshold.

Reference	Crystal size limits
Grattan-Bellew [6]. 1992.	<100 μm: Reactive
Joyce [8]. 1996.	<10 μm: Reactive >10 μm: Innocuous
Norwegian Standard [9]. 2000.	<60 μm: Reactive. 60 μm–130 μm: Ambiguous. >130 μm: Innocuous.

Germany is the unique country that takes into account the simultaneous effect of different reactive components: the reactivity of opal is five times higher than the reactivity assigned to the flint [11] (Table 4).

The rest of the countries apply individual limits for each reactive component or reactive rock but there is not a rule if the aggregate has more than one. Thus, a reactive aggregate could be erroneously classified as innocuous because the content of each reactive component or reactive rock does not exceed its individual limit.

Most of the damage caused by ASR in Spanish structures is due to the presence of micro and cryptocrystalline quartz in the aggregate. For this reason, it is important to know how different sizes of quartz crystals contribute to the ASR, the individual limit that should be applied for each size and also how to evaluate their simultaneous presence in natural aggregates.

In this research, the effect on the reactivity of aggregates with different crystal sizes of quartz (0–10 μm; 10–60 μm, 60–130 μm) has been studied, proposing a unique limit for all of them applied to their weighted sum (Equivalent Reactive Quartz). For this aim, values of the individual mathematic weights for different crystal sizes have been obtained.

Aggregates from three dams and a channel affected by ASR, because of their content of reactive quartz, have been studied. Also, two reactive sands, chert and eight mixtures of reactive aggregates prepared at the laboratory have been tested.

2. Materials and methods

2.1. Reactive aggregates

Four aggregates (A, B, C, D) have been taken from structures affected by alkali silica reaction in Spain. The signs of ASR in these structures were: expansion, movement and cracking of concrete. Gel deposits in cracks and inside cores from the structures have been identified as alkali-silica reaction products by SEM-EDX (scanning electron microscopy–energy dispersive X-ray spectroscopy). So, the reactivity of aggregates A to D is well known, as has been proved in practice. Fig. 1 is an example of one of the dams with expansion problems.

Table 2
Limits applied in different countries for rocks containing cryptocrystalline quartz.

Country/reference/year	Limit	Reactive component
Holland [11]. 1991.	2 vol.%	Opal + chalcedony + porous chert.
US Army Corps of Engineers [12]. 1994.	More than 5% of particles	Chert in which any chalcedony is detected.
United Kingdom [13]. 1995.	3 wt.%	Chert, flint or chalcedony (reduced from 5%)
Washington State Department of Transportation; Portland Cement Association [14]. 2002.	3 wt.%	Chert or chalcedony
Ireland [15]. 2003.	5%[a]	Micro or cryptocrystalline quartz or chalcedony.
Denmark [11]. 2004.	1–2 vol.%	Flint.
Germany [11]. 2004.	2 wt.%	Flint. fraction 1–4 mm. (Table 4)

[a] The units are not specified in Ref.[15].

Table 3
Limits applied in different countries for rocks containing microcrystalline quartz.

Country/reference/year	Limit	Reactive component
US Army Corps of Engineers [12]. 1994.	More than 15% of particles	Consisting of graywacke, argillite, phyllite, or siltstone containing any very finely divided quartz or chalcedony
Norway. NB21 [11]. 2004.	More than 20%	Consisting of an aggregate with typical grain size of quartz <60 μm.
Washington State Department of Transportation; Portland Cement Association [14]. 2002.	5 wt.%	Optically strained, microfractured, or microcrystalline quartz
Ireland [15]. 2003.	5%[a]	Micro or cryptocrystalline quartz or chalcedony.

[a] The units are not specified in Ref.[15].

Coarse aggregates (coarser than 4 mm) were extracted from the concrete cores and used as samples of reactive aggregates in this research because, due to its big volume, they still keep a high percentage of reactive components unaltered inside. The aggregates were removed from the concrete by a thermal shock procedure: the concrete is soaked in water for 3 h and then put into a crucible furnace for 30 min at 500 °C, so the cement paste is separated easily from the coarse aggregate.

Finally, these coarse aggregates are crushed to obtain sand for casting mortar bars. This crushing helps to reduce the presence of induced cracks occasionally formed as a result of the thermal shock, as they are weak planes where the coarse aggregates break during crushing. So, the effect of the thermal shock and the crushing is considered not significant.

The aggregates E and F were reactive river sands. Their reactivity was shown in the accelerated mortar bar test ASTM C1260 [21] (0.16%; 0.26% of expansion at 14 days, respectively).

All the aggregates used in this research were reactive because of their content of micro and cryptocrystalline quartz (see Tables 5 and 6).

Finally, chert (aggregate Sx) has been added to an innocuous limestone (aggregate G) in different proportions to evaluate the reactivity and behavior of the highest reactive form of quartz (cryptocrystalline quartz).

Table 5 shows the petrographic description of the aggregates used in this study.

2.2. Methodology

The *petrographic quantification of reactive components* in the aggregates has been carried out according to RILEM AAR-1 [10] (Point counting method). Thin sections have been prepared for fractions 2–4 mm and <2 mm, and 1000 effective points have been counted for each fraction. The Petrographic Microscopy used is Leyca DMRD with camera

Table 4
Classes of alkali-reactivity concerning aggregates with opaline sandstone and flint with a cement content >330 kg/m^3.

	Limits in % by weight for the reactivity groups 2004.		
	Non-reactive	Conditionally useful	Reactive
Opaline sandstone + other opal-containing rocks (Including reactive flint 1 to 4 mm)	<0.5	0.5–2	>2
Reactive flint over 4 mm	<3.0	3.0–10.0	>10.0
5 × (opaline sandstone + other opal-containing rocks) + reactive flint	<4.0	4.0–15.0	>15.0

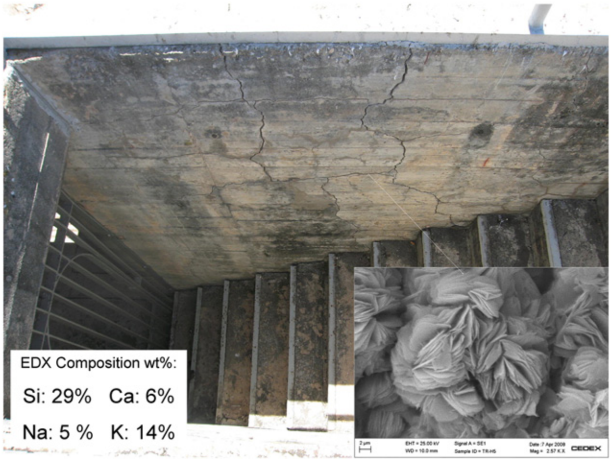

Fig. 1. Aggregate C was extracted from a dam affected by ASR. SEM–EDX confirms that expansion and cracking of concrete are due to alkali silica reaction.

Sony DXC 950 P. The statistic certainty of the point-counting method can be consulted in Annex 3 of the RILEM recommendation.

The *reactive forms of quartz* have been classified depending on the crystal size according to the Norwegian Criteria (Table 1, [9]). A new division has been included when the crystal size is less than 10 μm [8], classified as highly reactive and for which it is still easy to resolve individual crystals in the petrographic microscope. Thus, depending on the quartz crystal size, we have:

- Innocuous quartz: >130 μm. (I Qz)
- Doubtful quartz: 60–130 μm. (D Qz)
- Reactive quartz: 10–60 μm. (R Qz)Fig. 2.
- Highly reactive quartz: <10 μm. (HR Qz)Fig. 3.

The AMBT (*accelerated mortar bar test*; ASTM C1260 [21]) has been used to measure the reactivity of each aggregate (innocuous if expansion is less than 0.1% at 14 days [14,21]).

By this way the expansion of mortar bars can be correlated with the content of reactive components for each aggregate. As the petrographic composition of each fraction of the aggregate (RILEM AAR-1) is not exactly the same, the calculated content of reactive components in the sand of the bars has been used for this correlation, taking into account its grading. So, the final petrographic composition of the sands is calculated as follows: 10% of the fraction 2–4 mm and 90% of the fraction <2 mm (both evaluated according to RILEM AAR-1).

3. Experimental results

Table 6 shows the content of reactive and doubtful reactive forms of quartz measured in fraction 2–4 mm and <2 mm for all the aggregates tested. This table also compiles results of expansion at 14 days in accelerated mortar bar test ASTM C1260.

Mortar bars with different mixtures of reactive aggregates have been cast in order to increase the number of samples tested, looking for a wide range of results. Table 7 shows the mixtures of aggregates used and their expansion.

4. Discussion of results

4.1. Effect of quartz crystal size smaller than 10 μm in the reactivity of aggregates

Fig. 4 shows the results of expansion and highly reactive quartz content for all the aggregates tested. A lineal regression forced through the origin (least squares fitting) has been fitted.

Table 5
Petrographic description. Spanish natural aggregates.

Aggregate	Petrographic description	Main minerals	Secondary minerals	Accessory minerals
A Quartzite.	Granoblastic texture. Subidiomorphic contacts, sutured and/or straight contact and triple point. Heterogranular: 20–500 μm.	Quartz (90–99 vol.%).		Opaques, zircon, muscovite, iron oxide and micaceous clays.
B Quartzarenite	Homogeneous composition and heterogranular (micro-cryptocrystalline quartz veins). Subrounded and subangular grains with cryptocrystalline siliceous cement	Quartz (90–96 vol.%)		Opaques, zircon, sericite, muscovite, apatite, dolomite, iron oxide.
C Quartzite	Homogeneous composition. Heterogeneus fabric: - Cataclastic and heterogranular (from cryptocrystalline to millimetric strained quartz)	Quartz: 99–100 vol.%		Iron oxides (veins and intergranular), sericite, opaque, muscovite, microcline, carbonates, tourmaline and micaceous clays.
D Quartzarenite (60%) and quartzite (40%)	- Quartzarenite: angular grains. Heterogranular. Ferruginous cement - Quartzite: granoblastic and xenomorphic texture. Polygonal Fabric, sutured contact	Quartz. (90–99 vol.%) mainly coarse grained	Ferruginous cement in quartzarenite	Opaques, iron oxide, filosilicates, muscovite, tourmaline and micaceous clays.
E Quartz sand	- Quartzite: Xenomorphic and granoblastic texture. - Polycrystalline quartz with sutured contacts/boundaries: and grains of sheared quartz or stretched metamorphic quartz: crystals elongated in a preferred direction. - Monocrystalline quartz with undulatory extinction. - Chalcedony and chert - Quartzarenite with micaceous cement	Quartz (90–99 vol.%)	Ferruginous cement in quartzarenite	Feldspart, calcite, mica
F Quartzarenite	- Subangular grains homogranular (300–400 μm) with cryptocrystalline (sometimes micaceous or ferruginous) siliceous cement - Subangular grains heterogranular (300 μm–1 mm) with sutured and strained boundaries and siliceous compaction pressure-solution cement	Quartz (90–99 vol.%)		Micaceous clays, iron oxide, calcite.
G Innocuous calcite	Wackestone oosparite: Ooids of calcite with poorly preserved of the concentric laminate. The matrix between the ooids is of sparry calcite cement	Calcite 100%		
Sx chert	Granoblastic and subidiomorphic. Cryptocrystalline texture: polygonal fabric with sutured contact	Quartz 100%		

Table 6
Vol.% of reactive and doubtful reactive components and expansion in accelerated mortar bar test (14 days).

Aggregate	AMBT	Fraction 2–4 mm; vol.%			Fraction <2 mm; vol.%		
	% expansion 14 days	D Qz	R Qz	HR Qz	PR Qz	R Qz	HR Qz
A	0.33	32.3	20.9	2.2	18.8	12.9	1.2
B	0.20	12.8	4.4	3.3	7.7	6.0	5.7
C	0.29	10.1	13.1	3.3	9.3	9.8	2.8
D	0.42	34.8	17.9	5.0	30.1	12.3	10.0
E[a]	0.16				5.2	6.1	1.8
F	0.26	18.5	8.6	7.3	7.8	6.1	5.4
G	0.00	0	0	0	0	0	0
Sx	0.20	0	0	100	0	0	100

D Qz: Doubtful quartz; R Qz: Reactive quartz; HR Qz: Highly reactive quartz.
[a] Fraction >2 mm is an innocuous limestone (G).

The resulting limit for highly reactive quartz would be 1.9% (corresponding to 0.1% of expansion at 14 days, Fig. 4), quite close to the limits found in literature (Table 2). Although these standard limits in Table 2 are related to the rock content of chert, flint and/or chalcedony, which are composed of cryptocrystalline quartz, so they have been compared to the content of the reactive component found in this research.

According to RILEM AAR-1, the uncertainty of this limit is: $1.9 \pm 0.7\%$ HR $Qz_{(<10\ \mu m)}$ (lower 95% confidence bounds for 1000 points counted).

The correlation coefficient in Fig. 4 is low, with a special anomalous behavior of aggregate A, for which the content of highly reactive quartz is 1.3 vol.%, although the expansion is rather higher than expected. Subsequently, the content of quartz crystals between 10 and 60 μm has been also taken into account to improve the correlation results.

4.2. Effect of quartz crystal size between 10 and 60 μm in the reactivity of aggregates

Again, the lineal regression (giving the best fitting among others) forced through the origin (least squares fitting) has been fitted using in this case the amount of both reactive components (HR Qz: <10 μm and R Qz: 10–60 μm), allowing to explain how they contribute together to the expansion of the bars (Fig. 5).

The new lineal regression with two independent variables shown in Fig. 5 improves the correlation coefficient (Eq. 1):

$$\text{Expansion}(14\text{days}) = 0.012 \cdot (\text{vol.\%R Qz}) + 0.039 \cdot (\text{vol.\%HR Qz})\left(R^2 = 0.657\right). \quad (1)$$

The relative contribution of both components (HR Qz and R Qz) corresponds to a ratio 0.012/0.039 = 0.31.

It is known that the grain size reduction of quartz enhances reactivity increasing the surface area of quartz grain boundaries available for reaction [7]. Based on this, the numerical contribution of both crystal sizes can be explained if reactive quartz (grains between 10 and 60 μm; average diameter 35 μm) and highly reactive quartz (<10 μm; average diameter 5 μm) are supposed to be spherical grains. If the sphere packing is not taken into account, one crystal of reactive quartz RQz ($2.24 \cdot 10^4\ \mu m^3$) has the same volume than 343 crystals of highly reactive quartz HR Qz (each one $65.5\ \mu m^3$). If the crystals are in contact with an alkaline solution and the depth of dissolution is 2.5 μm, at the end of the reaction of highly reactive crystals $2.24 \cdot 10^4\ \mu m^3$ of HR Qz is dissolved (the whole of the crystals). This depth would be the same for the attack to the unique crystal of reactive quartz with the same volume, but it only had dissolved a surface layer of 2.5 μm thick (volume: $8312\ \mu m^3$) (Fig. 6).

So, the theoretical dissolved rate for crystals of reactive and highly reactive quartz with the same volume is 0.37 ($8312\ \mu m^3$ of R Qz/$2.24 \cdot 10^4\ \mu m^3$ of HR Qz), close to the experimental result of 0.31 obtained in the lineal regression (experimental relative contribution of both components was calculated from the coefficients of the lineal regression in Eq. 1: 0.012/0.039 = 0.31).

On the other hand, the lineal regression shows that the individual limit obtained for each reactive component in this case would be: 8.3 vol.% of RQz (10–60 μm); and 2.6 vol.% of HR Qz (<10 μm), corresponding to 0.1% expansion at 14 days.

According to RILEM-AAR1, the uncertainty of these limits is: $8 \pm 2\%$ R $Qz_{(10-60\ \mu m)}$; 2.6 ± 0.9 vol.% of HR $Qz_{(<10\ \mu m)}$ (lower 95% confidence bounds for 1000 points counted).

4.3. Effect of crystal quartz size between 60 and 130 μm in the reactivity of aggregates

In the petrographic study, the quartz crystal size between 60 and 130 μm has been classified as doubtful reactive.

The effect on expansion of this quartz size is studied in this section. Again, the lineal regression forced through the origin (least squares fitting) has been fitted using the amount of the three reactive components (<10 μm; 10–60 μm; 60–130 μm) (Table 8).

The results show that quartz crystal size higher than 60 μm has no effect on expansion (coefficient for quartz crystal size between 60 and 130 μm is 0.000), so it can be considered innocuous, and consequently the graph of the regression is the same as shown in Fig. 5.

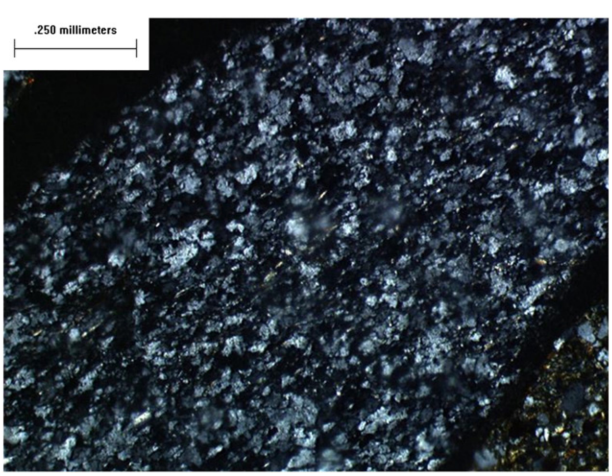

Fig. 2. Reactive quartz (R Qz: 10–60 μm). Aggregate D.

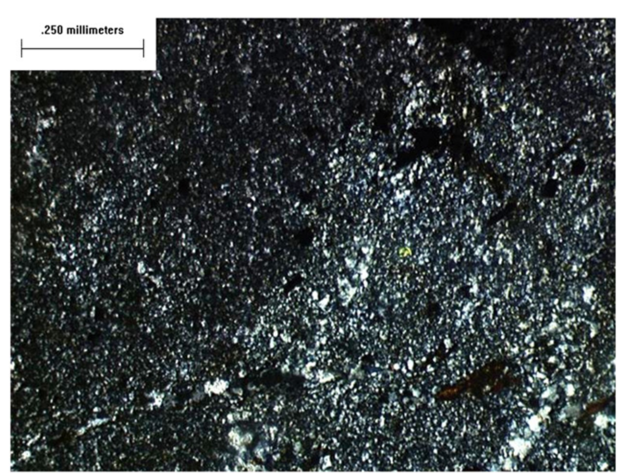

Fig. 3. Highly reactive quartz: (HR Qz: <10 μm). Aggregate D.

Table 7
Mixtures of aggregates and accelerated mortar bar test.

Mixtures of aggregates		AMBT % expansion 14 days
SX2	2 wt.% of chert in innocuous limestone	0.15
SX5	5 wt.% of chert in innocuous limestone	0.36
SX8	8 wt.% of chert in innocuous limestone	0.37
1	40 wt.% aggregate F + 60 wt.% innocuous limestone	0.09
2	30 wt.% aggregate F + 70 wt.% innocuous limestone	0.10
3	20 wt.% aggregate F + 80 wt.% innocuous limestone	0.04
4	10 wt.% aggregate F + 90 wt.% innocuous limestone	0.00
5	20 wt.% aggregate F + 80 wt.%of aggregate E	0.19
6	30 wt.% aggregate F + 70 wt.%of aggregate E	0.13
7	40 wt.% aggregate F + 60 wt.%of aggregate E	0.21
8	50 wt.% aggregate F + 50 wt.%of aggregate E	0.22

4.4. Equivalent Reactive Quartz

The effect of both reactive components: reactive quartz (10–60 μm) and highly reactive quartz (<10 μm), can be joined in one using the concept of Equivalent Reactive Quartz, as shown in Eq. 2.

$$\text{Equivalent Reactive Quartz(ERQ, vol.\%)} = \text{vol.\% HR Qz}_{(<10\ \mu m)} + 0.31\cdot\text{vol.\% R Qz}_{(10\text{–}60\ \mu m)}. \tag{2}$$

This parameter is related to the total grain boundary of quartz in the aggregate, which was evaluated in [7] by means of petrography and X ray diffraction.

Fig. 7 shows the relationship between Equivalent Reactive Quartz and expansion, for all the aggregates tested. Then, the individual limits for these two reactive components can be reduced to one unique limit of 2.6 vol.% (corresponding to 0.1% expansion at 14 days) applied to equivalent reactive quartz (Fig. 7).

However, Fig. 7 shows that 2.6 vol.% of Equivalent Reactive Quartz is not really a conservative limit, because bars with 2 vol.% of chert (sample Sx2) have shown an expansion higher than 0.1% at 14 days. Moreover, chert samples (Sx2; Sx5; Sx8) are the furthest results from the lineal regression. The explanation is that all reactive quartz <10 μm has been classified in the same group as highly reactive, but the grain size of chert is extremely small, so it is actually the most reactive kind of quartz, showing this behavior in Fig. 7.

Hence, the standard limit, from a conservative point of view, should be reduced from 2.6 vol.% to 2 vol.% of Equivalent Reactive Quartz. This limit is valid either for chert or other less reactive forms of cryptocrystalline quartz.

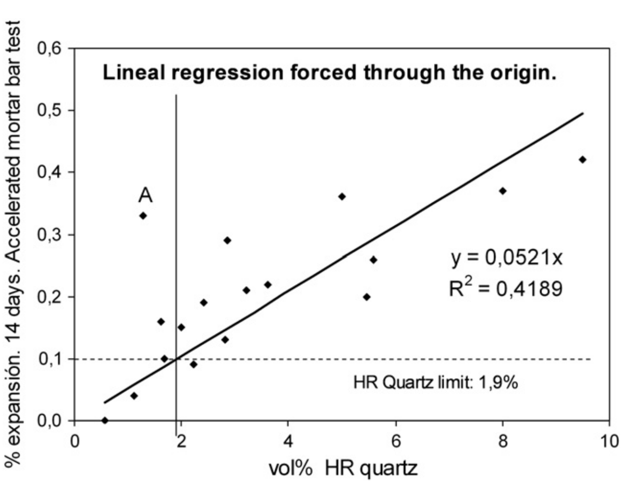

Fig. 4. 14 days expansion (AMBT) against HR Qz content.

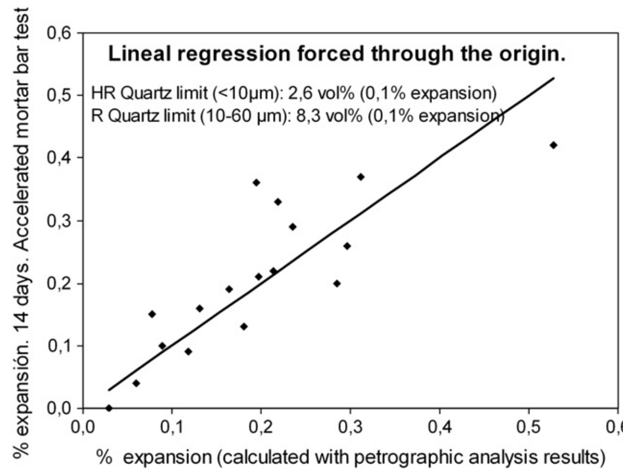

Fig. 5. 14 days expansion (AMBT) against 14 days expansion calculated from petrographic analysis results.

The calculated amount of Equivalent Reactive Quartz allows to evaluate the reactivity of aggregates in which there are simultaneously different forms of reactive quartz (<10 μm and 10–60 μm), avoiding to classify them erroneously as innocuous aggregates when each reactive component does not exceed the individual limit, but the Equivalent Reactive Quartz content does exceed the 2 vol.%. Thus, for example, the aggregate 2 has 1.7 vol.% quartz <10 μm and 1.9 vol.% quartz 10–60 μm, and it would satisfy the limits from literature (Tables 2 and 3), being classified as innocuous. However, the Equivalent Reactive Quartz, calculated by means of Eq. 3, is:

$$1.7\ \text{vol.\% HR Qz} + 1.9\ \text{vol.\% R Qz}\cdot 0.31 = 2.3\ \text{vol.\% Equivalent Reactive Quartz} > 2\ \text{vol.\%}. \tag{3}$$

Therefore, indeed this aggregate would be reactive and the expansion in AMBT (0.1% at 14 days) confirms its reactivity.

5. Conclusions

In this research, the effect of different crystal sizes of quartz (0–10 μm; 10–60 μm, 60–130 μm) on the reactivity of aggregates has been studied, proposing a unique limit for all of them, applied to their weighted sum (Equivalent Reactive Quartz). Values of the individual mathematic weights for different crystal sizes have been obtained.

- Aggregates from 3 dams and a channel affected by ASR, because of their content of reactive quartz, have been studied. Also two reactive sands, chert and different mixtures of these reactive aggregates have

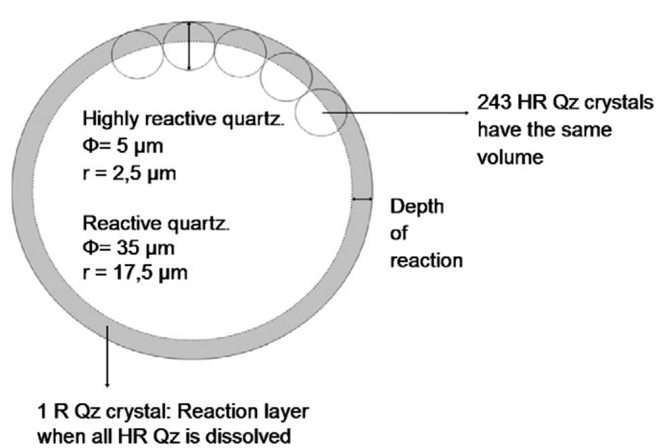

Fig. 6. Explanation of different contribution of both crystal sizes.

Table 8
Lineal regression forced through the origin. (14 days expansion — doubtful reactive; reactive; and highly reactive quartz content).

Expansion (14 days) = X1 (vol.% Qz 60–130 µm) + X2 (vol.% Qz 10–60 µm) + X3 (vol.% Qz <10 µm)		
Regression conditions: X1 ≥ 0; X2 ≥ 0; X3 ≥ 0		
	Parameters	Limits of reactive components (0.1% expansion 14 days)
R^2: 0,657	X1 = 0.000	–
17 points	X2 = 0.012	8.3 vol.% R Qz
	X3 = 0.039	2.6 vol.% HR Qz

been tested. A petrographic study has been carried out and the expansion of mortar bars has been measured for all of them.

- The *reactive forms of quartz* detected in the petrographic study have been classified depending on the crystal size: Innocuous quartz: >130 µm. (I Qz); Doubtful quartz: 60–130 µm. (D Qz); Reactive quartz: 10–60 µm. (R Qz); Highly reactive quartz: <10 µm. (HR Qz).
- The expansion in mortar bars has been correlated with the content of reactive components for each aggregate. The correlation coefficient is low when only highly reactive quartz is evaluated as reactive component, improving when the content of quartz crystals between 10 and 60 µm is also taken into account. However, the lineal regression including also doubtful quartz content demonstrates that quartz crystal size higher than 60 µm has no effect on expansion, so it can be considered innocuous.
- The individual limit obtained for each reactive component is: 8.3 vol.% of quartz 10–60 µm; and 2.6 vol.% of quartz <10 µm (corresponding to 0.1% expansion at 14 days). Therefore, the relative contribution of both components (HR Qz and R Qz) corresponds to a ratio 0.31.
- These two individual limits can be reduced to one equal to 2.6 vol.% and applied to Equivalent Reactive Quartz (ERQ, Fig. 7), defined as (Eq. 4):

$$ERQ = \text{vol.\% HR Qz}_{(<10\ \mu m)} + 0.31 \cdot \text{vol.\% R Qz}_{(10\text{–}60\ \mu m)}. \quad (4)$$

- To be used as standard limit, results show that 2.6 vol.% of Equivalent Reactive Quartz is not really a conservative limit for extremely reactive cryptocrystalline quartz (chert). Thus, it is advisable to reduce it to 2 vol.% of Equivalent Reactive Quartz.
- By means of the petrographic study, the calculated amount of Equivalent Reactive Quartz allows to evaluate the reactivity of aggregates in which there are simultaneously different forms of reactive quartz (<10 µm and 10–60 µm), avoiding to classify them erroneously as innocuous when each reactive component does not exceed the individual limit usually applied, but the Equivalent Reactive Quartz content exceeds the 2 vol.%. That was the case of aggregate 2 used in this research.
- The limits obtained for different forms of reactive quartz (<10 µm and 10–60 µm) work for the rocks tested: quartzites, quartzarenites and limestones with chert, but more samples and other different rock types should be tested to confirm these results.

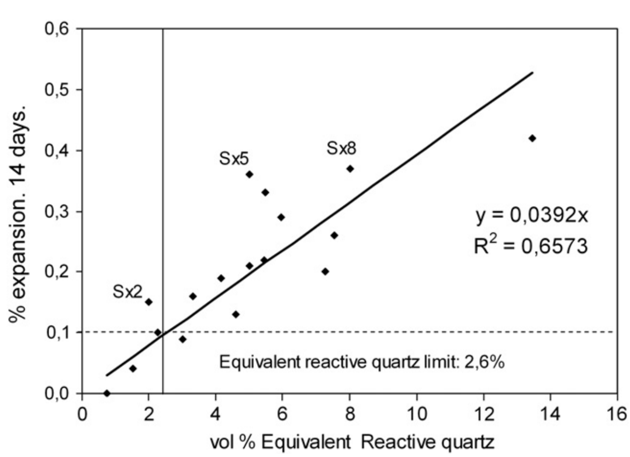

Fig. 7. Equivalent Reactive Quartz and expansion at 14 days in AMBT.

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