

The Reactivity of Aggregates in Southern Brazil

A Reatividade dos Agregados do Sul do Brasil

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Abstract

Some factors such as moisture are required to initiate the alkali-aggregate reaction in concrete structures. That can explain why AAR is very common in concrete dams. However, in recent years, many cases of the alkali-aggregate reaction have been reported in concrete structures of bridges, overpasses, highways and buildings. In contrast with the assessment of the reactive potential of aggregates used in concrete dams, the reactive potential of coarse aggregates used in the latter structures has never been assessed. The present report aims to evaluate the reactive potential of coarse aggregates used in the manufacture of concrete in Southern Brazil. The experimental program was carried out with 39 rock samples (the aggregates). These samples underwent petrographic characterization and a mortar produced with these aggregates and Portland cement Type I (MP), defined by ASTM C595, was tested using ASTM C 1260 accelerated test. The study showed that all 39 aggregates can be considered potentially reactive to alkalis. It was also observed that the type of aggregate has a significant influence on the degree of expansion, with basalt leading to bigger expansions.

Keywords: alkali-aggregate reaction, reactive aggregates.

Resumo

São necessários alguns fatores para que a reação álcali-agregado se manifeste nas estruturas, entre eles está a presença de umidade. Por esse motivo, esta reação é bastante comum em barragens de concreto. Contudo, nos últimos anos, muitos casos de reação álcali-agregado têm sido constatados em pontes, viadutos, rodovias e edifícios. Porém, para esse tipo de obra, nunca foi avaliada a potencialidade reativa dos agregados, atitude que é comum com os agregados utilizados em barragens. Em função disso, este estudo buscou avaliar a potencialidade reativa dos agregados mais utilizados para a confecção do concreto no sul do Brasil. Para tanto, realizou-se a análise petrográfica de 39 amostras de agregados e o ensaio acelerado da ASTM C 1260 com esses agregados e com o cimento composto do tipo CP II-Z 32, que é o cimento mais consumido na região. Ao final dos ensaios verificou-se que todos os agregados são potencialmente reativos do ponto de vista da reação álcali-agregado. Além disso, concluiu-se que o tipo de agregado utilizado exerce influência significativa na intensidade da expansão, sendo que os basaltos são os agregados que resultaram em maiores expansões.

Palavras-chave: reação álcali-agregado, agregados reativos.

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1 Introduction

The alkali-aggregate reaction (AAR), a chemical reaction between the alkalis from cement and the minerals found in aggregates, is one of many pathologies that can affect concrete structures. This reaction produces a gel that increases in volume when in contact with water. This increase in volume produces tensile forces within the concrete and results in widespread cracking.

Until recently, the AAR was not a concern in most civil construction structures because this reaction was thought to be common only in massive concrete structures exposed to high moisture content such as dams. However, in recent years, cases of AAR have been reported in bridges, overpasses, highways and buildings.

In Brazil, interest in the subject arose in 2004 and 2005 when instances of AAR were reported in buildings foundations in the state of Pernambuco, in Northeast Brazil. Concern over this pathology has grown because there has never been any kind of formal assessment of the aggregates used in smaller constructions and therefore, little is known about the reactive potential of Brazilian aggregates.

A study by Valduga [1] was the only attempt at mapping the characteristics of reactive aggregates in Brazil. This pioneering study was limited to the aggregates produced in the state of São Paulo and showed that 60% of all samples collected were reactive. This served as a warning sign that suggested that aggregates produced in other parts of Brazil also required investigation.

This evidence, added to the fact that it is not possible to stop AAR after it has started and that all measures used to inhibit this reaction are only palliative and are yet to be consolidated, served as the motivation behind this study, which aimed to investigate the reactivity of the minerals found in different types of aggregates in Southern Brazil (in the states of Paraná, Santa Catarina and Rio Grande do Sul).

Table 1– Chemical and physical properties of the cement used in the study

Químicas			
Al ₂ O ₃ (%)	6,42	Na ₂ O (%)	0,93
SiO ₂ (%)	20,31	K ₂ O (%)	0,10
Fe ₂ O ₃ (%)	3,12	Loss on ignition (%)	5,63
CaO (%)	53,01	Free CaO (%)	1,35
MgO (%)	5,06	Insoluble residue (%)	10,40
SO ₃ (%)	3,00	Alkali equivalent (%)	0,99
Physical			
Specific mass (g/cm ³)	2,87		
Autoclave expansion (%)	0,20		
Heat expansion (mm)	0,00		
Time of setting	Start	3:05	
(h:min)	End	3:45	
Normal consistency (%)	26,8		
Blaine fineness (cm ² /g)	3,530		
Particles retained sieve #200 (%)	1,50		
Particles retained sieve #325 (%)	8,80		

2 Materials

This study investigated the materials most commonly used in the production of concrete in Southern Brazil.

The cement used was pozzolanic Portland as defined by Brazilian standard NBR 11578 [2] (CP II-Z 32) or cement Type I (MP) as defined by ASTM C595 [3].

The properties of the cement used are shown in Table 1. To investigate the reactivity of the aggregates in Southern Brazil, samples of 39 aggregates were selected according to their potential use in the 3 states in the region.

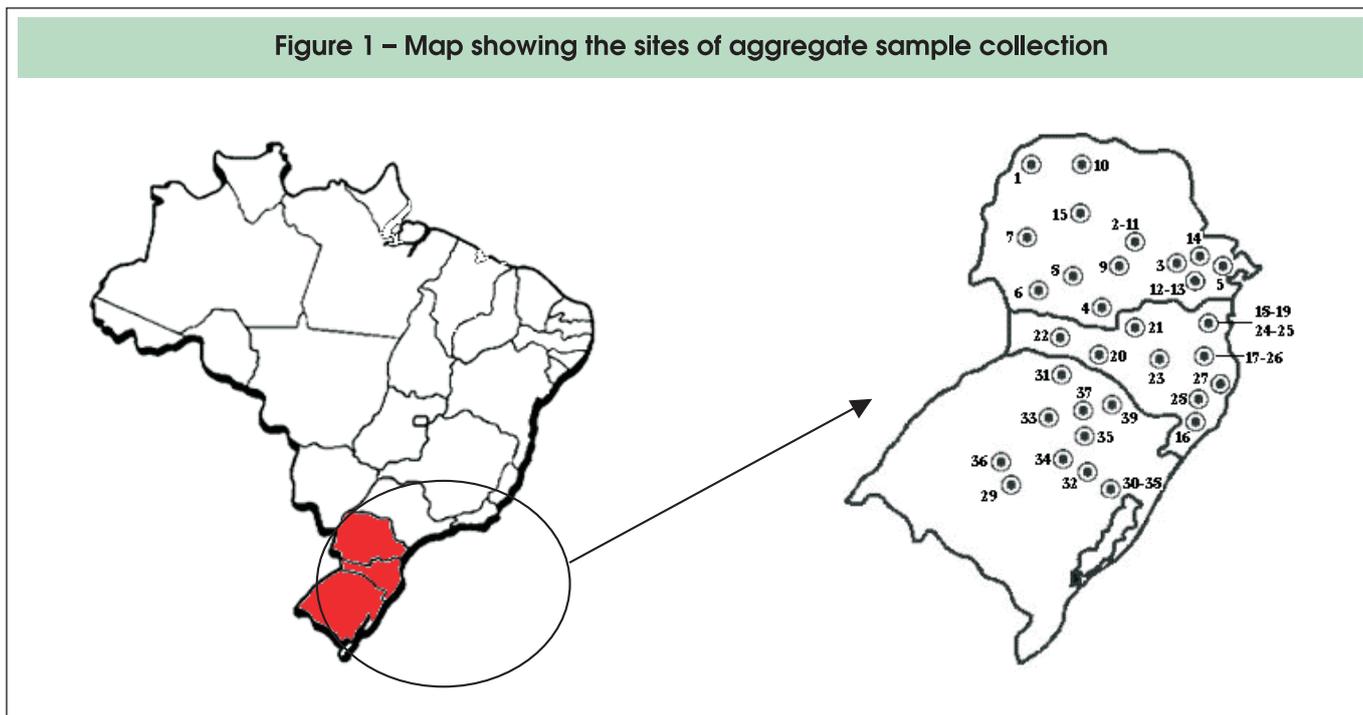
Table 2 – Origin of aggregates used

N°	Petrographic origin/State						
01	Sand/PR	11	Basalt/PR	21	Basalt/SC	31	Basalt/RS
02	Sand/PR	12	Rhyolite/PR	22	Basalt/SC	32	Basalt/RS
03	Sand/PR	13	Gneiss/PR	23	Basalt/SC	33	Rhyolite/RS
04	Sand/PR	14	Granite/PR	24	Granite/SC	34	Rhyolite/RS
05	Sand/PR	15	Rhyolite/PR	25	Rhyolite/SC	35	Basalt/RS
06	Basalt/PR	16	Sand/PR	26	Granite/SC	36	Rhyolite/RS
07	Basalt/PR	17	Granite/SC	27	Granite/SC	37	Rhyolite/RS
08	Basalt/PR	18	Sand/SC	28	Granite/SC	38	Granite/RS
09	Basalt/PR	19	Sand/SC	29	Sand/RS	39	Basalt/RS
10	Basalt/PR	20	Basalt/SC	30	Sand/RS		

PR: state of Parana; SC: state of Santa Catarina; RS: state of Rio Grande do Sul

PR: state of Parana; SC: state of Santa Catarina; RS: state of Rio Grande do Sul

Figure 1 – Map showing the sites of aggregate sample collection



These samples included rocks, which are commonly used as coarse aggregate in concrete, and sand, which is used as fine aggregate.

Table 2 lists the petrographic source of the concrete and the states where they come from. In some sites where different rock types are used, multiple samples were collected. In other places, samples of both fine and coarse aggregates were collected. No limestone samples were collected, even though they are commonly found in the region.

The collection sites of the samples are shown in the map in Figure 1.

3 Methods

The reactive potential of the aggregate samples was assessed using ASTM C1260 (accelerated test) [4] and the petrographic analysis was performed using ASTM C295 [5].

3.1 Mineralogical and petrographic analysis

Thin slices of the samples collected (30 μ m) were analyzed using an optical microscope.

The minerals present in the samples, their degree of deformation and change and their shape and size were recorded and an attempt was made to correlate this data with the alkali reaction in concrete.

It should be noted that the aggregates were first grouped according to their petrographic origin. This was done to group samples of similar characteristics and thus make comparisons among them easier. The samples were divided into 5 groups: granites, rhyolites, basalts, sands and gneiss.

3.2 Accelerated test

Three mortar bars for each aggregate type were molded using a mix composition of 1:1.25 (cement: aggregate by weight) and a water/binder ratio of 0.47. In addition, the aggregates were prepared to fall within the particle size distribution specified in the standard.

After molding, the test specimens were stored in a controlled temperature room (temperature = 20 \pm 1 $^{\circ}$ C; RH = 90%) for 24h. They were then removed from the moulds and cured in water at 80 $^{\circ}$ C for 24h, with the temperature of the water being raised gradually to prevent cracking due to thermal shock.

After this period, the length of the bars was measured and they were then immersed in a solution of 1N NaOH at 80 $^{\circ}$ C.

ASTM C1260 [4] classifies aggregates as deleterious when mean expansion at 16 days is greater than 0.20%. If expansion at 16 days is smaller than 0.10%, the aggregates are classified as innocuous. If expansion ranges from 0.10% to 0.20% at 16 days, the aggregates may be alkali reactive or not. If that is the case, the test must be extended to 30 days.

However, in this study a choice was made to keep all bars with expansion values below 0.20% at 16 days in the alkaline solution until 30 days had elapsed, even though these samples might be classified as innocuous in this period. This was done because of published studies that show that in some aggregates, the AAR may develop more slowly such as Berubé et al. [6], Wigun e French [7], Hasparyk [8], Shon et al. [9] e Andrade et al. [10].

4 Results and discussion

4.1 Mineralogical and petrographic analysis

As outlined above, the samples were broken down into 5 groups for the sake of petrographic analysis according to their petrographic origin, as follows:

- Granites: 14, 17, 24, 26, 27, 28 and 38;
- Rhyolites: 12, 15, 25, 33, 34, 36 and 37;
- Basalts: 06, 07, 08, 09, 10, 11, 20, 21, 22, 23, 31, 32, 35 and 39;
- Sands: 01, 02, 03, 04, 05, 16, 18, 19, 29 and 30;
- Gneiss: 13.

Granites

The granite samples are of igneous origin and are made up mainly by quartz, K-feldspar and plagioclase.

As these rocks are formed by the slow cooling of magma, they usually show large, well-formed crystallized minerals. As a result, the AAR in concrete mixes using reactive granite rock takes longer to start.

The main agent that initiates AAR in granite is quartz because it is composed by silicates only. However, quartz will only be reactive if it shows deformations in its crystalline structure, which can be determined by means of its undulose extinction or if it has a microcrystalline dimension.

With the exception of sample 14, all granite samples showed highly deformed quartz. However, larger amounts of this mineral were observed in samples 18, 26, 27 and 38, the latter showing particularly intense changes such as folds, as Figure 2 (a) shows.

In addition to the amount of quartz in the sample, another factor is the size of the quartz grains. The grain size in the samples in the study were varied sizes but all samples were similar. For this reason, granite reactivity cannot be classified according to its grain size.

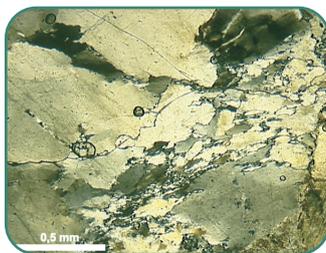
A review of the literature indicates that the presence of K-feldspars can contribute to increase the alkalinity in the concrete pores and thus accelerate the initiation of AAR, as studies by Van Aardt and Visser [11] and Constantiner and Diamond [12] show. However, the granite samples in the present study had nearly identical concentrations of these minerals.

Rhyolites

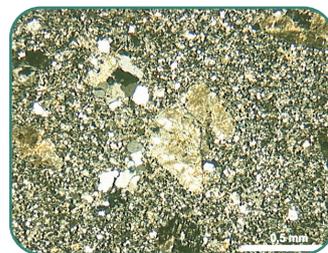
Rhyolites have the same minerals found in granites (K-feldspars, quartz and plagioclases) but they are formed when magma undergoes fast cooling. The difference is that these minerals are very small and there is also the presence of amorphous siliceous mesostasis in their matrix, which is highly reactive for AAR.

Also known as volcanic glass, this mesostasis was found in large amounts in nearly all rhyolite samples. The higher con-

Figure 2 – Microscope images of selected aggregate samples



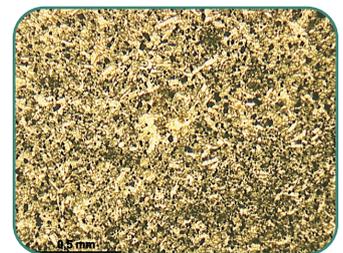
(a) Sample 38: Granite quartz with folds. Magnification 5x, crossed polarizer



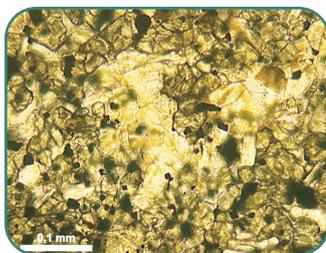
(b) Sample 12: Rhyolite very fine minerals. Magnification 5x, crossed polarizer



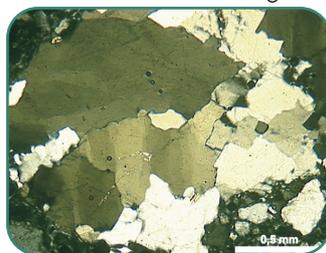
(c) Sample 37: Rhyolite amorphous siliceous material embedded between the crystals (M). Magnification 5x, natural light



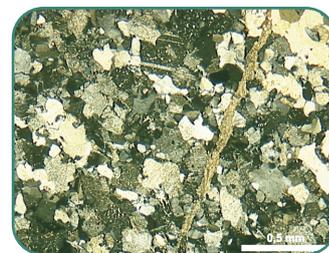
(d) Sample 20: Basalt extremely fine minerals. Magnification 5x, natural light



(e) Sample 20: Basalt amorphous siliceous mesostasis disseminated between the grains. Magnification 20x, polarized light



(f) Sample 29: Sand quartz grain with intense undulose extinction and the formation of sub-grains. Magnification 5x, polarized light



(g) Sample 13: Gneiss presence of large amounts of quartz and carbonate veins. Magnification 5x, polarized

centrations were observed in samples 15, 33 and 37, while in samples 12 and 36 there was no trace of mesostasis. In sample 12, however, quartz makes up nearly 60% of the rock. Figure 2(b) shows the aspect of the minerals in sample 12, which are all quite small. Figure 2(c) shows the siliceous mesostasis disseminated among the other crystals in sample 37.

Basalts

Like rhyolites, basalts are also igneous rocks created by fast cooling of the Earth’s magma. Therefore, they display amorphous mesostasis embedded in their matrix (volcanic glass). In addition to the mesostasis, the basalts in the study consist of plagioclase, pyroxene, clay minerals and opaque minerals.

In the present study, nearly all samples showed large amounts of amorphous materials (ranging from 30 to 50%). However, the highest concentrations were seen in samples 06, 11, 20, 21 and 31. Samples 11 and 31 also show the presence of small grains of quartz.

Sample 20 was also noteworthy because it was the aggregate showing the finest minerals (Figure 2 (d)), approximately 0.03mm. This characteristic results in a higher incidence of mesostasis, which is more widely disseminated (Figure 2 (e)).

Sands

Sands are a widely used concrete aggregate and are composed mainly of unconsolidated minerals, mostly quartz. In addition to quartz, some samples showed traces of alkali feldspars and plagioclases.

All sand samples showed highly deformed quartz, and this was more intense in samples 18, 19 and 29. Sample 18 also showed the presence of microcrystalline quartz (30%).

Figure 2 (f) shows a grain of quartz in sample 29 with intense undulose extinction and the formation of sub-grains.

Gneiss

One of the samples collected for the study is metamorphic: sample 13, a gneiss.

Petrographic examination reveals a very fine matrix com-

posed of 50% quartz grains. There are also carbonate veins which could trigger an alkali-carbonate reaction.

In addition to quartz and carbonates, there is the presence of K-feldspars, plagioclases, chlorites and traces of granada. Figure 2 (g) shows the overall appearance of sample 13.

4.2 Accelerated test

The accelerated test revealed that according to the ASTM C 1260 [4] classification, none of the aggregates can be classified as innocuous to AAR when cement CP II-Z 32 is used.

However, different amounts of expansion were observed and these were related to the type of aggregate used, which means that the choice of aggregate may result in greater or lesser expansion.

Tables 3, 4, 5, 6 and 7 list the expansion values for each type of rock and their reactivity.

Expansion values at 30 days are shown in Table 3 and they indicate that most granite samples (approx. 70%) fall in the intermediate range of the ASTM Standard and are classified as showing potentially deleterious behavior.

Rhyolites, on the other hand, displayed far greater expansion values when compared with granites. Table 4 shows that approximately 86% of rhyolite samples have expansion values above 0.20% and are therefore reactive at 16 or 30 days.

Table 5 shows that basalts, the most commonly used coarse aggregates in Southern Brazil, have the highest expansion values of all samples. As it was the case with rhyolites, 86% of basalt samples were classified as reactive through a global analysis.

Table 6 shows the expansion values of the bars molded with sand, with 60% of all samples being classified as reactive. The gneiss sample was also classified as reactive to alkalis, as Table 7 shows.

The changes in the expansion values along time of each sample are shown in Figure 03.

A comparison of the graphs in Figure 3 reveals that granite (Figure 3 (a)) and sand (Figure 3 (d)) follow a similar pattern. The same comparison can be made for rhyolites (Figure 3 (b)) and basalts (Figure 3 (c)).

This similar pattern that was observed between granites and sands and between rhyolites and basalts can be at-

Table 3 – Mean expansion – Granites

Sample number	Expansion (%)		Classification
	16 days	30 days	
14	0.18	0.21	R
17	0.25	-	R
24	0.06	0.11	PR
26	0.14	0.19	PR
27	0.12	0.16	PR
28	0.12	0.15	PR
38	0.09	0.19	PR

R= reactive; PR= potentially reactive

Table 4 – Mean expansion – Rhyolites

Sample number	Expansion (%)		Classification
	16 days	30 days	
12	0.28	-	R
15	0.34	-	R
25	0.09	0.14	PR
33	0.17	0.36	R
34	0.10	0.22	R
36	0.13	0.21	R
37	0.31	-	R

R= reactive; PR= potentially reactive

Table 5 – Mean expansion – Basalts

Sample number	Expansion (%)		Classification
	16 days	30 days	
06	0.26	-	R
07	0.25	-	R
08	0.15	0.17	PR
09	0.33	-	R
10	0.28	-	R
11	0.69	-	R
20	0.57	-	R
21	0.18	0.25	R
22	0.33	-	R
23	0.12	0.19	PR
31	0.47	-	R
32	0.20	0.35	R
35	0.15	0.26	R
39	0.23	-	R

R= reactive; PR= potentially reactive

Table 6 – Mean expansion – Natural Sands

Sample number	Expansion (%)		Classification
	16 days	30 days	
01	0.10	0.17	PR
02	0.11	0.18	PR
03	0.16	0.29	R
04	0.17	0.18	PR
05	0.11	0.12	PR
16	0.21	-	R
18	0.20	0.20	R
19	0.24	-	R
29	0.20	0.24	R
30	0.19	0.27	R

R= reactive; PR= potentially reactive

Table 7 – Mean expansion – Gneiss

Rock	Sample number	Expansion (%)		Classification
		16 days	28 days	
Gneiss	13	0.18	0.20	R

R= reactive

tributed to the agents that start AAR in these aggregates. In granite and sand, the main source of reactive silica is deformed quartz. In rhyolite and basalt, the silica is found in the form of amorphous mesostasis. In addition, the

composition of rhyolites includes well-formed quartz crystals as well as K-feldspars.

Overall, it was observed that both the samples molded with granite and the samples molded with sand showed slower expansion than the samples molded with basalts and rhyolites, i.e. most samples with granite or sand had to be kept in the NaOH solution for 30 days so that their reactivity could be assessed.

This indicates that the presence of amorphous siliceous mesostasis in basalt and rhyolite can increase the reactive potential of the aggregates.

To check for the influence of the type of aggregate in the initiation of AAR, an analysis of variance (ANOVA) of the type of aggregate in relation to the expansion values obtained was performed.

The analysis was performed using the aggregates with the highest expansion values in each group, with the exception of gneiss, of which there was only one sample.

The following aggregate samples were thus selected:

- Granite: 17;
- Rhyolite: 33;
- Basalt: 11;
- Sand: 03.

Table 8 shows the ANOVA results and which effects actually influenced expansion. The effect is significant when the p-value is lower than 0.05.

The ANOVA shows that the type of aggregate can be statistically significant for a greater or lesser expansion.

However, as it was expected, the influence of granite and sand is not significant, i.e. the expansion values for these aggregates were similar. This indicates that the deformed quartz found in granite and sand will produce the same degree of expansion regardless of which of these aggregates is used.

In contrast, the ANOVA of the expansion values of rhyolite and basalt shows that the effect of the type of aggregate used is significant. This indicates that although both aggregates have amorphous siliceous mesostasis, the effects of this alkali-reactive composition are different for each type of rock.

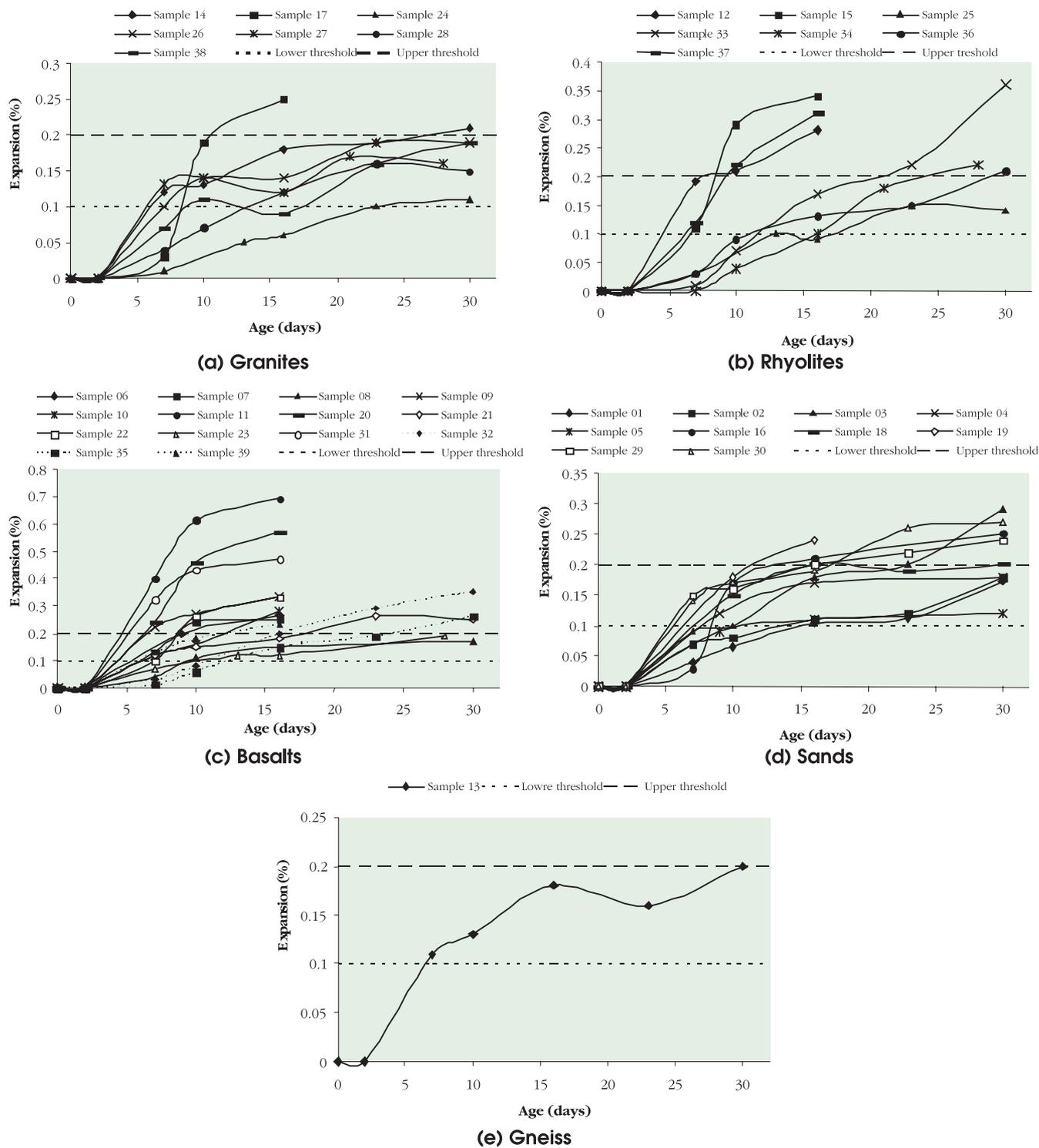
A possible explanation for this difference is the presence of quartz in the rhyolite samples, as there are no differences in the percentage of mesostasis in both aggregates.

Another possibility would be the different percentages of K-feldspars in rhyolite and basalt. Some authors have studied the possibility of alkali release from K-feldspars into the concrete solution, which would increase AAR potential [11, 12]. However, as the present study is an accelerated test using mortar bars immersed in a highly concentrated alkali solution, it is unlikely that this effect would have affected more the expansion of one type of aggregate or another.

The graph in Figure 4 shows the mean expansion values of the aggregates at 16 days and allows the assessment of the influence of the type of aggregate on expansion.

We can see from the graph in Figure 4 that while the expansion values in granite and sand ranged from 0.25 to 0.27%, the value for rhyolite was 0.47% and for basalts it was 0.69%.

Figure 3 – Expansion of aggregate samples according to their petrographic origin



Another important factor to be taken into account is the extremely small grain size in rhyolite and basalt when compared to granite and sand (Figure 2). The grain size of

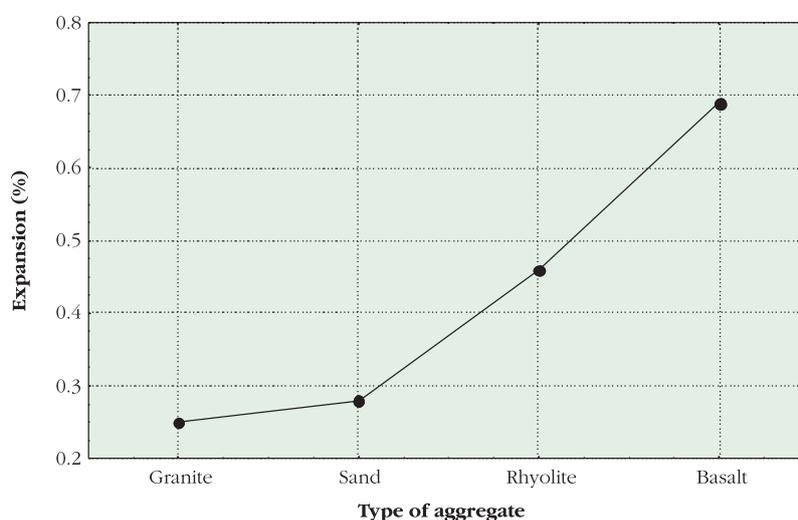
minerals is related to their formation process and increases the amount of existing silica, which in turn increases the reaction potential of the aggregate.

Table 8 – Analysis of variance of expansion values for each type of aggregate

Factor	Sum of squares	Degrees of freedom	Mean square	F-test	p-value	Significance
1	0.250117	3	0.83372	481.7829	0.000014	Significant
Error 1	0.000692	4	0.000173			
2	0.001208	1	0.001208	4.631942	0.164279	Not significant
Error 2	0.000522	2	0.000261			
3	0.053343	1	0.053343	625.7127	0.001594	Significant
Error 3	0.000171	2	0.000085			

1= relationship between granite, rhyolite, basalt and sand; 2= relationship between granite and sand; 3= relationship between rhyolite and basalt. F-test = mean square of group/mean square of error; p-value = Student's t-distribution.

Figure 4 – Influence of the type of aggregate on expansion values



Finally, a comparison between the results of petrographic analysis and the accelerated test shows that the aggregates with the highest expansions in the mortar bars had the highest amounts of deformed silica (granite and sand) or amorphous silica (rhyolite and basalt), with mesostasis always present in the samples with the highest expansion values.

5 Conclusions

The results of the laboratory tests show that none of the aggregate samples collected for analysis could be considered innocuous to AAR, which means that the aggregates most commonly used in the production of concrete in Southern Brazil can act as AAR initiators.

By correlating the influence of the petrographic origin of these aggregates with the expansions recorded in the accelerated test, it was found that:

- The mineralogical characteristics of the aggregate can influence expansion values;
- Granite and sand have deformed quartz as their main reactive mineral. For this reason, the expansions of the bars molded with these aggregates were similar

over time, which means that the influence of the type of aggregate used is not significant for granite and sand;

- The bars molded with rhyolite or basalt resulted in greater expansion than those molded with granite, sand or gneiss in most cases. This behavior can be attributed to the presence of amorphous siliceous mesostases in these aggregates, which originates from the rapid cooling in the formation of these rocks. In addition, the small grain size of the minerals present in rhyolite and basalt increases the amount of potentially reactive components in their matrix;
- Basalt, the most commonly used coarse aggregate in Southern Brazil, showed the highest expansion in the accelerated test;
- The presence of deformed quartz in granite and sand and the presence of amorphous siliceous mesostases in rhyolite and basalt will increase the reactivity potential for these aggregates.

Finally, it can be concluded that the rocks that have been used as aggregates in concrete in Southern Brazil are potentially reactive, even when the cement used is CP II-Z 32, with approximately 15% pozzolan. As it is

known, pozzolanic additions are effective AAR inhibitors. However, the concentration found in this type of cement was not enough to inhibit AAR.

It must be remembered that the definition of AAR reactivity of an aggregate cannot be based exclusively in laboratory tests. The conditions of use of these materials and the type of structures in which they will be employed must be taken into account, with special attention being given to aspects such as humidity, presence of aggressive agents and others.

6 Acknowledgements

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