Evaluation of basaltic aggregates from Iceland and the Archipelagos of Hawaii and Azores regarding alkali-silica reaction: a comparative study

Sara Medeiros, IDL/Faculdade de Ciências e Tecnologia, Universidade dos Açores, Rua da Mãe de Deus, 9500-321 Ponta Delgada, Portugal, sara.mt.medeiros@uac.pt

Isabel Fernandes, IDL/Faculdade de Ciências, Universidade de Lisboa, Campo Grande, 1749-016 Lisboa, Portugal, mifernandes@fc.ul.pt

Benoît Fournier, Geology and geological engineering Department, 1065 avenue de la médecine, Pavillon Adrien Pouliot, Université Laval, Québec, Qc, Canada, G1V 0A6, benoit.fournier@ggl.ulaval.ca

João Carlos Nunes, Faculdade de Ciências e Tecnologia, Universidade dos Açores, Rua da Mãe de Deus, 9500-321 Ponta Delgada, Portugal, joao.cc.nunes@uac.pt

Violeta Ramos, ICT, Institute of Earth Sciences-Pole Porto, Rua do Campo Alegre, 4169-007 Porto, Portugal, violetaramos@fc.up.pt

António Santos Silva, Laboratório Nacional de Engenharia Civil, Avenida do Brasil, 101 1700-066 Lisboa, Portugal, ssilva@lnec.pt

Dora Soares, Laboratório Nacional de Engenharia Civil, Avenida do Brasil, 101 1700-066 Lisboa, Portugal, dsoares@lnec.pt

INTRODUCTION

Basalt is a volcanic rock with low content in SiO_2 and is the least understood in terms of reactivity to alkalis. In the Hawaii Archipelago, there is no history of aggregates being responsible for concrete deterioration due to alkali-silica reaction (ASR). However, there are some reports regarding the results of laboratory tests that indicated a potential reactivity of some basaltic aggregates from these islands [1]. In Azores there is only one case involving basalts with ASR of an airport concrete pavement after more than 60 years old in service [2]. On the other hand, in Iceland, ASR has been identified more than 50 years ago with local reactive basaltic aggregates. Nowadays, the problem in Iceland seems to be solved with the use of pozzolanic materials, (e.g. silica fume) [3]. Therefore, basalt is amongst the aggregates considered as potentially reactive in Iceland, especially if it is quartz-normative [4] or altered [5]. Aggregates in Hawaii and in Azores are commonly produced in quarrying operations. In Iceland, the aggregates are produced both from quarries and from gravel pits that are scattered all over the country, as terrestrial and marine sources; however, most of the aggregate production is from sand and gravel deposits. In general, the aggregates are formed by fluvial and glaciofluvial sediments, sea-dredged aggregates (mostly from erosion of lava beds, pillow lavas and pillow lava fragments) and crushed rocks [4].

Cases of alkali-silica reaction related to the use of basalts have been reported in countries such as Argentina, Brazil and New Zealand [5,6,7,8]. International experience has shown that basalt is considered potentially reactive when it contains volcanic glass and different types of silica (e.g. chalcedony, opal) [5]. Also, devitrified glass has been considered to be potentially reactive [9]. In order to understand the performance of basaltic aggregates in terms of their potential alkali-reactivity, a first approach was done by comparing materials from the above volcanic environments through the use of optical microscopy and the accelerated mortar bar tests.

MATERIALS AND METHODS

A total of twenty-four aggregates were selected for this study. Seven of them are from Hawaii Archipelago (series HW), four from Iceland (series ICL) and thirteen from Azores (series SM). All Hawaiian and Azorean aggregates were obtained from quarrying operations, while three out of the four Icelandic aggregates correspond to materials extracted from gravel deposits of basaltic composition in their majority. The potential alkali-reactivity of the selected volcanic aggregates was first assessed with an Olympus CX31 polarizing microscope. Additional analyses were carried out at Laval University (Canada) to further identify reactive forms of silica using a CAMECA SX-100 microprobe (EMPA). Geochemical analyses of the aggregates were performed at the Activation Laboratories, Actlabs, in Canada, by using the Lithium Metaborate/Tetraborate Fusion – ICP and ICP/MS method; however, their results were not considered for the gravel aggregates because of their heterogeneity. The results of these analyses were plotted in a TAS (Total Alkali Silica) diagram [10] by using the free software GCDKit3.00 [11], in order to obtain the chemical classification of the rocks. The accelerated mortar bar test (AMBT, ASTM C 1260) was performed on all aggregates. For the Hawaii and Iceland aggregates the tests were done at Laval University, for the Azores aggregates the tests were executed in the National Laboratory for Civil Engineering, in Lisbon. The mortar mixtures incorporated a GU type cement with an alkali content of 0.94% Na_2O_{equiv}. The water/cement (w/c) ratio was of 0.50 and aggregates graded from 0.15 to 5.0 mm. For Azores aggregates the mix incorporated a cement type CEM I 42.5 R [12] with 0.86% of Na_2O_{equiv}, and a w/c ratio of 0.47. The bars were immersed in a 1N NaOH solution at 80°C and measurements were taken up to 28 days [13].

RESULTS

Table 1 summarizes the main results of the geochemical analyses, petrography and expansion tests for each aggregate studied. According to the results of the geochemical analysis and to the TAS diagram [10], the majority of the rocks from the Hawaii Archipelago are classified as basalts. For Azores, the rocks range mostly between basalts and trachybasalts. For Iceland, only one of the aggregates is classified as a basalt. The rest of the aggregates are considered to be mixed gravels, where rocks of basic composition represent the largest part. The petrographic analysis of the Hawaiian and Azorean aggregates studied showed that they are similar with each other, porphyritic to poorly porphyritic, with a fine to coarse-grained intergranular groundmass. Phenocrysts and microphenocrysts of olivine, plagioclase and pyroxene are present in different proportions depending on the sample. The matrix is formed more or less by the same mineral assemblage and by opaque minerals.

Table 1. Results of the different methods used to assess the reactivity to alkalis of the volcanic aggregates

Aggregate	*Location*	*Chemical classification*	*Petrography*	*Accelerated mortar bar test* [12]
HW1	Hawaii Archipelago (HW)	basalt	vg	Reactive
HW2		basalt	-	Non-reactive
HW3		basalt	vg	Reactive
HW4		basaltic trachyandesite	-	Non-reactive
HW5		basalt	vg	Reactive
HW6		basalt	vg	Reactive
HW7		basalt	vg	Reactive
ICL1	Iceland (ICL)	-	vg, dvg zeo,ch, qz	Reactive
ICL2		-	vg, dvg,zeo,ch, qz	Non-reactive
ICL3		basalt	vg	Ptnl. reactive
ICL4		-	dvg, vg	Reactive
SMA-SM1	Azores Archipelago (SM)	basanite	-	Non-reactive
SMA-SM2		basanite	-	Non-reactive
SMG-SM1		trachybasalt	vg	Non-reactive
SMG-SM2		trachybasalt	-	Non-reactive
SMG-SM3		basalt	-	Non-reactive
TER-SM1		brachyte	mqz, vg	Ptnl. reactive
TER-SM2		basalt	vg	Non-reactive
GRA-SM1		trachybasalt	-	Non-reactive
SJO-SM1		basalt	-	Non-reactive
PIC-SM1		basalt	-	Non-reactive
FAI-SM1		trachybasalt	-	Non-reactive
FLO-SM1		basaltic trachyandesite	-	Non-reactive
FLO-SM2		basaltic trachyandesite	-	Non-reactive

zeo = zeolites; cl = chlorite; vg = volcanic glass; dvg = devitrified volcanic glass;
ch = chlorite; qz = quartz; mqz = microcrystalline quartz
- = no potential deleterious species; Ptnl = potentially

In Azores, volcanic glass is scarce. On the other hand, in Hawaii a brownish volcanic glass is present in most of the analyzed aggregates. One of the particularities that appear in some of these aggregates is that the glass seems to fill some kind of vesicles in the rock (Figure 1a). The petrography of the gravels from Iceland shows different fragments of rocks. They are composed mainly by rocks of basic composition such as

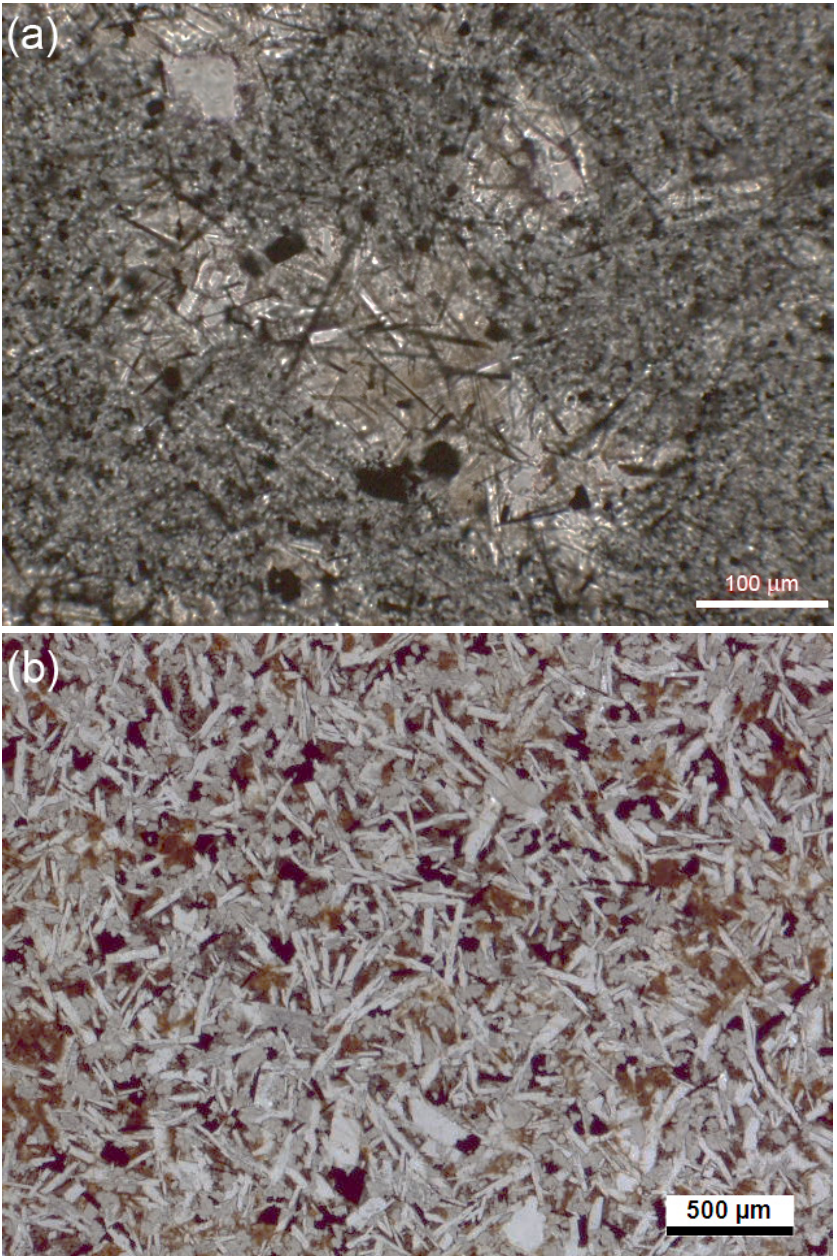

Figure 1. Basalts - brown volcanic glass filling vesicles in an aggregate from Hawaii Islands (a) and rusty-coloured devitrified glass in an aggregate from Iceland (b).

basalts; there is also what could be considered metabasalts, some rhyolites, glaciofluvial fragments with some banding of matrix material and a few plutonic rocks. The fragments of basic composition show fine to coarser grained intergranular groundmass with some phenocrysts mainly of plagioclase and olivine. The rusty color mass that is scattered in the groundmass is present in most of the fragments of basaltic composition as volcanic glass or devitrified volcanic glass (Figure 1b). The fragments of metabasalts show, in some cases, the pore spaces filled with zeolite in the center and chlorite at the edge of the pores. The rhyolites fragments have a fine-grained groundmass where quartz and feldspar are the dominant minerals as phenocrysts. The basaltic aggregates from the quarry (ICL3) show from coarse to fine intergranular groundmass. Volcanic glass is less frequent in these aggregates. Skeletal plagioclase and pyroxene are present in some of the fragments of this quarry.

EMPA was performed on selected aggregates from Hawaii, Azores and Iceland. The presence of volcanic glass was confirmed in three of the samples analyzed from Hawaii, with values of SiO_2 of 77-80% (wt). For Azores, the volcanic glass of SMG-SM1 and TER-SM2 samples has a SiO_2 content of 58% and 55%, respectively. In TER-SM1 sample the presence of microcrystalline quartz was confirmed [14]. For Iceland, the EMPA analyses identified volcanic glass with 47-40% (wt) of SiO_2, zeolite, chlorite and quartz (the last one identified probably in a rhyolite fragment) present in two of the gravel materials used as concrete aggregates.

The AMBT showed that most of the aggregates from Hawaii and Iceland are considered reactive with the exception of two aggregates from Hawaii and one of the gravels from Iceland. For Azores the majority is considered non-reactive. The rest of the mortar bars are heavily cracked and present high expansion (i.e. ranging from 0.1007 to 0.8163%) at the end of 14 days.

DISCUSSION AND CONCLUSIONS

The petrographic analyses confirmed the presence of volcanic glass in aggregates from Iceland and Hawaii Archipelago and very rare for Azores. The composition of volcanic glass from the aggregates analyzed from Hawaii is higher than 77% in SiO_2. However, for Iceland and Azores the content of SiO_2 of the volcanic glass is much lower with values reaching 47% (Iceland) and 58% (Azores). According to Katayama et al. [15] volcanic glasses with $SiO_2 > 65\%$ (rhyolite glass) are considered potentially reactive even when present in basalts or andesites while basaltic and andesitic glass are considered innocuous. However, Katayama et al [15] refers that a basalt studied by other researchers was considered reactive with a composition of 20% of andesitic volcanic glass. In Iceland samples, some of the volcanic glass appears to be devitrified with some crystalline structures. Silica minerals, like quartz, are present in some of the gravels from Iceland but probably belong to fragments of rhyolitic composition. Devitrified volcanic glass has also been considered potentially reactive according to RILEM AAR-1.1 [9]. The presence of chlorite can have an important role in this type of reactions. According to Ali et al. [16], the presence of chlorite can make the aggregate susceptible to expansion by absorbing water. The results of the accelerated mortar bar test showed that the majority of the aggregates from Iceland and Hawaii are considered alkali reactive. However, this method has not always been accepted for reliable results. The results from the concrete prism test (CPT at 38°C) (in progress) will clarify the potential alkali- reactivity of these aggregates and will allow better comparison with the results from petrography. The results from the AMBT seem to confirm the results obtained from petrography. However, it is important to analyse the thin sections from the mortar bars to clarify which is the cause of the cracking and the expansion, as well as to verify if the same cracking and expansion occurs in the CPT at 38°C and which aggregates are causing them, especially in gravels. For Azores, the results from the CPT considered all the aggregates non-reactive after one year of testing which seems to confirm the results obtained from the petrography and the AMBT.

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