CONDITION ASSESSMENT OF SHOTCRETE IN 10 YEAR OLD SHOTCRETE IN HVALFJORDUR TUNNEL IN WESTERN ICELAND

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Abstract

ASR have been found in shotcrete in a 10 year old traffic tunnel in Iceland. The reactions are characterized by gel in isolated voids, and occasionally in cracks cross-cutting aggregate.

The chemical composition of the gel mirrors its position within the shotcrete, Ca is high and Si is low close to aggregates, while the Si content increases towards center voids. The suggestion is that the source of silica is in the pore water, originating from the accelerator used.

Since the ASR occur when the concrete is young, calcium can easily penetrate into the gel and reduce its detrimental nature. The shotcrete is in a very good condition, the ASR have not caused any damage so far and unlikely will in the future.

KEYWORDS: shotcrete, ASR, gel composition, accelerator

1. INTRODUCTION

The Hvalfjordur Tunnel is a 5.8 km long road tunnel in Iceland, constructed in basalt. Approximately 4 km of the length of the tunnel lies beneath the seabed as the road extends across the mouth of Hvalfjordur to link the national highway on the south side of the fjord with that on the north side.

The tunneling project started in April 1996 and was completed in July 1998. The permanent rock support was determined in view of the geology and rock mass classification and comprises predominantly mortar grouted rock bolts and sprayed concrete or shotcrete. During the construction phase shotcrete was applied in about 40 to 80 mm thick layers, mainly on the roof section. In limited areas of heavily jointed rock, clay filled dykes and fault zones and a few areas of sedimentary rock in the crown, additional support using 100 to 150 mm of fiber reinforced shotcrete was used. Following the breakthrough walls where shotcreted and additional shotcrete was applied to the roof, where necessary, to obtain the designed shotcrete thickness.

In two areas water temperature as high as 58 ºC, was encountered. The salinity of the groundwater was also relatively high in these two areas.

Pre-testing of the shotcrete and testing during the construction phase is described in [1]. Alkali silica reactivity of the intended aggregates and cement were studied thoroughly and concluded unlikely that alkali silica reactions would cause any damage to the shotcrete.

Three condition surveys have been carried out since the tunnel was completed [2, 3, 4]. The surveys showed alkali silica gel in the shotcrete, suggesting that the shotcrete could be in danger of deleterious alkali silica reactions.

Recently, the condition of the shotcrete in seven tunnels in Iceland has been surveyed [5]. The shotcrete in most of the tunnels showed signs of alkali silica reactions but in these tunnels no deterioration of the shotcrete, due to ASR, was visible. The purpose of the work presented here was to study the nature of these presumed alkali silica reactions.

2. ASR IN SHOTCRETE

Internationally, only a limited number of references describe ASR in shotcreted structures. In [6] the possibility of ASR in Norwegian shotcrete was assessed. During the period from 1975 to 1980 the Na_2O_{eq} content of Norwegian shotcrete was as high as 14.9 kg/m^3, due to high accelerator dosage (water glass), with typical values ranging from 8.2 to 12.7 kg/m^3. Alkali-aggregate reactions were studied in 19 to 44 years old shotcreted and concreted tunnels in Switzerland [7]. At the time of the construction ASR were unknown in Switzerland, hence no preventive measures were taken to avoid

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ASR. The alkali content of the shotcrete was higher than 3.3 kg/m^3, the maximum value for shotcrete with reactive aggregates [8], therefore the shotcrete was in danger of ASR. Field observations and physical properties of the shotcrete suggested that the shotcrete was intact, in spite of reactive aggregates and indications of ASR in the shotcrete.

3. ASR IN ICELAND

Serious damages were caused by alkali silica reactions in domestic houses in Iceland in the years from 1961 to 1979. During this period, preventive actions (use of pozzolan cement - non reactive aggregates) were taken for larger concrete structures. However, no such actions were taken for domestic houses since, at the time, they were not considered in any danger [9]. Icelandic Portland cement has extremely high alkali content, currently about 1.65 wt% as $Na_2O_{eq.}$ with the sodium to potassium oxide ratio of about 3:1 by weight [10]. The aggregates used in concrete are mostly volcanic, some of which are very reactive in terms of ASR. The high reactivity is mostly due to high content of rhyolitic material, altered basalt and, at that time, unwashed sea dredged material. In 1979 preventive measures were taken to fight ASR in concrete: 1) blending silica fume into cement, 2) changing the criteria on reactive materials, 3) sea dredged material must be washed, and 4) limiting the use of reactive material. Since then, there have been no serious reported cases of ASR in concrete.

In [11] 20 year experience of utilizing silica fume in concrete is described, including examples of alkali silica reactions from a silica fume cluster. The major concern was whether the silica fume lumps, which are commonly found in shotcrete, could cause silica fume reactions. Now after almost 30 years experience of using silica fume in concrete there are no evidence that silica fume lumps cause deleterious reactions in concrete structures, including shotcrete structures [5].

During the period from about 1970 to 1995, the potential risk of ASR in concrete was mainly monitored with the mortar bar test method ASTM C 227 and the quick chemical method ASTM C 289. The ASTM C 1260 test method was first used in Iceland in the Hvalfjordur Tunnel Project.

4. ASR-TESTING DURING AND PRIOR TO CONSTRUCTION

Due to the presence of geothermal area with saline water in the tunnel, strict requirements were made on the shotcrete with regards to ASR in the Hvalfjordur Tunnel project. Detailed petrographic examinations of the potential aggregates were performed and results interpreted in relation to existing ASTM C 227 and ASTM C 289 test results.

Based on initial testing it was proposed that a combination of two materials A and B would be used, subject to approval following further testing, utilizing the new ASTM C 1260 test mothod. The results of the joint testing programme are shown in Table 1 which provides a comparison of UK and Icelandic test results [1].

After testing selected prisms were subjected to detailed petrographic examination to support the assessments made from the expansion test results. No evidence of expansive reactions was detected in any of the samples.

The shotcrete was made with a mixture of aggregates A and B and Icelandic cement, containing 7.5 % silica fume (CEM II/A-M 42,5R). The cement content was about 525 kg/m^3, the water cement ratio was 0.45. The accelerator was modified sodium silicate, Kemquick 34, and the dosage was 20 l/m^3 of the accelerator [5]. The Na_2O_{eq} of the cement and the accelerator was about 1.65 and < 8.5 %, respectively.

Further to the above mentioned tests, the contract blend was tested according to the ASTM C 1260 test method, except the sodium hydroxide solutions was replaced with the natural saline geothermal water from the geothermal areas and the temperature was kept at 65 °C. Samples in sodium hydroxide solutions were tested for comparison. The results of the tests are given in Table 2.

The accelerator (modified sodium silicate) used in the shotcrete mix was also tested with the ASTM C 1260 mortar bar test method, see Table 3. The results of these tests did not indicate any deleterious reactions in conjunction with these components.

During the construction phase presumed alkali silica gel was found in new shotcrete from one of the geothermal area. The gel was present in voids, it was brownish and it did not show any signs of deleterious reactions. Due to these findings detailed petrographic examinations were carried out on the shotcrete from the geothermal area. The result did not confirm any ASR in the shotcrete.

5. CONDITION SURVEYS

The first survey of the shotcrete in the Hvalfjordur Tunnel was carried out in 2003 [2]. In this survey shotcrete from the geothermal areas was examined. The results of the survey were that alkali silica gel was found in the shotcrete where it had not been found during the construction period. The gel was normally found in voids which were not connected to any cracks in the concrete, but occasionally gel was found in cracks which could be traced to cracked aggregates.

The second survey was carried out in 2005 [3]. In general the shotcrete was found to be in good condition, the shotcrete was solid and no visual evidence was found of deleterious reactions in the concrete. In this survey representative samples from major susceptible areas in the entire tunnel were examined, see Figure 1.

Samples with surface net-cracks, the cracks penetrated into the shotcrete and often through the shotcrete. These cracks were often associated with alkali silica gel and cracked aggregates were fond connected to these cracks. Usually, the cracked aggregates were weak aggregates like sedimentary rocks, but solid basaltic aggregates were also found in connection with these cracks, see Figure 2.

The crack shown in Figure 2 originated from the host rock.

The third condition survey was carried out in 2006 [4]. This survey was carried based on the results of the 2nd survey. Shotcrete from areas with net cracks were sampled and studied under the microscope. Net cracks, similar to what is shown in Figure 1, penetrate into the concrete and can penetrate through aggregates. In Figure 3 is an example of cracked aggregates (volcanic glass). On both sides of the aggregate is alkali silica gel.

As a result of the conditions survey three types of gel were recognized in the shotcrete: gel in voids, gel in cracked aggregates and gel in relatively large cracks which penetrate far into the shotcrete.

6. COMPOSITION OF THE ALKALI SILICA GEL

Thin sections were made on cores collected in the three condition surveys in order to study the composition of the alkali silica gel. Few thin sections were selected for this study, the cover glass from the thin section was removed before the SEM study. All the analyses were recalculated to anhydrous basis and minor elements were omitted from the analysis.

Gel associated with cracked aggregate

The composition of the gel which was found in the crack shown in Figure 3 was studied with SEM. The studied area is shown in Figure 4. Area 1 is close to the basaltic glass and areas 2 and 3 are further away from the basaltic glass. The chemical composition of the gel is given in Table 4.

The composition of the gel is characterized with high calcium content and low alkali content. Sodium and potassium is only found in the gel which is next to the basaltic glass, except that sodium is present in gel found in area 3.

Gel on crack walls

Composition of a gel which was found in a crack which penetrated the entire shotcrete was studied at different depth intervals. The composition is given in Table 4.

The gel close to the surface had Ca/Si ratio of about 0.4, but no alkali metals were found in the gel. Further from the surface the Ca/Si ratio of the gel increases. At about 3 cm depth from the surface, the gel is crystallized and is mostly made up of calcium carbonate, silica is all gone from the gel. The gel close to the surface and at about 2 cm form the surface is brownish in color.

Gel in voids

The composition of gel in voids not connected to any cracks was studied. The composition of gel in two voids was analyzed, in one of the void, the gel was in contact with basaltic aggregates, see Figure 5 and in the other the gel was in contact with rhyolite, see Figure 6. The areas which were analyzed are indicated with arrows on the Figures.

The results of the analysis on the gel are given in Table 6.

The alkali content, as sodium equivalent, of the gel in contact with basaltic aggregate is about 1.7 to 2wt%. The gel which is close to the basalt aggregate is high in calcium and the gel which is far from the basalt aggregate is low in calcium, but very high in silica. The composition of the gel in contact with the rhyolite shows similar trend, the highest calcium content is highest closest to the rhyolite (#77) and lowest furthest away from the rhyolite (#80). As the calcium content of the gel decreases, the silica content increases. The alkali content of the gel as sodium equivalent ranges from 2.7-3.7 wt%.

7. DISCUSSION

During the construction phases of the tunnel great care was taken to avoid ASR in the shotcrete mix. The selected aggregates were proven innocuous with the ASTM C 1260 test method and petrographic examination. Furthermore, the selected aggregates have been used in the Reykjavik area for a long period with good experience and no reported case of ASR. The cement used contained 7.5 % silica fume. Therefore, the risk of ASR in the shotcrete was considered unlikely, regardless of the geothermal area which the tunnel encountered. In spite of all the precautions taken, ASR was observed in the shotcrete. The ASR was mainly detected as gel in voids, not connected to any cracks, but gel was also observed in cracks which penetrated aggregates.

Analysis of the gel shows that calcium content is relatively high and alkali content is relatively low. There is a distinct difference between the compositions of the gel, depending on their position within the shotcrete. Gel found in voids has relatively low Ca/Si ratio, ranging from 0.1 to 0.3 and the Ca/(Na+K) ratio is ranging between 2 to 7. Gel in cracks has higher Ca/Si ratio, ranging from about 0.4 to about 1, and the alkali content is very low.

The Ca/Si ratios are similar to ratios of ASR gel reported by [12, 13]. In [12] five types of ASR gels were recognized and [13] three types of gel were reported. Gels which were found in cracks penetrating through aggregates have low Ca/Si ratio, but other types have higher Ca/Si ratio.

A very basic model of ASR in concrete would be that the source of silica is the aggregates and the source of alkalis and calcium is the cement paste. The alkali content of gels is normally much higher in potassium than sodium, simply due to the fact that the cement contains normally more potassium than sodium. The source of alkali and silica in the shotcrete, which has been the subject of this study, does not follow this simple model. The Ca/Si ratio of the paste is highest closest to aggregates and lower further away. Furthermore, gels are frequently found in voids with no connection to any cracks. This suggests that the gels were formed in the voids when the shotcrete was relatively young. The alkali content of the gel is very low and the sodium content is always higher than the potassium content. The source of alkalis and silica is considered to be the accelerator used for the shotcrete. Cracked aggregates were found in the shotcrete, these cracks were normally a part of surface net cracks or wider cracks which originated from the host rock. The origin of the net cracks is considered to be shrinkage of the shotcrete during the early stages of the hardening phase. When these cracks formed the pore water of the shotcrete was still contaminated by the accelerator and, due to this, gels were able to form. Since the shotcrete was young, calcium was available, which the gel absorbed. The relatively high calcium content of the gel prevented the gel from causing serious damage to the shotcrete.

The Na_2O_{eq} of the cement is high and with the accelerator, the Na_2O_{eq} content of the shotcrete was about 11 kg/m^3, where about 8.7 kg/m^3 are contributed from the cement and about 2.3 kg/m^3 from the accelerator. Normally, when the $Na_2O_{eq.}$ is above 3.5 kg/m^3 in concrete, the concrete is considered to be at risk of ASR. Therefore, it is not unlikely that the major cause of the apparent ASR found in the shotcrete lies with the accelerator.

Some of the aggregates which were found cracked and associated with gel were basaltic glass (Figure 3) and basalt (Figure 2). Basaltic glass has never been related to ASR in Iceland and basalt is rarely found to be reactive. This supports the idea that the major source of silica are from the accelerator, but not the aggregates, as is the case in normal ASR process.

Condition survey of shotcrete in six other tunnles in Iceland [5] show similar findings, e.g. gel formation in voids and occational cracks with gel penetrating aggregates. The shotcrete in two of the tunnels contained possolanic cement and in four of the tunnels the shotcrete was made with silica fume cement. All these tunnles were lined with shotcrete which contained high amounts of $Na_2O_{eq.}$, the oldest structure was 22 years old at the time of the survey. Despite of the gel formation, all the structure are in good conditions and not affected by the ASR and there are no signs of delayed ASR in these structures.

8. CONCLUSIONS

Indications of ASR in a ten year old shotcrete in a sub-sea tunnel in Iceland has been found. The gel is mainly present in voids, which are not connected to any cracks, but gel is also found in cracks which penetrate through aggregates. Based on the initial tests, the shotcrete mixture was considered to be non-alkali-silica reactive, although the sodium equivalent of the mixture was very high. The source of the silica and the alkalis is considered to be the accelerator which was used.

The Ca/Si ratio of the gel is relatively high and the Si content increases towards the center of the voids, suggesting that the source of the silica is within the void, i.e. the pore water but not the aggregates. High calcium and low alkali gels have less expansion that the true ASR gels, therefore the damage due to expansion is very limited with high calcium and low alkali gels.

The fact that the gel formation took place when the shotcrete was young, causes the calcium to participate into the gel. In older concrete, this will not happen since calcium will be bound in the cement paste.

9. ACKNOWLEDGEMENTS

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TABLE 1 SUMMARY OF ASTM C-1260 EXPANSION TEST RESULTS (14 days)			
Mix Combination		Icelandic RESULTS	UK RESULTS
Aggregate	Cement	% Expansion	% Expansion
Material A	UK Lab	0.09	0.10
Material B	UK Lab	0.03	0.05
Contract Blend	UK Lab	0.07	0.08
Contract Blend	Contract	0.04	0.04

TABLE 2. TEST RESULTS FROM "ASTM C 1260" TEST METHOD TESTED WITH SALINE WATER AND NAOH SOLUTION AT 65 °C. EXPANSION, %		
Days	Saline water	NaOH - solutin
4	0.001	0.002
7	0.002	0.007
10	0.004	0.012
21	0.010	0.025
28	0.005	0.035
42	0.016	0.073
56	0.012	0.106

TABLE 3. TEST RESULTS FROM ASTM C 1260 TEST METHOD ON SHOTCRETE WITH AND WITHOUT ACCELERATOR. EXPANSION, %		
Days	Shotcrete without accelerator	Shotcrete with accelerator
5	0.022	0.035
10	0.039	0.048
14	0.060	0.071

TABLE 4. CHEMICAL COMPOSITION OF GEL SHOWN IN FIGURE 4. WEIGHT %								
	Area 1		Area 2			Area 3		
	10	11	7	8	9	12	10	14
SiO_2	59.51	53.89	60.31	42.40	62.99	67.21	51.46	62.38
Al_2O_3	5.89	5.04	4.38	7.28	5.19	4.76	5.49	4.65
CaO	32.52	38.38	35.30	43.77	31.82	28.03	39.85	32.97
Na_2O	1.65	2.68	-	-	-	-	3.20	-
K_2O	0.42	-	-	-	-	-	-	-
SO3	-	-	-	6.55	-	-	-	-
Total	100	100	100	100	100	100	100	100
Ca/Si	0.59	0.76	0.63	1.11	0.54	0.45	0.83	0.57

TABLE 5. CHEMICAL COMPOSITION OF GEL A CRACK. WEIGHT %.								
	Close to the surface		About 2 cm from the surface			About 3 cm from the surface		
	15	16	17	18	19	21	22	23
SiO_2	70.28	70.20	65.20	63.52	65.37	3.17	-	32.21
Al_2O_3	1.77	2.04	0.79	1.51	1.26	-	-	2.50
CaO	27.95	27.76	32.93	34.97	33.37	96.83	100.00	63.53
Na_2O	-	-	1.08	-	-	-	-	1.77
	100	100	100	100	100	100	100	100
Ca/Si	0.43	0.42	0.54	0.59	0.55	33		2.11

TABLE 6. CHEMICAL COMPOSITION OF GEL IN VOIDS. WEIGHT %.								
	Area 1		Area 2		Area 3			
	68	69	72	73	77	78	79	80
SiO_2	95.54	93.10	76.31	76.92	70.16	76.53	84.80	87.12
Al_2O_3	0.84	0.86	1.54	0.69	3.30	0.66	0.44	0.57
CaO	1.65	3.85	19.82	20.46	22.28	18.52	11.62	8.77
Na_2O	1.09	1.26	1.26	1.12	2.63	2.54	1.79	2.32
K_2O	0.88	0.90	1.07	0.80	1.62	1.76	1.35	1.22
Total	100	100	100	100	100	100	100	100
Ca/Si	0.02	0.04	0.28	0.28	0.34	0.26	0.15	0.11
Ca/(Na+K)	0.54	1.16	5.54	6.86	3.33	2.77	2.40	1.55

Figure 1: AAR suspect area with surface cracks. Core was taken for further examination. The card is 75×105mm, and shows the location of the core.

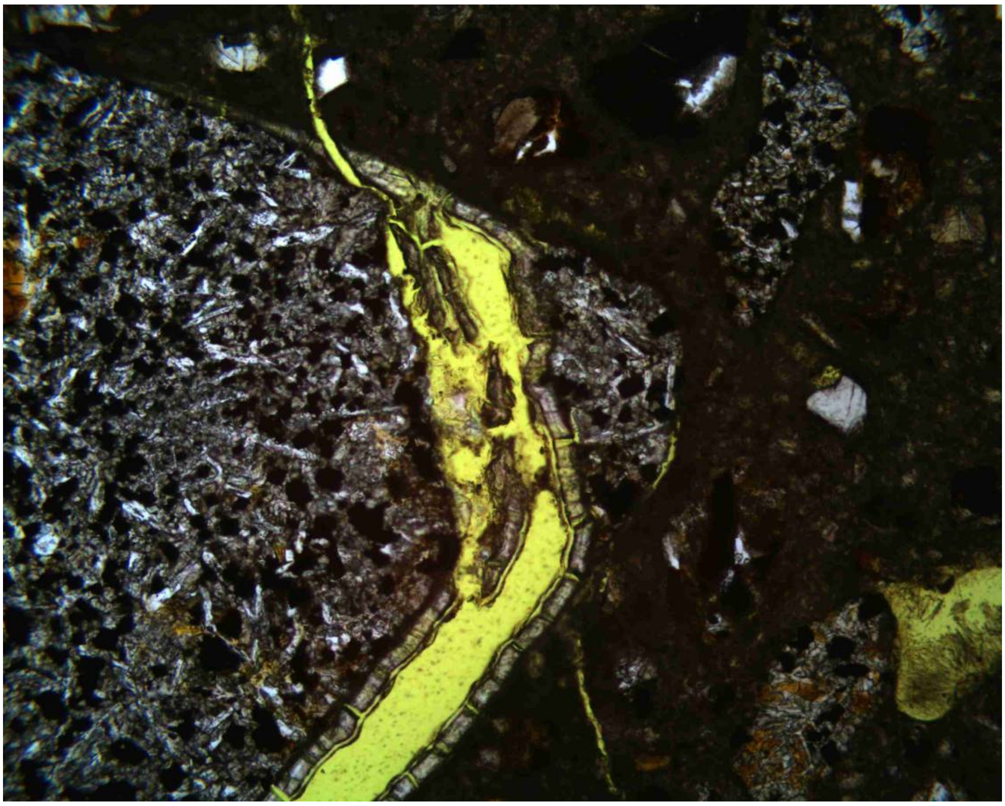

Figure 2: Photomicrograph of shotcrete showing ASR crack carrying gel in basaltic aggregate. The field of view is 1.39×0.965mm.

Figure 3. Photomicrograph of shotcrete showing ASR crack carrying gel in basaltic glass aggregate. The field of view is 1.39×0.965mm.

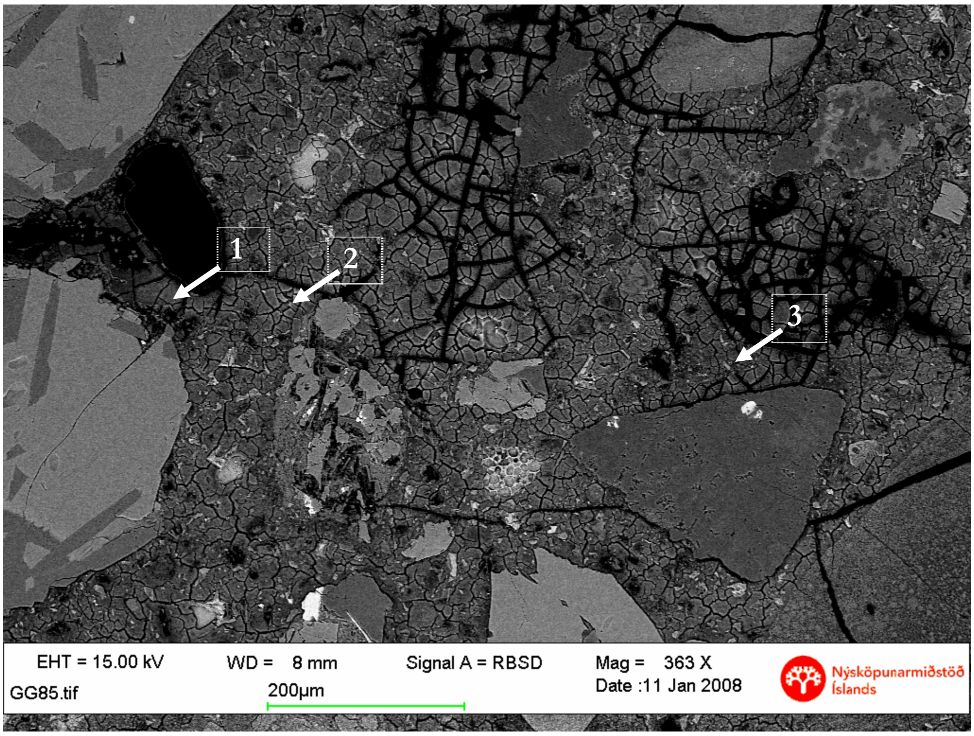

Figure 4: SEM microphotograph of alkali silica gel in shotcrete. The gel is connected to a crack. The arrows point to the areas where the composition of the gel was analyzed.

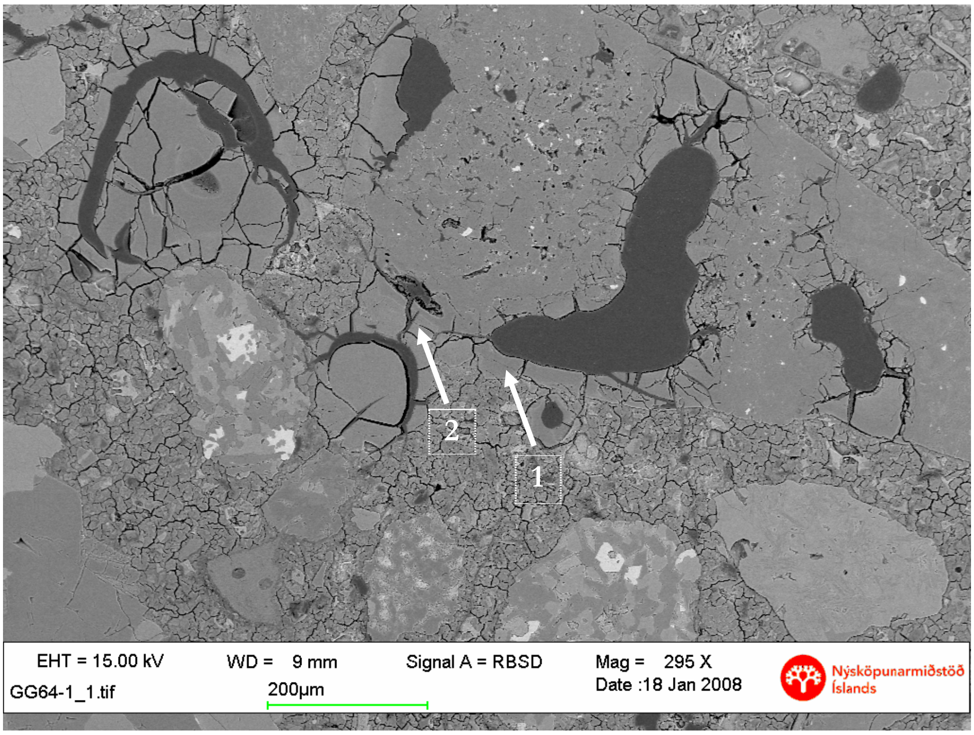

Figure 5: Alkali silica gel in a void adjacent to a basaltic aggregate. The arrows point to the areas which were analyzed.

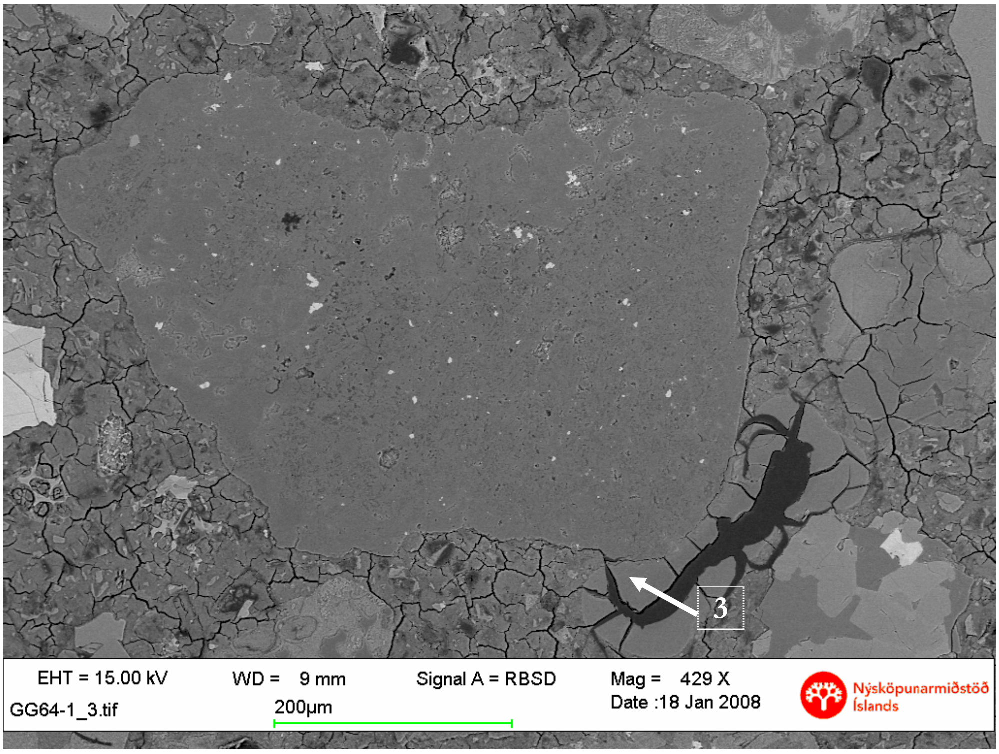

Figure 6: Alkali silica gel in void adjacent to rhyolitic aggregate. The arrow point to the area which was analyzed.