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Alkali-silica reactions and silica fume 20 years of experience in Iceland

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Abstract

In Iceland, silica fume has been blended with all Icelandic cement since 1979. Icelandic cement is unique in many ways. Common raw material for cement production is not found; therefore, less appropriate material is utilised for production. As a result, the alkali content of the cement clinker is relatively high. Because alkali-silica reactive aggregates are relatively common and favourable environmental conditions for alkali-silica reaction (ASR) prevail, ASR became a serious problem in Iceland during the 1970s. At that time research began in Iceland to look for pozzolanic material to counteract ASR reactions in Icelandic concrete. Since the opening of a ferrosilicium plant in Iceland in 1979, silica fume has been utilised as pozzolanic material in all concrete. After 20 years of service there are no signs of ASR in this concrete in Iceland. These findings are supported by scientific research, standardised alkali-silica test methods, and field observations. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Aggregate; Cement; Alkali-aggregate reaction; Silica fume; Long-term performance

1. Introduction

Silica fume has been utilised in concrete for some decades now. Initially it was used as a cement replacement material, but in recent years silica fume has been used more frequently as a solid additive (microfiller) in concrete [1]. Increased strength and improved durability are the main benefits. Incorporation of superplasticizers and silica fume offers flowable concrete with a low w/c ratio. In other words, silica fume affects concrete quality in many ways, and when properly proportioned it will greatly improve the quality of both fresh (green) and hardened concrete. Moreover, the utilisation of silica fume in concrete affects the environment in a beneficial way. Silica fume is a by-product or a waste product, mainly from ferrosilicon plants. As such, it would be disposed of, either buried or more likely dumped into the ocean. As a cement replacement material, its usage lowers cement consumption; hence, less carbon dioxide will be emitted into the atmosphere. For each ton of cement clinker produced, generally one ton of carbon dioxide is emitted into the atmosphere.

As a cement replacement material, silica fume is highly effective as a pozzolan. In Iceland, silica fume has been used for 20 years and has virtually eliminated all alkali-silica reactions (ASR) in concrete [2–12]. Before this, serious damage was caused by ASR in domestic houses in Iceland from 1961 to 1979. Preventive actions (pozzolan cement–nonreactive aggregates) were taken for larger concrete structures. No such actions were taken for houses during this period. At that time, houses were not considered in any danger [6]. Icelandic Portland cement has an extremely high alkali content, currently about 1.65 %wt as $Na_2O_{eq.}$, with a sodium to potassium oxide ratio of about 3:1 by weight [13]. The aggregates used in concrete are mostly volcanic, and some of them are very reactive in terms of ASR. The high reactivity is mostly due to a high content of rhyolitic material, altered basalt and sea dredged material that was commonly used unwashed. In 1979 four preventive measures were taken to fight ASR in concrete. These were (1) silica fume was blended into cement, (2) the criteria on reactive materials was changed, (3) sea dredged material had to be washed, and (4) the use of reactive material was limited. Since then, there have been no reported cases of ASR damage in concrete. Many condition surveys have been conducted on houses built after 1979 (for a complete list of references of theses surveys see reference [13]). In these surveys the structures are observed visually and cores are taken for laboratory inspection. No signs of ASR damage have been reported. Furthermore, all aggregates intended for concrete must be tested with the ASTM C 227 mortar bar test method. The aggregates must be tested with Icelan-

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dic ordinary Portland cement without any pozzolanic addition. If the test result shows the aggregate to be alkali-silica reactive, the test must be conducted once again but with silica fume blended cement. The ASTM C 1260 test method also can be utilised for this purpose.

Damage due to ASR in concrete was first discovered in the 1930s [14]. To avoid the use of harmful materials, the need for reliable test methods became obvious. Therefore, during this era many ASR test methods were developed that later became standardised test methods, such as the ASTM C 227 test method. Other test methods like the ultra accelerated test method ASTM C 1260, generally called the S-African test method [15], were developed in these early days of ASR testing. The aggregates used in these tests, and other similar tests, are all in sand fractions, i.e., all gravel must be crushed into sand fractions before testing. Generally it is better to test the material as it will appear in the concrete. When aggregates are crushed, some aggregates may become less expansive or vice versa. Expansion characteristics may be changed, and larger grains are likely to expand more than small grains; therefore, grinding down active aggregate could result in less expansion, which could lead to incorrect interpretation of test results. Test methods have been developed where concrete is tested for ASR, such as the RILEM test (RILEM TC-106) and the Canadian test method CSA A23.2-14AM94 Concrete Prism Test.

In this paper we will review the current status of ASR in concrete in Iceland after the utilisation of silica fume for 20 years. We will show examples of test methods, show samples of real structures, and speculate about the long-term behaviour of silica fume in concrete.

2. Standardized tests

In this research four types of cements were used:

1. Pure Icelandic Portland cement (HP), without silica fume—used in all the test methods
2. Icelandic Portland cement (VP) with 7.5% silica fume and about 3% rhyolite, both intermilled with the cement clinker—used in all the test methods
3. Icelandic Pozzolanic cement (PP), with 10% silica fume and 25% rhyolite (as a natural pozzolan), both intermilled with the cement clinker—used only in the ASTM C 1260 test method
4. Norwegian Portland cement (P30-4A), which does not contain any pozzolans—used only in the RILEM and the ASTM C 227 test methods.

The chemical composition of each cement type is listed in Table 1. All the Icelandic cement types are based on the same clinker, but various amounts of pozzolans are added to the clinker. The main difference between the Icelandic cements and the Norwegian cement is the alkali content. Pure Icelandic cement contains about 1.6% $Na_2O_{eq.}$, and the Norwegian cement contains only about 0.7% $Na_2O_{eq.}$.

Table 1
Chemical composition of the cements

	HP	VP	PP	P30-4A
SiO_2	20.8	26.2	37.8	21.2
Al_2O_3	4.8	4.7	6.7	3.7
Fe_2O_3	3.2	3.1	4.0	3.5
CaO	61.8	56.1	42.2	63.6
MgO	2.9	2.7	2.3	1.7
K_2O	0.4	0.5	0.8	0.6
Na_2O	1.4	1.4	1.9	0.4
SO_3	3	3.5	??	2.6

The aggregates were prepared for each test according to descriptions in the test methods. The aggregates used in this study came from seven different sources: Hvalfjordur, Bjorgun, Esjuberg, Vatnsskard, material S, material G, and material H.

Hvalfjordur is a sea dredged material from the Hvalfjordur area in Western Iceland. It is not used as a single source of aggregates today. Bjorgun is also a sea dredged material from the Faxafloi Area in Western Iceland; this material contains about 20% of Hvalfjordur material. Esjuberg is a combination of crushed and sea dredged material from Western Iceland. Vatnsskard is a crushed material from SW Iceland. These four materials have been thoroughly tested over the years and their field performance is well documented. Hvalfjordur material is very alkali reactive; the other three are not alkali reactive. The reactive material is both rhyolite and altered basalt [16]. Those three materials (Bjorgun, Esjuberg and Vatnsskard) are used for concrete in Reykjavik and vicinity. Material S and G have not been tested for over 20 years, but at that time these were very reactive. Material H has never been tested before.

The cement-aggregate combinations used are listed in Table 2. HP cement was tested with all the aggregates; VP cement, PH cement, and P30-4A were only tested with

Table 2
Test methods and cement-aggregate combinations

Test method	Aggregate	Cement type
ASTM C-277/RILEM	Hvalfjordur	HP, VP, P30-4A, P30-4A + added Na_2O
ASTM C 1260	Hvalfjordur	HP, VP, PP
ASTM C-227/RILEM	Bjorgun	Pure Portland cement (HP)
ASTM C 1260	Bjorgun	HP, VP, PP
ASTM C-227/RILEM	Esjuberg	Pure Portland cement (HP)
ASTM C 1260	Esjuberg	HP, VP
ASTM C-227/RILEM	Vatnsskard	Pure Portland cement (HP)
ASTM C 1260	Vatnsskard	HP, VP
ASTM C-227/RILEM	Material S	Pure Portland cement (HP)
ASTM C 1260	Material S	HP, VP
ASTM C-227/RILEM	Material G	Pure Portland cement (HP)
ASTM C 1260	Material G	HP, VP
ASTM C-227/RILEM	Material H	Pure Portland cement (HP)
ASTM C 1260	Material H	HP, VP

Table 3
RILEM concrete prism test and ASTM C 227 mortar bar test method (average % expansion)

	36 days		93 days		190 days		278 days		365 days	
	RILEM	ASTM	RILEM	ASTM	RILEM	ASTM	RILEM	ASTM	RILEM	ASTM
HP-Hvalfjordur	0.013	0.076	0.084	0.138	0.116	0.152	0.128	0.158	0.146	0.158
VP-Hvalfjordur	0.006	0.009	0.008	0.018	0.013	0.024	0.010	0.025	0.011	0.027
P30-A-Hvalfjordur	0.012	0.023	0.029	0.029	0.015	0.033	0.015	0.003	0.011	0.032
P30-A-Na_2O-Hvalfjordur	0.067	0.106	0.100	0.193	0.158	0.217	0.188	0.221	0.238	0.225
HP-Bjorgun	−0.007*	0.010	−0.005	0.016	0.026	0.021	0.004	0.021	0.015	0.022
HP-Esjuberg	−0.006	0.008	−0.006	0.012	0.006	0.019	−0.003	0.019	0.002	0.020
HP-Vatnsskard	−0.006	0.007	−0.005	0.010	0.003	0.017	0.010	0.017	0	0.017
HP-Material S	−0.002	0.006	0.002	0.010	0.019	0.014	0.010	0.014	0	0.014
HP-Material G	0.001	0.017	0.004	0.027	0.022	0.036	0.029	0.037	0.006	0.037
HP-Material H	0.007	0.047	0.063	0.148	0.180	0.167	0.190	No data	0.194	0.197

*Shrinkage is reported in negative numbers.

Hvalfjordur material. Additionally, NaOH was added to the Norwegian cement, so that its $Na_2O_{eq.}$ content was 1.25%; it was tested with the Hvalfjordur material.

The RILEM and the ASTM C 227 test methods are intended to test the potential reactivity of cement and aggregate combinations. The ASTM C 1260 test method is intended to test the potential reactivity of aggregates; it does not evaluate cement and aggregate combinations. Because the mortar bars are exposed to a relatively concentrated NaOH solution, the alkali content of the cement is considered neutral in terms of contribution to the measured expansions. Comparative length measurements were taken at days 4, 9, and 14. Selected specimens also were measured on day 28.

The same aggregate types were tested in the ASTM C 1260 test method as in the other two test methods. To evaluate the effect of pozzolans in this test method, all the aggregate types also were tested with VP cement, and two aggregate types (Hvalfjordur and Bjorgun) were tested with Icelandic pozzolanic cement.

Preparation of the raw material used in this study, casting of all of the samples, and subsequent storage and measurements were conducted according to guidelines for each test method.

3. Test results

Test results of the RILEM and the ASTM C 227 test methods are listed in Table 3. The test results from the ASTM C 1260 test method are listed in Table 4.

4. Interpretation of test results

The relationship between the RILEM and the ASTM C 227 test methods is shown in Figure 1, where the measured expansion in the ASTM test is plotted vs. the measured expansion in the RILEM test. The data for each run are sequential with respect to time. The measurements were taken at 1, 3, 6, 9, and 12 months. The expansion is much faster in the ASTM test and there is hardly any expansion after 3 months. In the RILEM test, however, the expansion is much more even over the whole period. It is interesting to note that when extra NaOH is added to the Norwegian cement (P-30+Na_2O-Hvalfj), to make the alkali content of the binder 1.25% as $Na_2O_{eq.}$, the measured expansion in both test methods is much higher than with pure Icelandic Portland cement (HP-Hvalfjordur), although the $Na_2O_{eq.}$ content of the Icelandic cement is about 1.6%. When NaOH is added to mixtures it produces more expansion than the equivalent amount of sodium in the cement clinker.

Generally the measured expansion is somewhat higher in the ASTM test, but the 12-month expansion results fall very close to the 1:1 line, suggesting a good relationship between the two test methods.

In the ASTM C 1260 standard it is suggested that if the measured expansion after 14 days is less than 0.1%, the aggregates presumably are innocuous. However, if the expansion is more than 0.2% after the same period, the aggregates are potentially deleterious. Different countries have adopted their own expansion limits. The material from Esjuberg is used frequently in Iceland and field experience with this material is very good, but this material is considered poten-

Table 4
ASTM C 1260 mortar bar test method (% expansion)

	4 days	9 days	14 days	28 days
HP-Hvalfjordur	0.26	0.42	0.49	Not measured
VP-Hvalfjordur	0.05	0.18	0.25	Not measured
PP-Hvalfjordur	0.02	0.02	0.03	Not measured
HP-Bjorgun	0.01	0.01	0.02	Not measured
VP-Bjorgun	0.03	0.03	0.03	0.04
PP-Bjorgun	0.02	0.02	0.03	0.03
HP-Esjuberg	0.04	0.10	0.17	0.28
VP-Esjuberg	0.02	0.04	0.08	Not measured
HP-Vatnsskard	0.02	0.06	0.09	Not measured
VP-Vatnsskard	0.03	0.05	0.07	0.10
HP-Material S	0.04	0.09	0.16	0.25
VP-Material S	0.03	0.05	0.09	0.17
HP-Material G	0.28	0.55	0.63	Not measured
VP-Material G	0.03	0.12	0.27	Not measured
HP-Material H	0.17	0.39	0.50	Not measured
VP-Material H	0.04	0.21	0.33	Not measured

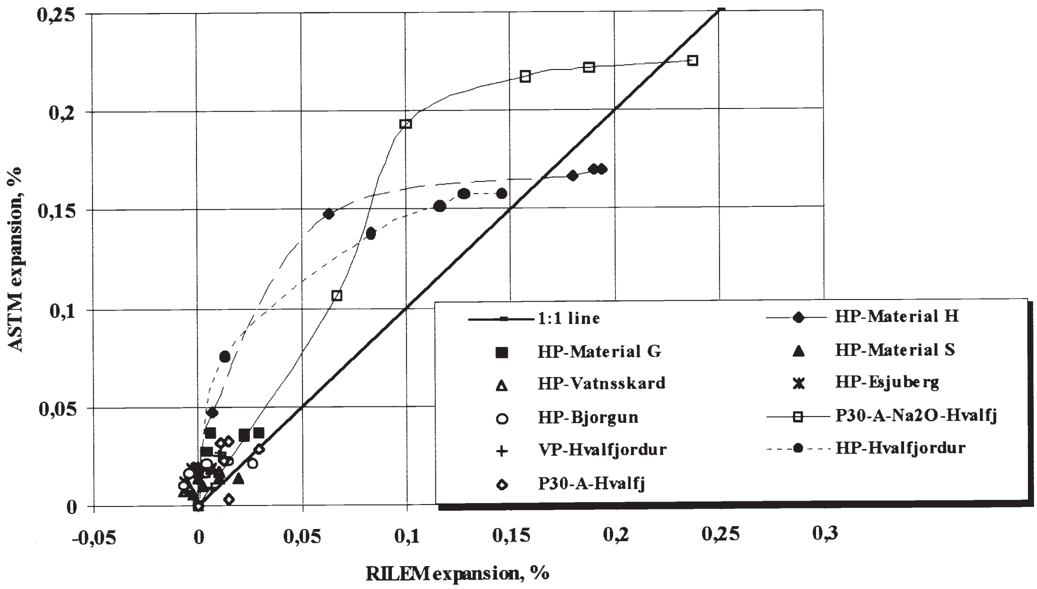

Fig. 1. Relationship between the RILEM (concrete) and ASTM (mortar) test methods. The measurements were taken at 1, 3, 6, 9, and 12 months.

tially deleterious based on the test results. The same is true for material S. We do not have as much experience with this material, but it is used today, presumably with good results. If we were to use ASTM C 1260 with these expansion limits, these materials presumably would be rejected. The material from Hvalfjordur is regarded as very alkali-silica reactive. This is based on results from the old ASTM C 227 test method and on field experience. Results of the ASTM C 1260 test method, using Hvalfjordur aggregate and Icelandic cement, with no silica fume, 7.5% silica fume, and 10% silica fume with 25% natural pozzolans, respectively, are shown in Fig. 2. It is obvious that the pozzolanic content of the cement influences the results. Therefore, when the ASTM C 1260 test method is used with pozzolan blended cement, the expansion limits must depend on the pozzolanic content. In other words, the test method evaluates combinations of aggregates and cementitious material, if the cementitious material contains pozzolans.

It is difficult to compare the RILEM results (and the ASTM C 227 data) to the results from the ASTM C 1260 test method, due to the different nature of the two test methods. These three test results are compared in Table 5. The

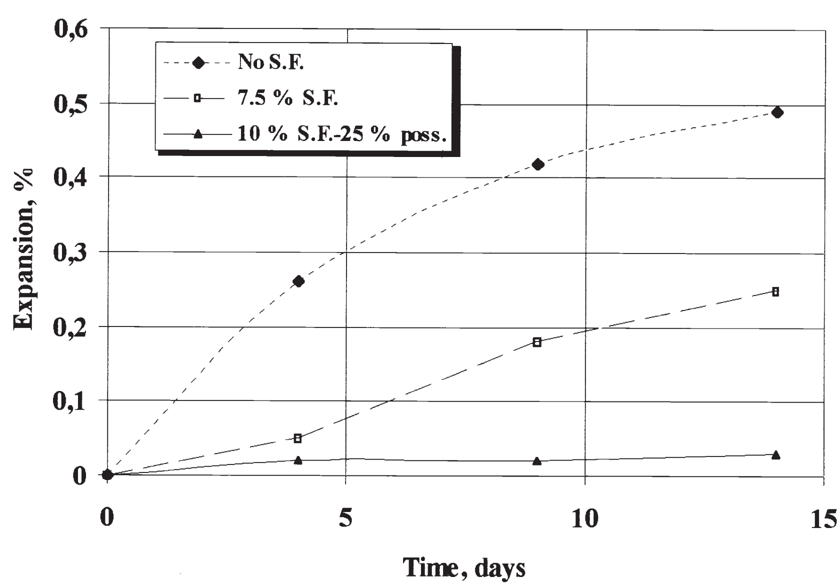

Fig. 2. ASTM C 1260 results with Hvalfjordur material and various types of Icelandic cement.

Table 5
Comparison of test results among three different test methods with the same type of cement

Cement-aggregate combination	RILEM (12 months)	ASTM C 227 (12 months)	ASTM C 1260 (14–[28] days)	Remarks (according to field evidence)
HP-Hvalfjordur	0.158	0.146	0.49	Reactive aggregates
HP-Bjorgun	0.022	0.015	0.02	Unreactive aggregates
HP-Esjuberg	0.002	0.02	0.17 – [0.28]	Unreactive aggregates
HP-Vatnsskard	0.010	0.017	0.09	Unreactive aggregates
HP-Material S	0.014	0	0.16 – [0.25]	Not known, but the material is used today
HP-Material G	0.037	0.03	0.63	Reactive aggregates
HP-Material H	0.194	0.197	0.50	Not known—not used for concrete

results from runs with pure Portland cement (without any pozzolans) and the classification of the aggregates based on field evidence are listed. The suggested limits in the ASTM C 1260 test method are given as if the measured expansion is less than 0.1% at 14 days then the material is innocuous; if it is more than 0.2% at 14 days the material is potentially deleterious. Because the measured expansions for the Esjuberg material and material S fall between these limits, this test cannot be used to estimate the reactivity of these materials. The measured expansion in the ASTM C 227 and the RILEM tests are very low and there is very good field experience with these two materials, especially the Esjuberg material. Based on this, the expansion limit in the ASTM C 1260 test has been set at 0.2% for Icelandic aggregates, i.e., if the measured expansion at 14 days is less than 0.2% with pure ordinary Portland cement (without silica fume) then aggregate is classified as innocuous.

The two test methods, RILEM and ASTM C 227, underestimate the reactivity of material G. This material has not been used for many years, because according to field evidence it was very reactive and according to the ASTM C 1260 it is still very reactive. In the case of this material, different batches were tested in ASTM C 1260 and in the other test methods. There is some doubt about the purity of the samples tested in the RILEM and ASTM C 227 test methods. However, we cannot offer any explanation for this apparent discrepancy.

5. Field observations

Since 1979 several field surveys have been conducted on concrete structures in Iceland (for a full list of references see reference [13]). In this work, houses from 1981, 1982, and 1983 were inspected. During this period, Icelandic ordinary Portland cement contained 5% silica fume. The aggregates are all from the same source and are classified as alkali-silica reactive. Measured ASTM C 227 expansion is more than 0.15% after 1 year and measured ASTM C 1260 expansion is about 0.2% after 14 days, when tested with nonsilica fume blended cement (HP cement). Cores were taken from the houses and a full petrographic examination was made on the cores to determine the presence and extent of ASR. The cores also were tested at 98% humidity and 40°C for residual alkali growth.

The concrete in all the houses can be considered in good condition after 14 to 16 years of service. In general, no visual cracks were observed on the concrete walls, except for one wall, where map cracking was detected. Some gel formation was observed in two houses. The gel formation was only found in voids and often close to rhyolitic or altered basaltic aggregates. There were no cracks observed in the samples that can be associated with the alkali-gel formation. An example of alkali-silica gel formation is shown in Fig. 3. The gel was formed in a void adjacent to rhyolitic aggregate. There is no sign of any crack formation associated with this gel formation.

A very limited alkali-gel formation is shown in Fig. 4. The gel is just a thin scale on the surface of the air void. However, it maybe that some of the gel was accidentally removed during the sample preparation, but none theless there is no crack formation in the cement paste associated with the gel.

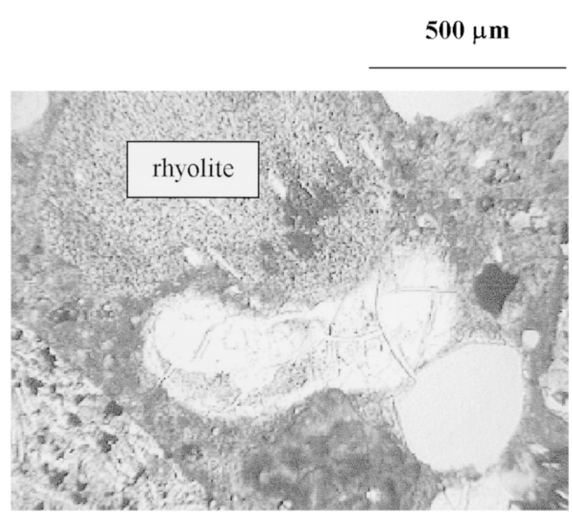

Fig. 3. Example of alkali-silica gel formation. The gel was formed in a void adjacent to rhyolitic aggregate. Thin section 2459 (magnification 100×).

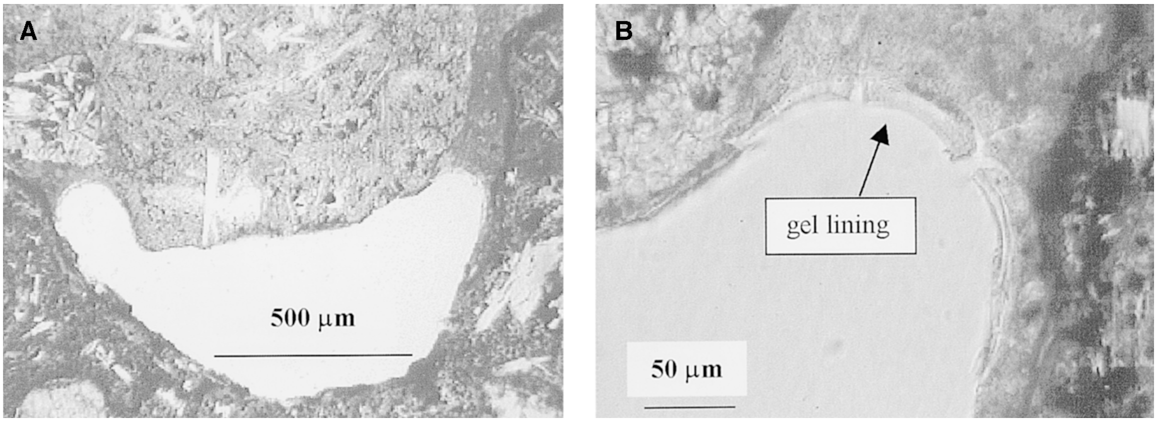

Fig. 4. Alkali-silica gel lining an air void. (a) Magnification 100×. (b) Magnification 500×.

On absorption of water the gel will swell. Swelling builds up a pressure within the gel. Where the rate of gel formation is high, the pressure buildup is rapid and eventually can break the concrete. This process of internal cracking is the initiation of damaging ASR. It is clear from Figs. 3 and 4 that the situation in theses samples is far from this stage. It is safe to say that the utilisation of silica fume has reduced the ASR in these samples; hence, the alkali-silica gel formation is very limited and not capable of producing any expansion. One does not know how the situation will develop in the years to come, whether the alkali-silica growth rate will suddenly increase or remain the same. Whatever happens, these houses underline the effectiveness of silica fume in the fight against ASR in concrete. Theses houses have only minimum ASR after 14 to 16 years of service.

Evidence from other structures and laboratory tests with the same types of aggregates suggest that these structures would have suffered serious ASR if silica fume had not been used.

In some of the samples, silica clusters could be found (Fig. 5). The total number of these clusters was low, and in some thin sections no clusters were found. In all the cases the clusters did not show any signs of ASR.

6. Silica fume lumps in cement and hardened concrete

It is a common misunderstanding in the literature that all silica fume used in mortars and concrete is a very fine powder. Recently, is has been shown that some of the silica fume is in relatively large lumps in hardened concrete [12,13,17,18]. These lumps are typically from 50 to 100 µm in diameter, but much larger lumps have been observed [19]. If the bulk density of the densified silica fume is too high, it may be difficult to disperse the silica fume in the concrete. Poorly dispersed silica fume lumps larger than 30 µm could be alkali-silica reactive [20], and obviously large number of lumps will reduce the beneficial filling role of silica fume in concrete.

Raw undensified silica fume collected from the filters at production sites consists mainly of spherical particles, smaller than 10−6 m in diameter and with a relatively low bulk density. Silica fume is either supplied as such to concrete producers, but more commonly, to gain more workability, it is compacted to a bulk density from $>$500 kg/m^3 (air-densified silica fume) to about 1000 kg/m^3 (moist-pelletised silica fume). It is common to make a liquid suspension of silica fume particles, i.e., a slurry. Usually the dry content of silica fume in slurries is about 50% by mass.

The silica fume utilised in Icelandic cement is a by-product from a ferrosilicon plant (Icelandic Alloys, Ltd.), located within 10 km from the cement plant. The silica fume is compacted at the ferrosilicon plant in two different ways. It is either compacted with air, which results in relatively small grains (up to a few millimeters in diameter), or it is pelletised with water, which results in relatively large and hard (dense) silica fume pellets. In the grinding process

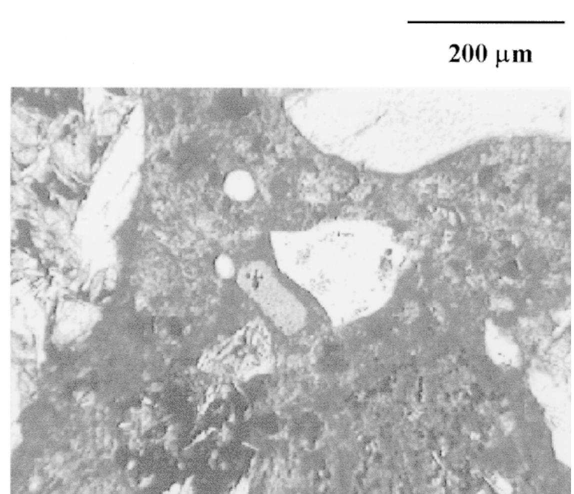

Fig. 5. Silica fume cluster in a concrete sample. The cluster, seen in the middle of the photograph, is 115 µm long and 50 µm wide (magnification 200×).

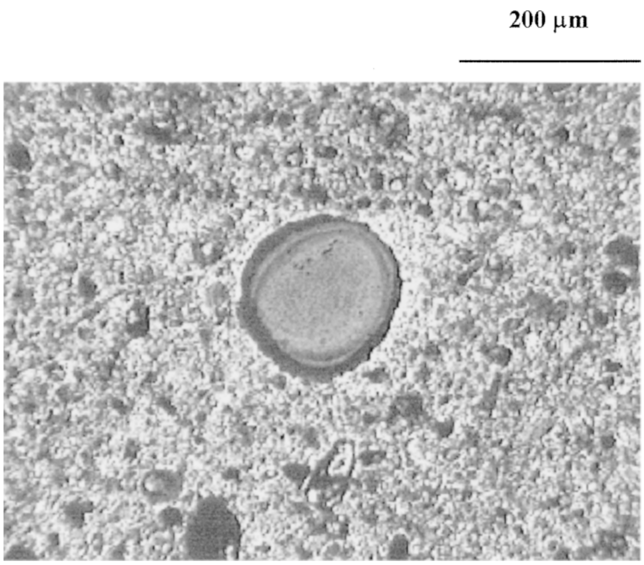

Fig. 6. Photomicrograph of silica fume cluster in an unhydrated ordinary Portland cement.

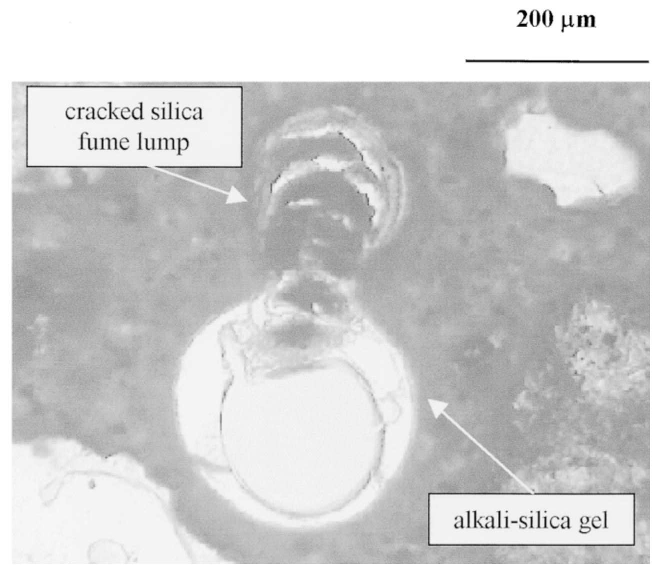

Fig. 7. Photomicrograph of silica fume lump and an alkali-silica gel in an air void.

some relatively large and dense silica fume grains manage to pass through it without being crushed down. Such cement with some of the silica fume present as relatively large lumps is shown in Fig. 6.. In this case the silica fume lump is much larger than the clinker grains; therefore, it does not have any pozzolanic activity. It must be at least 100 times smaller than the clinker to display any pozzolanic activity.

Although there is no field evidence of ASR in concrete since 1979, we have found evidence of ASR in experimental samples. These reactions involve the silica fume lumps. A mortar bar sample that was tested according to ASTM C 227 is shown in Fig. 7. The concrete contained some silica fume lumps, and during the test some of the lumps were reactive and produced alkali-silica gel. The measured expansions were 0.123%, 0.188%, and 0.245% after 6 months, 1 year, and 2 years, respectively. The expansion limits in this test method are 0.05% and 0.1% after 6 months and 1 year, respectively; therefore, this sample is very alkali-silica reactive.

In general, these lumps are far more common in "labcrete" and in rendering coats applied to concrete surfaces, i.e., in samples that are not mixed in heavy concrete production mixers, but in relatively small mixers. In "realcrete" these lumps is not nearly as common. The disappearance of the lumps in "realcrete" presumably is due to better mixing in powerful mixers and to some extent to more mechanical breakdown or grinding that takes place when relatively large gravel aggregates are present.

7. Long-term durabilty of silica fume blended concrete

The key question with regard to ASR and silica fume is whether the silica fume permanently prevents ASR in concrete or if it only delays it for some unknown period. Standardised tests such as ASTM C 227 and C 1260 show that silica fume is very effective against ASR in concrete. Furthermore, concrete structures with silica fume blended cement that were built 20 years ago do not show any sign of ASR. Based on this result it can be safely stated that utilising silica fume in this manner avoids ASR for at least 20 years. But what about the next 20 to 30 years? How will a 50-year-old concrete perform?

Most of the damage that took place in Iceland prior to 1979 occurred in relatively young structures. In 1977 to 1978, a field survey was conducted on houses built during the years from 1955 to 1972 [21]. Serious ASR damage was identified in houses as young as 6 years old. Actually, ASR was most frequent in the youngest houses. If it takes less than 6 years for ASR to take place in concrete structures, it means that by using silica fume we have delayed ASR for at least 14 years. This is very beneficial for society, because it reduces the maintenance cost greatly.

It is difficult to design tests that will predict the long-term behaviour of silica fume blended concrete with respect to ASR. The new ASTM C 1260 is a very aggressive test. If the measured expansion is, say, lower than 0.05% after 14 days of testing, it can be assumed that such concrete is not likely to produce any ASR.

To evaluate the long-term performance of silica fume blended concrete, ASTM C 227 tests were conducted over a long periods of time. The test itself is controversial and the results can be misleading, because leaching of alkalies out of the mortar bars can take place [22]. Apparently the leaching of alkalies, which reduces expansions, is only serious when the mortar bars are stored in wick-lined containers. In all ASTM C 227 tests conducted in Iceland the samples are

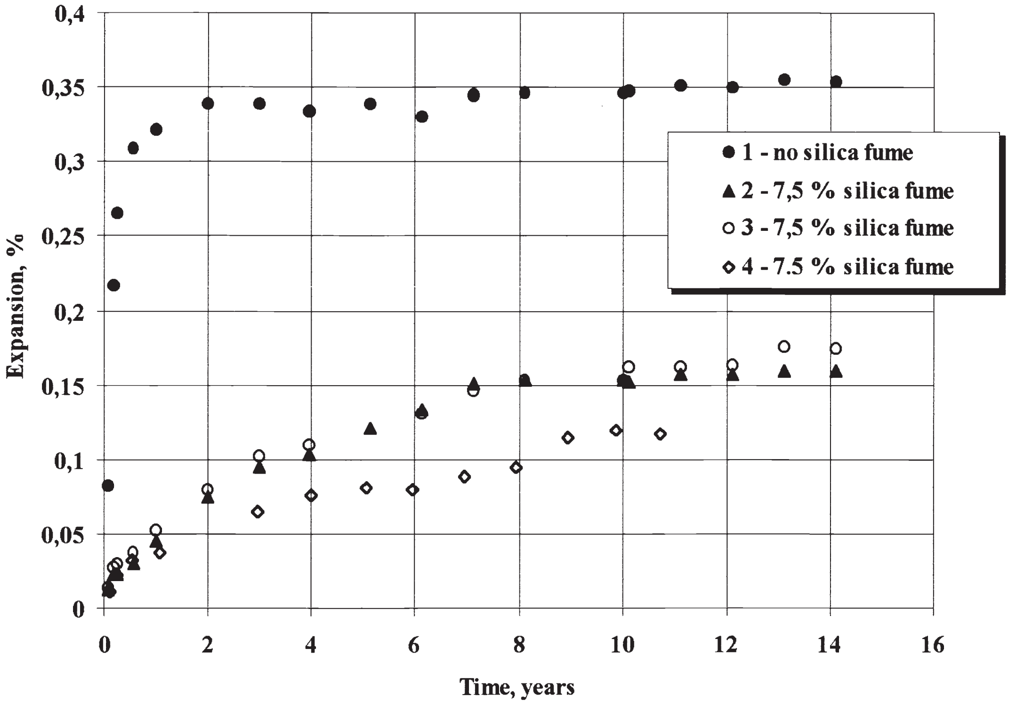

Fig. 8. Measured ASTM C 227 expansion in sample that has been tested for 11 to 14 years.

never stored in wick-lined containers. Results of four independent studies are shown in Fig. 8. In these studies the samples were tested in the ASTM C 227 test for 11 to 14 years. The source of aggregate was the same in all the runs: Hvalfjordur material. The cement type was the same in all the studies: Icelandic Portland cement. In study 1 the cement did not contain any silica fume, but in all other studies it contained 7.5% intermilled silica fume. As expected, the measured expansion was highest in the samples from study 1. The measured expansions were similar and much lower in the others studies. The expansion rate was highest during the first 2 years, then it decreased for a while. After some 4 to 6 years it seems that the expansion increased over a period of a few years, then the expansion leveled out.

The interpretation of this increased expansion after 4 to 6 years is not simple and may be controversial. One could suggest that by this time the silica fume is used up and, therefore, the silica fume only delays the ASR for some years, but does not fully prevent it.

8. Conclusions

The purpose of utilising silica fume in Icelandic cement was to reduce or eliminate the risk of damaging ASR in concrete. The experience after 20 years shows this main goal has been achieved. Many condition surveys have shown that in no case can damaged concrete be traced to ASR.

The homogeneity of silica fume in cement is not always as good as expected, because small lumps of silica fume are found in hardened concrete. There is some concern that these lumps may reduce the beneficial effect silica fume has against ASR in concrete. The alkali content of Icelandic cement is very high and the climate in Iceland is favourable for ASR (high humidity and many freeze/thaw cycles, which may promote ASR). Therefore, the risk of ASR is always imminent. However, 20 years of experience have proven silica fume very useful in the fight against ASR in concrete.

There is no doubt that the utilisation of silica fume is the major factor in the reduction of ASR damage in concrete in Iceland, as demonstrated here. But one must bear in mind that in 1979, when silica fume was added, two other important but often forgotten factors were implemented: sea dredged material was washed and use of reactive material was limited. These two factors are very important in relations to ASR in concrete, but when compared to the effect of silica fume one would tend to call theses two factors secondary in relation to ASR.

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