SILICA FUME IN CONCRETE - 16 YEARS OF EXPERIENCE IN IÇELAND

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ABSTRACT

During the period 1961 - 1979 AAR caused serious damages to concrete structures (mostly to housing) in Iceland. In 1979 several actions were taken to prevent AAR damages in future constructions. Probably the most important one was using silica fume (SF) as a partial replacement in all Icelandic OPC and RPC as these cement types are used in over 95 % of all concrete houses. The SF is, with small exceptions, inter grounded with the cement clinker for better homogeneity. Approximately every third year a condition survey is carried out on houses in order to investigate if any AAR damages still occur. The latest and the most extensive survey, carried out in 1993, studied houses from the period 1977 - 1991. For the first time (in Iceland) a microscope was utilised in the study.

In this paper results from these investigations are presented. Assessment of the general quality of concrete in this period is made. Furthermore the homogeneity of the concrete and the distribution of SF is discussed and related to the way it is blended into the cement. AAR expansion of up to 12 years old mortar bar prisms according to ASTM C 227 are shown. Finally, a comparisons between ASTM C 227 and the recommended RILEM Concrete prism method are made in this paper.

INTRODUCTION

Serious damages were caused by AAR in concrete structures in Iceland in the years from 1961 to 1979. Preventive actions (possolan cement - non reactive aggregates) were taken for larger concrete structures. For house construction no actions were taken during this period, since these structures were not considered in any danger, partially due to low moisture content (Gudmundsson & Asgeirsson 1983). Icelandic Portland cement has a extremely high alkali content, currently about 1,65 % wt. as Na_2O eq., with the ratio of sodium to potassium oxide about 3:1 by weight (Gudmundsson 1995). The aggregates utilised in concrete are mostly volcanic in origin and some of which are very reactive with respect to AAR. The high reactivity of the aggregates is due to relatively high content of rhyolitic (acidic) material, altered basalt and the fact that some of the material is sea dredged and unwashed. In 1979 preventive measures were taken against AAR in concrete, those were: 1) blending silica fume (SF) into cement, 2) changing the criteria on reactive materials, 3) sea dredged material must be washed, and 4) use of reactive material was limited.

Tests on SF as a counteraction to deleterious AAR in concrete were first conducted in Iceland in 1972 (Gudmundsson 1975, Gudmundsson & Asgeirsson 1975). Since then the effect of SF on various properties of concrete has been studied (Gudmundsson & Asgeirsson 1979, Olafsson 1982, Olafsson & Helgason 1983, Asgeirsson et al. 1985, Asgeirsson 1986, Olafsson 1989, Wallevik 1990, Olafsson 1992, Gudmundsson & Moller 1992). In July 1979 the use of SF in commercial concrete started and has been used in almost all ordinary concrete ever since. Research had shown that a relatively small amount of SF was sufficient to suppress AAR expansions effectively in concrete with reactive Icelandic aggregates (Gudmundsson 1975, Gudmundsson & Asgeirsson 1975). Thus 7,5 % as cement replacement has been used since 1983, but before 5 % was used, due to some technical and practical problems in the cement production. By using so limited amount most of the undesired side effects such as increased water requirement, drying shrinkage etc. are mostly avoided. Instead of mixing SF into the concrete it was mixed with the cement itself, mostly by inter grinding it with the cement clinker. By doing it this way one reasoned that the homogeneity of the cement and the concrete as well was secured.

Annual freeze/thaw cycles in Iceland are relatively many, more so in the southern part (including the Metropolitan area) than elsewhere. Therefore, shifts from driving rain (near horizontal) to freezing conditions can take place within few hours. Due to these harsh climatic conditions a theory has been put forward that AAR damages in Icelandic concrete is not solely due to chemical reactions, but more to interactions between chemical reactions and freeze/thaw actions (Kristjansson 1985, Olafsson 1989).

The dominant laboratory method for assessment of the reactivity of aggregates used in Iceland has been the well known ASTM C 227 mortar bar method. This method has given indications of reactivity that seem to coincide with practical experience. The criteria set in 1979 for housing concrete was expansion under 0,1 % after 12 months.

CONDITION SURVEY

The preventive actions taken in 1979 have been followed up by condition surveys in order to investigate their effectiveness (Kristjansson et al. 1979). The methodology in carrying these surveys out has changed a little with time. The first ones were based on visual inspection, but in houses where map cracking was observed, cores were taken for laboratory inspection. In 1984 additional cores were taken from houses built in the period 1979 - 1983. The cores were initially inspected for AAR and again after 12 months storage at 100 % RH and 38 °C. In 1986 a similar survey was carried out on cores from houses build in 1984 and 1985, but this time the cores were reacted for 3 months in the AAR reactor. In 1993 an extensive study was made on concrete houses built in the years 1976 - 1990 (Sveinsdottir & Gudmundsson 1993). For each year approximately 15 houses were picked randomly and cores drilled from all of them. The cores were inspected for the first time by use of microscopy and thin sections. The purpose was to evaluate the quality of concrete in exterior walls of houses, like the AAR, w/c-ratio, air entrainment and SF distribution.

Table 1. Frequency of AAR damages in exterior walls of houses in Reykjavík from 1972-1982, survey 1983.

Year	Number of houses	Frequency of damaged houses (%) None	Small	Considerable	Severe	Comments
1972-1973	60	15	45	35	5	
1974-1975	58	23	59	10	0	
1976-1977	61	48	48	4	0	
1978-1979	60	54	43[1)]	3[1)]	0	[1)]from 1978
1980-1981	56	91	9[1)]	0	0	
1982	8	100	0	0	0	

Table 1 shows the results of the survey carried out in 1983. As can be seen the frequency of considerable to severe AAR was up to 40 % of the houses built in 1972 - 1973, but decreases to 3 % in houses from 1976 and 1977, and after 1979 AAR can not be found.

In table 2 the result from the last survey is shown. A gelatinous reaction product was found in voids and cracks in 8 out of 16 houses from 1977 and in 6 out of 15 houses from 1978. After 1979 no gel was found in any samples, with the exception of 1981 where some gel was observed in few isolated voids. On the other hand some silica fume clusters were observed, somewhat contrary to expectations. These lumps are of similar amount each year. No trace of AAR were observed around these clusters.

Table 2. Alkali gel and silica fume clusters in concrete, survey 1993

Year cast	Number o f houses	Alkali gel no. of houses	Clusters of silica fume (no/mm^2*10^{-2})	Comments
1977	16	8	0	
1978	15	6	0	
1981	16	2 1)	13	1) trace
1983	15	0	10	
1985	16	0	10	
1988	13	0	11	
1990	16	0	11	

On figure 1 is shown a typical silica fume cluster in hardened concrete. Silica fume clusters are also relatively common in laboratory sample like mortar bars or similar samples made with relatively small mixers. Identical findings have been reported by (Lagerblad & Utkin 1995).

Figure 1. Photomicrograph of silica fume cluster in concrete, 200 x magnification.

DISTRIBUTION OF SILICA FUME IN HARDENED CONCRETE

The SF utilised in Icelandic cement is a by-product from the production of iron-silicon alloys, located within 10 km from the cement plant. Initially the SF powder is relatively lightweight, with a bulk density of about 0,24 g/cm^3. To be used in the cement production, it's density must exceed 0,6 g/cm^3. Therefore, the SF is compacted at the ferrosilicon plant. It is either compacted with air, which results in a relatively small **grains** (up to few mm in diameter); or it is palletised with water, which results in relatively large and hard SF **pellets.** Upon grinding the cement clinker, the SF is inter ground with the clinker. The pellets are added to the mill with the clinker, but the grains are added to the cement after the mill. Then the cement is "sieved" in a centrifugal sieve, the portion that is fully ground, passes through the sieve, but the remaining portion is sent back to the mill for regrinding. The layout of the grinding process is shown in figure 2 (Gudmundsson 1995).

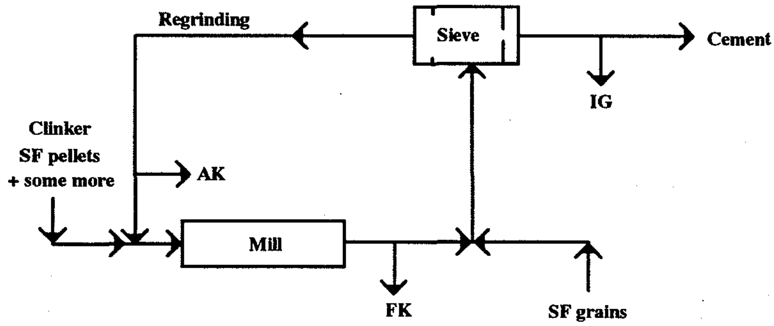

Figure 2. Schematics of the grinding process and location of sample sites and sample numbers.

In order to investigate the origin of silica fume clusters in hardened concrete, as shown on figure 1, few grinding experiments were carried out at the cement plant (Gudmundsson 1995). In the experiments the ratio of SF grains to SF pellets was varied. Samples were taken from the grinding process, location of the sites and the sample numbers are shown on figure 2.

The morphology of SF grains/pellets in these cement samples was measured. In the study only grains larger than 30 μm in diameter were considered. On figure 3 is shown the length of the grains vs. the width/length ratio (average of about 60 measurements). The SF in the AK samples are distinctly different in shape, being relatively large and round, while the SF in FK and IG samples are relatively small and more elongated.

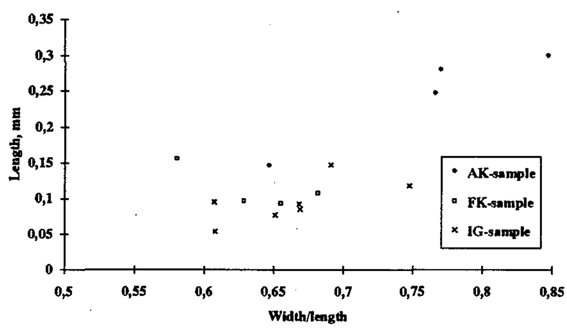

Figure 3. Morphology of SF in cement samples

The bulk composition of these samples was determined and the result of the chemical analysis was used to calculate the SF content in the cement samples. The result of the calculations is shown in figure 4.

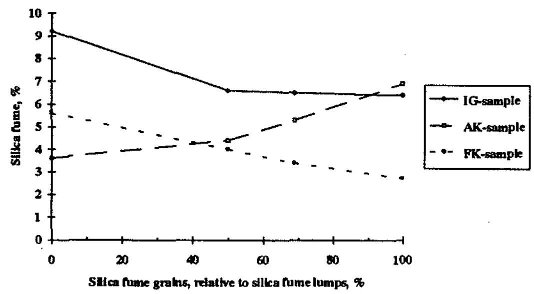

Figure 4. Calculated amount of SF in cement samples

On figure 4 is shown how the calculated % of SF varies as a function of the grain to lump ratio. The SF content of the rejects (sample AK) is proportional to the grain to lump ratio, the higher the SF grain content, the higher is the SF content. This suggest that the SF grains are too large when they are added to the mixture, and most of it is rejected by the centrifugal sieve. We therefore, suggest that the SF grains should be added to the mill with the SF pellets and the clinker, in order to avoid any danger of it passing through the sieve by an accident, which we fear is the common cause for SF clusters observed in hardened concrete.

EXPANSION OF MORTAR BARS - CONCRETE PRISMS

As mentioned earlier research on the effect of SF on alkali aggregate expansion started in 1972. The test method was mostly ASTM C 227 mortar bar method. Most of the research has been done at IBRI with Icelandic material. In 1980 some tests were made with Pyrex glass and three types of cement with Na_2O eq. from 0,86 - 1,39 at NBS (now NIST) in Gaithersburg, USA.

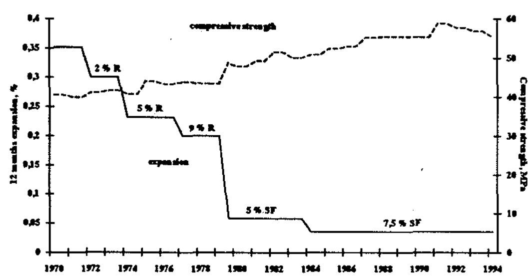

Figure 5. Average AAR expansion and compressive strength in Icelandic OPC. Modified and updated from Asgeirsson 1990. R = Rhyolitic glass, SF = silica fume

In figure 5 the development of Icelandic OPC with regard to AAR expansions and compressive strength can be seen, mostly as a result of the use of pozzolan (rhyolitic glass and silica fume). Research at IBRI has shown that the measured expansion when SF is used not only decreases substantially but is also to some degree delayed. Now we have 12 years old mortar bars that have been measured annually. These samples were made with OPC with no SF, with OPC with 7,5 % SF intermilled with the cement (ENV 197-1 CEM II/A-M 42,5) and OPC with 7,5 % SF added to the cement during mixing. The aggregate source is the same in all the samples, from Hvalfjordur, which has proven to be very reactive. The results are given in table 3 and figure 6. As expected the measured expansion is highest with OPC, but similar in the two SF blended cements. Even though the measured expansion for the SF blended cements, after 12 months, is only 50 % of the allowed limit, the one year allowed limit is reached after 4 years and increase slowly every year. After 12 years the measured expansion is about 60 % over the one year allowed limit. The consequences of these slow expansions are unclear and may not be a cause of any danger.

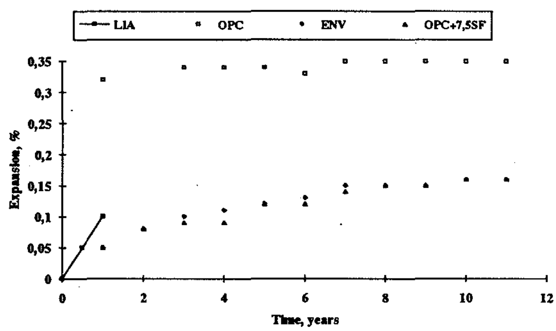

Figure 6. Measured expansion of various types of Portland cements, see the text for discussions. The solid line represents the limits set by Icelandic authorities (LIA).

As earlier mentioned has the ASTM mortar bar method given results that are in a good coherence with practical experience in Iceland. At the moment (1995) comparison measurements are under way between this method and the concrete prism method recommended by RILEM TC 106. First results indicate good coherence but final results will be presented at the conference.

Table 3. Expansion of mortar bars (%), ASTM C 227

Cement type	Year of casting	Expansion by years										
		1	2	3	4	5	6	7	8	9	10	11
ENV	1983	0,05	0,08	0,10	0,11	0,12	0,13	0,15	0,15	0,15	0,16	0,16
OPC+7,5 SF	1983	0,05	0,08	0,09	0,09	0,12	0,12	0,14	0,15	0,15	0,16	0,16
OPC	1983	0,32		0,34	0,34	0,34	0,33	0,35	0,35	0,35	0,35	0,35

CONCLUSIONS

The original purpose of utilising SF in Icelandic cement was to reduce or eliminate the risk for damaging AAR in concrete. After 16 years of experience this report shows that this main goal has been achieved. Through various conditions surveys it has been shown that in no case damage can be trace to AAR after 1979 when silica fume was first utilised. As expected, considering the limited amount of silica fume used, a trace of AAR gel is found in few samples.

The homogeneity of silica fume in the cement was not as good as expected since small clusters of SF is found in hardened concrete. Grinding experiments at the Cement factory indicate that the reason for this is that a part of the SF compacted with air is not as effectively inter ground with the clinker as the palletised part of the SF. Even though this does not have any harmful effect on the concrete, it is bound to reduce the efficiency of the SF replacement.

Criteria for aggregate reactivity based on mortar bars or concrete prisms methods may need to take into account that SF partial replacement prolongs the expansion, as well as reducing it. However, the actual effects of the prolonged expansion is not fully understood.

In summary one can state after 16 years of experience of SF in Iceland that one has been able to solve the AAR problem in an effective and economical way by utilising SF as a partial cement replacement. In the process the general quality of Icelandic cement and concrete has been improved.

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