INFLUENCE OF ASR EXPANSION ON THE FROST RESISTANCE OF CONCRETE

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ABSTRACT

Results are presented of water absorption and freeze-thaw tests carried out on laboratory concretes casted with and without a deleterious amount of reactive aggregates and a high alkali cement. A petrographic study including thin section study, SEM-EDAX analysis and image analysis was carried out on both laboratory and field concretes. Prior to the freeze-thaw and water absorption tests the laboratory concrete specimens have been stored in a 100% humidity room for three and a half years. During this time the concrete which contained reactive material developed ASR expansion and cracking. The concretes were prepared with two different dosages of an air-entrainment agent and with two different W/C ratios (0.40 and 0.55). For the concretes which developed cracks due to ASR expansion, it is shown that the frost resistance is significantly decreased. This is more pronounced for the specimens with the lower W/C ratio and air-void content. For these specimens it is also shown that the level where the concrete reaches a critical water saturation is decreased when it is affected by ASR. It was also found that the expansion caused by frost action during freeze-thaw testing is directly proportional to the initial crack widths caused by ASR.

A microscope analysis showed that frost action induces cement deterioation. This is brought by microcracking followed by leaching of calcium hydroxide and sulphates from cement components. The dissolution and leaching is caused by water movements during recurrent cycles of freezing and thawing which eventually leads to the breakdown of cement gel components. The dissolved constituents precipitate in cracks and air voids as secondary products such as portlandite and ettringite/monosulphate. In the microscope it is observed that microcracks filled with portlandite radiate out from air voids which indicate expansion of water in air voids during freezing.

A petrographic examination of core samples from field structures which showed cracking due to both ASR and frost attack was carried out. Crack pattern, cement deterioation and alteration products were the same for field and laboratory concretes. Cracks caused by ASR can be distinguished from cracks caused by frost attack. Geometry, spacing and crack widths are different.

INTRODUCTION

ASR may influence the frost resistance of concretes in several ways. ASR cause internal cracks which emanate at the concrete surface . If the cracks are left open and then water filled freezing may induce such a pressure that the deterioration of concrete increases in comparison with uncracked concrete. Concrete members with exposed horizontal surfaces are especially potentially susceptible to frost attack.

Another effect of ASR is that it produces gel which can fill the air-voids and result in a reduced amount of active air-voids and an increasing spacing factor. ASR-gel can also densify the cement paste structure which results in a decreased capillary pore volume and thus a decrease in the permeability to displaced water caused by freezing. This may change the conditions for water migration which in turn will reduce the frost resistance.

This investigation includes studies on laboratory samples as well as petrography of field concrete in case objects. Water absorption/desorption test and freeze-thaw testing on primarily air-entrained concrete was made. Prior to the testing, some of the specimens had developed cracks due to ASR.

INVESTIGATION

Laboratory investigation

Cube samples with the side 150 mm were cast with reactive aggregates and a high alkali cement. The samples were stored at 20 °C and 100 % relative humidity. After three and a half years storage the samples had developed cracks due to ASR and were subjected to water absorption and freeze-thaw tests and microscope analysis.

The reactive component in the aggregate phase was flint and the cement used was Slite Std portland cement with an alkali content of 1.2 weight % Na_2O equivalent. Reference samples were prepared with a non-deleterious aggregate. The concrete mixes had an alkali content of 4.6 kg/m^3 and an aggregate content of about 1700 kg/m^3. The size range of the aggregates was 0-8 mm. The aggregates can be considered as non-porous with a water absorption value below 1 %. Two different dosages of an air-entrainment agent were used in order to reach a moderate (4.6 vol. %) and a high (7.5 vol. %) air content in the hardened concrete. The water - cement ratios were 0.40 and 0.55. *Table 1* show the concretes subjected to water absorption and freeze-thaw tests.

Table 1

Batch no.	Sample	W/C ratio	Crack width (mm)	Air void content (vol.%)	Power's spacing factor (mm)
1	Flint 1	0.40	0.1-0.2	4.60	0.255
1	Flint 2	0.40	0.1	4.65	0.250
1	Flint 3	0.40	0.2-0.3	4.62	0.257
1	Flint 4	0.40	0.4-0.8	4.55	0.260
1	Ref. 1	0.40	no cracks	5.0	0.235
1	Ref. 2	0.40	no cracks	5.10	0.230
2	Flint 5	0.55	0.5-0.7	7.72	0.200
2	Flint 6	0.55	0.2	7.69	0.200
2	Flint 7	0.55	0.6-1.0	7.65	0.210
2	Ref. 3	0.55	no cracks	7.95	0.190
2	Ref. 4	0.55	no cracks	7.90	0.195
2	Ref. 5	0.55	no cracks	8.0	0.190

Investigation of bridge structures

Two railway bridges in central Sweden were selected as case studies. The bridges were erected in 1940 and 1962. The climate in the region is normally rather wet summers with long cold winters with many freeze-thaw cycles. The aggregates from the region are dominated by slowly reacting metevolcanic rocks.

The structures showed surface-parallel cracking with spalling and leaching of calcium hydroxide superimposed on a map cracking pattern conspicuous for ASR. This was predominantly observed on sidebeams and sidewings. The surface-parallel cracks develop in sequential stages, progressing from the horizontal surface and the edge of a concrete member to the vertical face. This leads eventually to disintegration of the cement paste and spalling of the concrete cover down to the reinforcement. This type of cracking and spalling of the concrete is confined to the most exposed parts of the structure such as sidebeams and horizontal parts of sidewings where the concrete has reached a critical degree of water saturation.

Reinforcement corrosion does not seem to start until the cover is completey lost. In some cases it was observed that the rebar was unaffected by corrosion even if the conrete was laminated by cracks down to the level of the reinforcement. This could be due to the high water saturation which is indicated by the limited carbonation in the cover. Carbonation is predominantly confined to areas close to cracks.

The cracks which are attributed to a map cracking pattern conspicuous for ASR measured about 0.3 mm in the bridge from 1940 and 0.5-1.0 mm in the bridge from 1962.

RESULTS

Water absorption and freeze-thaw tests of laboratory concretes

The volume of pores filled by capillary action as % of specimen volume and the degree of capillary saturation (S,cap) was measured in accordance with a method developed by Fagerlund (1977) for RILEM Committee 4 CDC. Before the water absorption test started, the samples were dried until constant weight was recorded.

The diagrams in *Fig. 1* (batch 1) show that the total pore volume is reduced in samples damaged by ASR leading to a smaller total water uptake in kg/m^3. In *Fig. 2* (batch 1) it is also shown that the ASR damaged samples reached a higher degree of capillary saturation than the reference samples. The fact that the degree of capillary saturation is higher at the same time as the total water uptake in kg/m^3 is decreased compared to ASR unaffected samples indicates that the structure has been densified by ASR and that the pore volume has been reduced. The degree of capillary saturation (S,cap) was calculated from the values obtained by the water absorption test. In the microscope it was observed that the amount of coarse capillary pores and small air pores have been gel-filled.

The freeze-thaw test was done in accordance with Swedish standard SS 13 72 44, with the exception that the nunber of freeze-thaw cycles was increased. A rubber insulation was put on all sides of the sample, except the upper horizontal side which was covered by 1-2 mm thick film of <u>pure</u> water. The same specimens were used as in the water absorption test, but they were dried before the freeze-thaw test. Metal studs were applied on oppsite sides and perpendicular to the freezing surface. The expansion was measured regularly during the freeze-thaw testing.

During the freeze-thaw test the samples absorbed water which made it possible to determine the degree of capillary saturation periodically with an interval of approximately 20 freeze-thaw cycles. This was done by measuring the weight of the samples and relating the amount of water absorbed to the corresponding degree of capillary saturation which was obtained earlier from the water absorption test. Pure water was added regularly in order to keep a 1-2 mm thick waterfilm on the top surface. At the same time expansion measurements perpendicular to the freezing surface were carried out. This made it possible to determine the critical degree of capillary saturation (S,cap,crit.). The critical degree of saturation is defined as the degree of saturation when the samples started to expand due to internal damage caused by ice formation.

The diagrams in *Fig. 3* and *Fig. 4* show the critical degree of capillary saturation for the samples in batch 1. The ASR damaged samples showed a decreased critical degree of capillary saturation compared to the reference samples. The amount of damage (expansion) is also increasing with increasing crack width. The critical degree of saturation for ASR damaged samples was reached at 15-30 freeze-thaw cycles and at a capillary degree of saturation of 60-80%, depending on the crack width. At the same time the reference samples did not show any sign of internal damage at a degree of capillary saturation of 95 % and more than 200 freeze-thaw cycles.

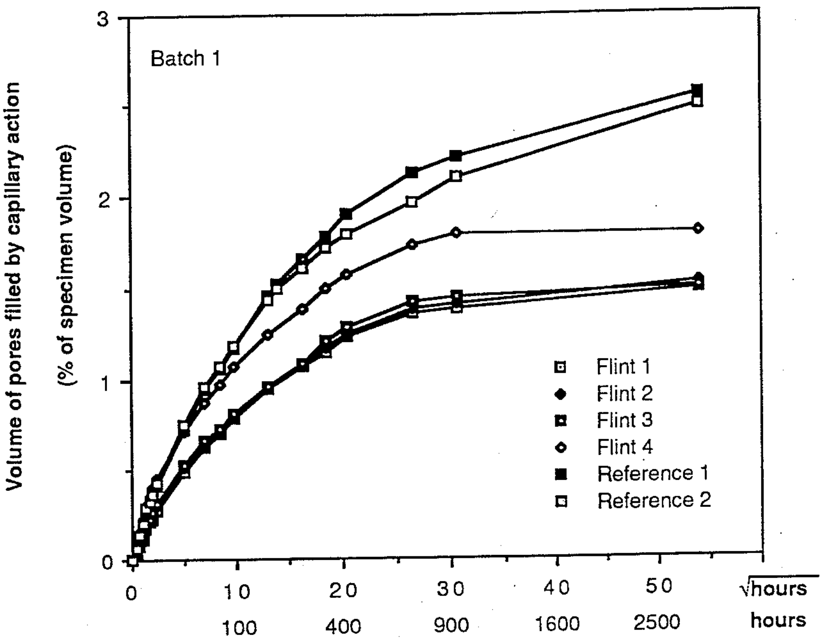

Fig. 1. Water absorption test of samples in batch 1. ASR damaged samples (Flint 1-4) show a smaller volume of pores filled by water absorption than the reference samnples (% of specimen volume). W/C ratio 0.40.

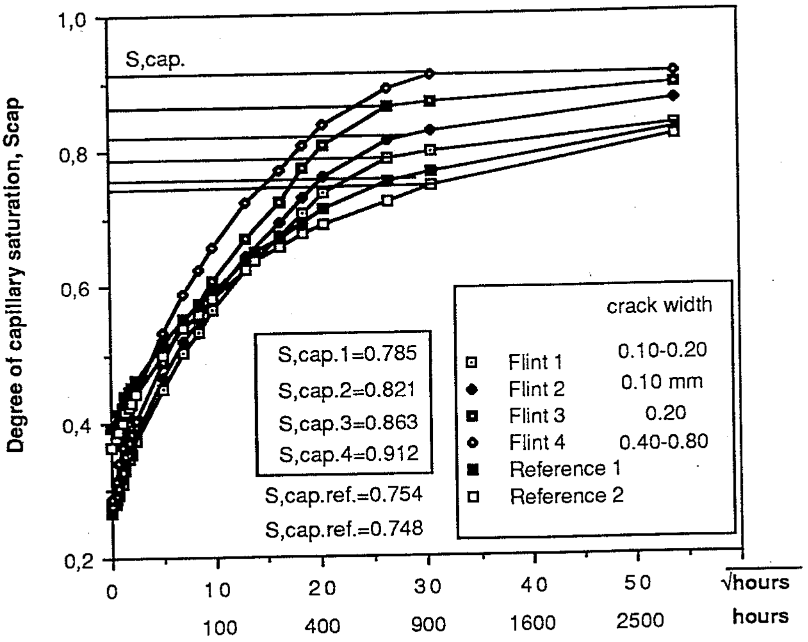

Fig. 2. Diagram showing the capillary degree of saturation (S,cap) for samples in batch 1. The ASR damaged samples show a higher degree of water saturation than the reference samples.

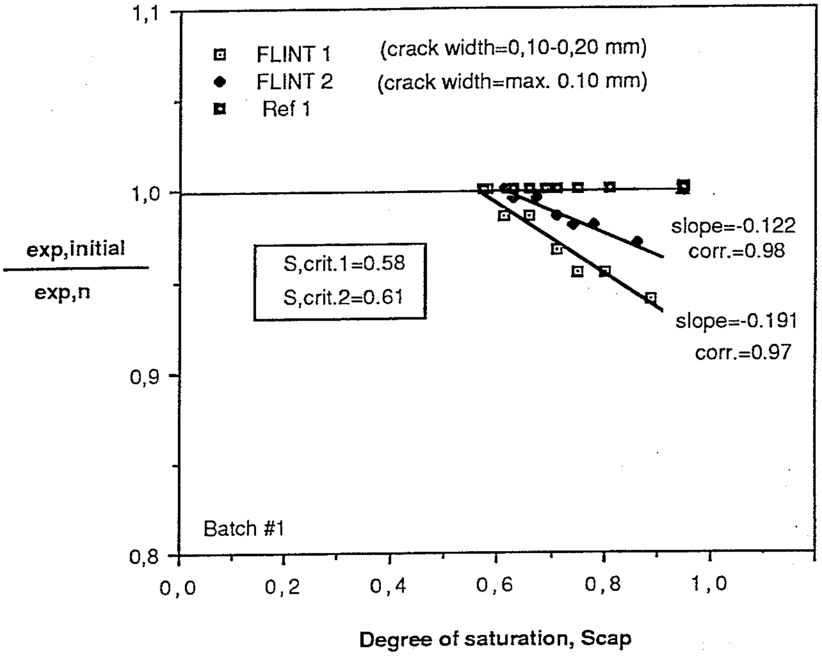

Fig. 3. Diagram showing the critical degree of saturation (S,crit.) from freeze-thaw testing of samples in batch 1. The amount of expansion and the expansion rate (steepness of curves) is increasing with increasing crack width.

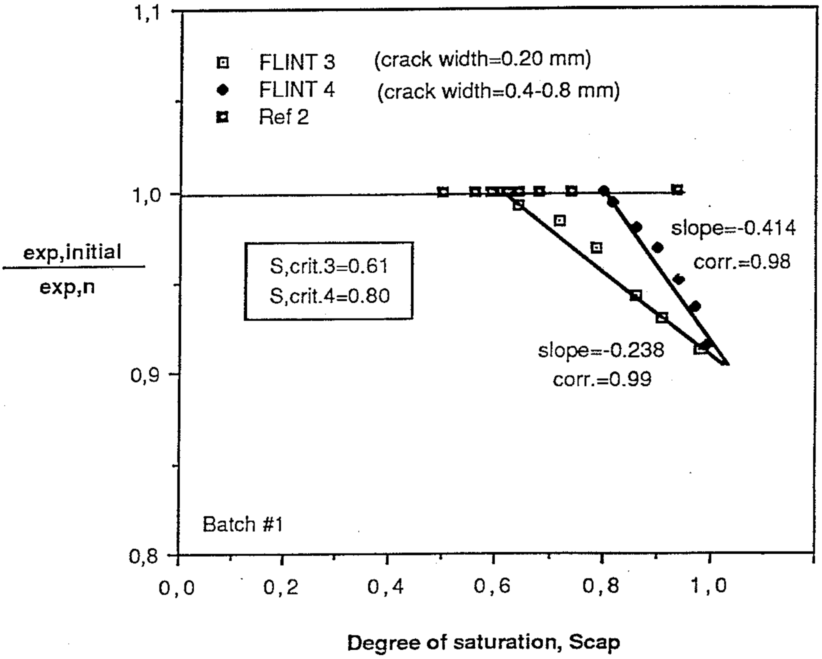

Fig. 4. Same as *Fig. 3.*

Petrography of laboratory concretes

The cement paste structure in the ASR damaged samples show alteration due to freezing and thawing. Wide ASR-induced cracks are open and empty to depths of about 40-50 mm from the surface. The cement paste around these vertical cracks is recrystallized and attains a "grainy" texture due to portlandite crystallization. The crack walls are carbonated. Below 40-50 mm the cracks contain gel fragments surrounded by ettringite needles. The ettringite formation indicate moist migration along the cracks. At even greater depths the crack thins out and is filled with massive deposits of finely crystalline, brownish grey ettringite with a core of gel. When the cracks can be followed into a reactive aggregate particle they are often filled with massive ASR-gel.

From the surface and down to depths about 20-30 mm, a network of microcracks radiating out from air voids exist. This is also observed at much greater depths around the ASR-induced cracks which can be followed from the surface. Both air voids and microcracks are often completely filled with portlandite and ettringite. The interpretation is that these microcracks have been caused by frost action when water filled air voids expanded. It seems that migrating water in concrete subjected to feezing and thawing can dissolve and precipitate calcium hydroxide more efficiently than water migration under normal temperature conditions. The temperature controls whether calcium hydroxide is dissolved or precipitated and frost action leads to increased water movements in the cement paste. The increased amount of secondary portlandite in frost damaged concrete can thus be explained by the fact that the solubility of calcium hydroxide is about 2.5 g/l higher in pure water at temperatures around zero than at 20 °C.

Apart from recrystallization of calcium hydroxide, recurrent freezing and thawing which induces water migration in cracks and capillary pores, also increase the rate of crystallization of secondary ettringite in air voids. The air voids often show an outer shell of dense portlandite and a core of ettringite. Air voids up to about 0.2 mm are often completly filled, while larger air voids only have a coating on the wall leaving most of the air void empty. If the wall coating consists of dense portlandite the air voids can still be considered as inactive. At greater depths the air voids are commonly filled with ASR gel instead of portlandite and ettringite. The radiating microcracks from air voids are interconnected to a fine network pattern which join ASR-induced cracks.

The above observations indicate that ASR cracking opens the concrete structure and can make the concrete more susceptible to frost attack if the cement paste is near saturated state and if the cracks become water filled.

Petrography of field concretes

After examination of thin sections from core samples from the structures, evidence for both frost attack and ASR was observed. The core samples were drilled perpendicular to the horizontal surface on sidewings and sidebeams. *Fig. 5* shows a sketch of the crack pattern from a petrographic examination of a core sample. The microscope examination revealed three types of cracks in the upper 30-40 mm. The wide vertical cracks emanating at the surface contain carbonated gel remnants on the crack walls which make it probable that these cracks are related to ASR cracking. The vertical cracks are intersected by a set of fairly straight and wide horizontal cracks which laminates the upper part of the concrete. The third type of cracks form a network of microcracks radiating out from air voids resembling a map cracking pattern. The radiating microcracks are related to the expansion of air voids which indicate that the air voids have been water filled during freezing.

The horizontal cracks partially contain portlandite and ettringite and the microcracks and smaller air voids (< 0.3 mm) are completely filled with portlandite and ettringite. At deeper levels ASR related cracks dominate and cracks as well as air voids are patially or completely filled with gel and secondary ettringite.

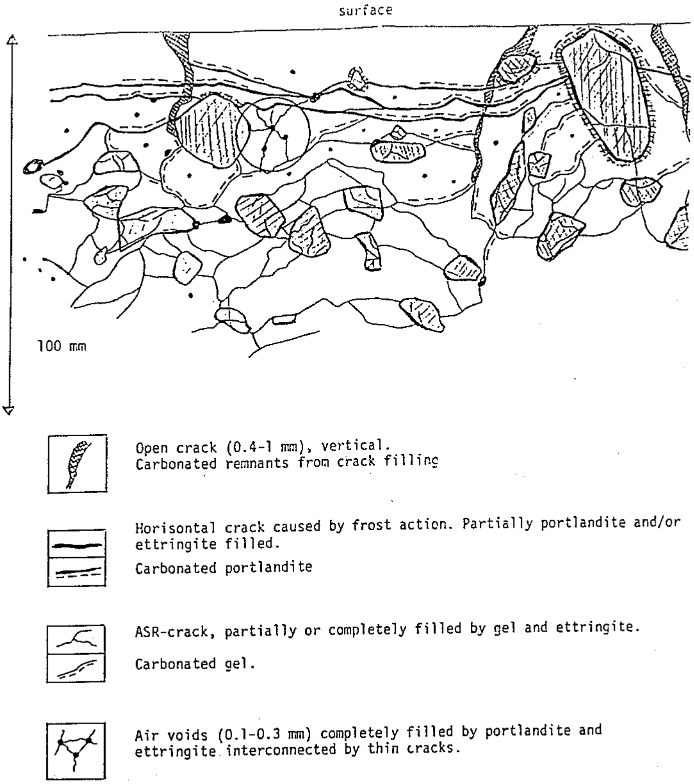

Fig. 5. Sketch showing the crack pattern in a drill core from one of the bridge structures. The core was drilled perpendicular to the horizontal surface on a sidebeam. In the upper part the wide ASR-induced vertical cracks are overprinted by horizontal cracks caused by frost action. The framed area (circule) symbolize radiating cracks from ettringite and portlandite filled air voids. Shaded aggregates = reactive aggregates.

Water absorption of field concrete

A water absorption test was carried out on ASR cracked and uncracked core samples from one of the structures. The test showed that the ASR affected concrete absorbed less water in kg/m^3 than the unaffected concrete. However, the rate and the degree of water saturation was higher for the ASR affected concrete than for the unaffected concrete. This is in agreement with the results from the water absorption test with the laboratory samples.

CONCLUSIONS

The results from water absorption tests, freeze-thaw tests and microscope analysis of field and laboratory concretes indicate that cracking due to ASR can significantly decrease the frost resistance. It should be pointed out that the concrete must reach a critical degree of saturation (S=S,crit.). Factors which have an influence on the critical degree of saturation are: cracks which provide easy accsess of water into the concrete, amount of active air voids in the size range of about 0.030-0.80 mm, spacing factor and the geometry and structure of the capillary pore system (W/C ratio). Frost attack is most likely to occur in concrete members which have exposed horizontal surfaces or if the concrete is exposed to a constant moisture load.

From the laboratory tests it can be concluded that compared with uncracked concretes the ASR-cracked concretes show a decreased critical degree of saturation at the same W/C ratio. It can also be concluded that ASR-cracked concretes show a decreased volume of coarse capillary pores and small air voids filled by water. At the same time the level of water saturation is higher in ASR affected concretes. This indicates that the cement paste structure has been densified by ASR. It is also shown that the degree of capillary water saturation is higher for samples with the larger crack widths. Especially crack widths wider than about 0.3 mm result in a high degree of capillary water saturation.

The amount of expansion, which can be regarded as a measure of the internal stress forces built up in the concrete, was found to be proportional to crack widths. This is true for W/C ratios about 0.40, air void contents of about 5 % and a spacing factor of about 0.23 mm. In concretes with higher W/C ratios (0.55) and air void contents (about 7 %) the effect of crack widths on expansion seemed to diminish.

From the petrographic examination of field and laboratory concretes it is shown that not only ASR-gel fills and inactivates the air voids, but also secondary alteration products caused by water movements during freezing and thawing fill the air voids. Such secondary products are portlandite and ettringite. The secondary products indicate leaching of components in the cement paste during freezing and thawing. This will eventually lead to decomposition of the cement paste.

The investigation show that if ASR-induced cracking is present in a structure the rate and the susceptibility to frost attack can increase. This aspect of synergism must be considered when ASR is identified in a structure. Even if ASR itself will not destroy the structure it can induce frost damage which will lower the residual service life of the structure. The frost damage will lead to scaling and reduction of the concrete cover which eventually will cause corrosion of the reinforcement. It is important to consider the detailing of the structure as the freezing will occur in concrete details with poor drainage.

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