

**INFLUENCES ON THE ALKALI-AGGREGATE REACTION  
UNDER FIELD CONDITIONS**

**Jürgen Dahms  
Forschungsinstitut der Zementindustrie  
Düsseldorf**

### Introduction

Up to 1965 the generally held view in Germany was that there was in this country no alkali-aggregate reaction causing severe damage to concrete. Although in a few instances alkali-aggregate reaction was considered as a possible cause of cracking and scaling on concrete constructions in north Germany, this was done more in view of relevant findings in the neighbouring country of Denmark. Usually the deterioration was mostly seen as the result of other causes, such as frost action and excessively high stress due to shrinkage or temperature. This until then widely accepted view about a possible deleterious alkali-aggregate reaction changed when in 1968 near Lübeck a bridge had to be pulled down, because its stability could no longer be guaranteed. In 1974 a further bridge was for the same reason closed to traffic and replaced by a new one. After 1968 there were more frequent reports about cases of concrete deterioration due to alkali-aggregate reaction in north Germany, and even trivial damage resulting from all kinds of causes was often attributed to deleterious alkali-aggregate reaction. This is hardly surprising, since damage due to alkali-aggregate reaction can easily be confused with damage which has in fact been caused by frost or other expansive reactions.

To get some idea of the possible risk alkali-aggregate reaction may constitute to concrete constructions in Germany, extensive tests were performed. Because of the complex nature of the alkali-aggregate reaction and the numerous influential factors, a great number of aspects had to be considered, such as the influence of type, quantity and grain size of the aggregate as well as that of the alkali content. This involved short-time tests on normally small specimens under severe conditions. S. Sprung already reported on some of these tests at the last symposium at Reykjavik. But short-time and simplified tests alone do not yield sufficiently reliable information if it has not first been established whether these findings can safely be applied to the behaviour of corresponding concrete units. It was with this in mind that over the last 8 years extensive concrete tests and investigations into the behaviour of construc-

tions have been carried out at our institute.

The research into the behaviour of constructions was necessary because concrete tests in laboratories naturally do not cover all practical construction factors, such as concrete production under field conditions, the influence of the dimensions of the building units, loading and stress conditions of the reinforcement and design details.

The concrete tests I am going to speak about were compared with the structural behaviour of concrete constructions which had been erected in north Germany several years - in some cases even decades - previously and for which aggregate of this area had been used. The publication by Bonzel and Dahms on alkali-aggregate reaction in concrete [1], of which you all received a copy, is mainly concerned with these studies.

#### Concrete Tests, Composition, Storage

The composition of the concretes was such that in addition to concretes of different strength and density also the direct influence of the concrete composition, such as differences in the effective alkali content of the concrete as well as quantity and size range of the alkali-reactive aggregates, could be investigated. We therefore used for the testing concretes with equal cement content and different water-cement ratio as well as those with equal effective alkali content, but different  $\text{Na}_2\text{O}$ -equivalent of cement and relevant cement content. The water-cement ratio ranged from 0.40 to 0.70, the cement content from 300 to 600  $\text{kg/m}^3$ .

The primary storage conditions were storage in the open, that is exposure to the normal weather conditions, wet storage at 40 °C and 100 % relative humidity (fog-chamber) and dry storage at 20 °C and 65 % relative humidity. To study in addition the influence of the dimensions of the specimens, concrete beams measuring 10 cm x 10 cm x 50 cm and 10 cm and 30 cm sized cubes were made for the various tests.

As evidences of deterioration we registered gel precipitation, efflorescence, scaling and cracking on cubes and beams and differently large longitudinal expansions of beams stored in the fog-chamber. Especially when studying parameters, about which little is known, the assessment of the alkali-aggregate reaction solely on the basis of expansions, as one frequently finds in the literature, is not sufficient. The dimensions too may affect the deterioration. For example, no expansions or only very small ones could be found on beams and yet the 30 cm sized cubes showed quite substantial cracks and precipitations of alkali silicate gel. We therefore used - as table 1 illustrates - for the assessment of the degree of deterioration a classification of five stages, whereby 0 for instance means no expansions and cracks and 3 some bigger cracks, which would also in practice be described as more severe damage. Group 5 covers very severe cracking and expansions over 3 mm/m. For each of the three types of storage the most unfavourable deterioration degree was determined.

TABLE 1: Assessment of Damage

Degree of damage	Damage to beams or cubes stored in the open or in the fog-chamber	Expansions in mm/m of beams stored in the fog-chamber <sup>†)</sup>
0	no cracks	up to 0.3
1	some isolated fine cracks	0.3 to 0.5
2	several fine cracks	0.5 to 0.8
3	some bigger cracks (with a width over 0.2 mm), also some fine cracks	0.8 to 1.5
4	several bigger and fine cracks	1.5 to 3
5	very severe cracking on all surfaces	>3

<sup>†)</sup> including an expansion of approximately 0.2 mm/m due to a temperature increase from 20 to 40 °C

## Test Results

### a) Influence of Moisture

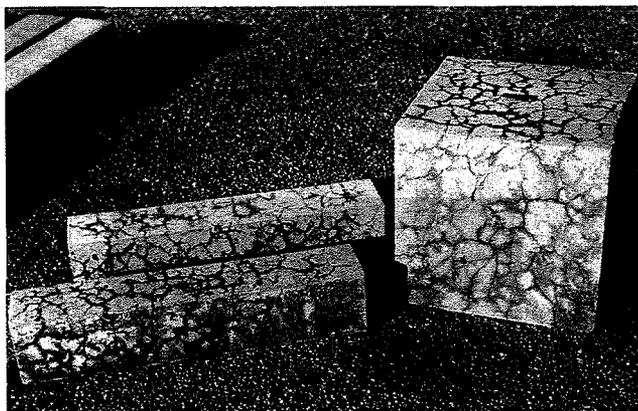
When concretes of an unfavourable composition were tested which over several years had been exposed to different storage conditions, first evidences of a deleterious alkali-aggregate reaction could be found during storage in the fog-chamber and at temperatures of 40 °C two to four weeks after the start of the wet storage. As time passed this damage increased to reach its climax at concrete ages of 6 months to one year at the latest (Fig. 1).



Deleterious alkali-aggregate reaction on a 30 cm sized cube stored in the fog-chamber (damage degree 5)

FIG. 1

With a storage in the open, that is an unrestricted exposure to the weather, the damage on similarly composed concretes reached the same extent, only a little later (Fig. 2). These results are in line with findings on constructions in north Germany as regards their environmental conditions.



Deleterious alkali-aggregate reaction on beams and 30 cm sized cubes stored in the open (degree 5)

FIG. 2

To find out in how far the inherent moisture of massive concrete constructions even in dry surroundings is responsible for the occurrence of a deleterious alkali-aggregate reaction, specimens were immediately on demoulding wrapped in foil. After three months they were unwrapped and the deterioration seen in Fig. 3 became apparent, consisting mainly of damage to the surface in the form of precipitations and a few fine cracks. It must therefore be concluded that in massive constructions the inherent moisture may suffice to cause a certain amount of damage. This problem needs to be studied further.

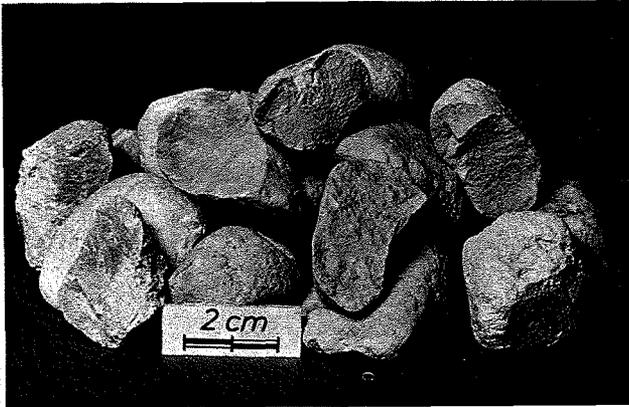
b) Influence of the Aggregate and the Granulometric Composition  
In north Germany occurs as alkali-reactive aggregate opaline



Deleterious alkali-aggregate reaction on a 30 cm sized cube which has immediately on demoulding been wrapped in foil

FIG. 3

sandstone (Fig. 4) and to a lesser extent reactive flint. As a consequence of various tests we today assess the alkali-reactivity of concrete aggregate on the basis of its contents of opaline sandstone and reactive flint (see also recommendations). As table 2 shows it is distinguished between "safe", "conditionally useful" and "critical" aggregates.



Opaline sandstone

FIG. 4

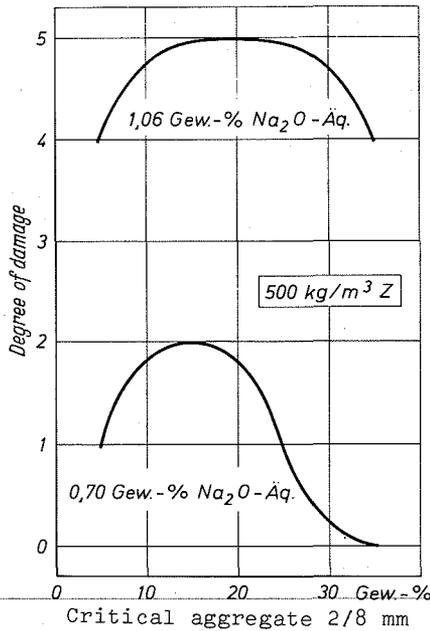
TABLE 2: Assessment of Aggregate with alkali-reactive Constituents

Constituents	Limit values in % by weight for the reactivity groups		
	safe	conditionally useful	critical
opaline sandstone + other opal-containing rocks <sup>1)</sup> over 1 mm	<0.5	0.5 to 2.0	> 2.0
reactive flint over 4 mm	<3.0	3.0 to 10.0	>10.0
5 x (opaline sandstone + other opal-containing rocks) + reactive flint	< 4.0	4.0 to 15.0	>15.0

<sup>1)</sup> including reactive flint 1 to 4 mm

If the aggregates contained as critical constituents opaline sandstone, it was under adverse conditions possible to produce damage, no matter whether size range 0/32 mm or only size range 4/32 mm consisted of critical aggregate. But under otherwise equal conditions the highest degree of damage was reached when size range 2/8 mm contained critical aggregate and the remaining aggregate was made up of useful material.

The content of the alkali-reactive aggregate in the size range 2/8 mm was also found to be of considerable significance. In Fig. 5 the degree of the damage to the concrete due to alkali-aggregate reaction has been plotted versus the amount of the alkali-reactive aggregate in the size range 2/8 mm. The highest degree of damage was mostly reached for the concrete with approximately 15 to 25 % by weight of alkali-reactive aggregate in the size range 2/8 mm, based on the total amount of aggregate.



Degree of damage to concrete due to alkali-aggregate reaction versus the amount of the alkali-reactive aggregate in the size range 2/8 mm

FIG. 5

With a few further tests we also studied the performance of a similar concrete which contained no alkali-reactive aggregate of the size range 2/8 mm, that means only the remaining aggregate up to 32 mm was alkali-reactive. Here we merely obtained damage up to degree 2 instead of degree 5 when the size range 2/8 mm consisted of alkali-reactive aggregate.

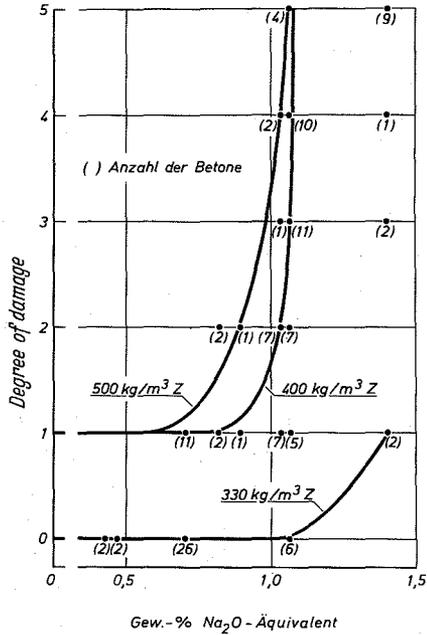
#### c) Influence of the Cement and the Cement Content

The effective alkali content in the concrete results from the effective alkali content of the cement and the cement content per  $m^3$  concrete. Although both factors may determine the total alkali content in the concrete, they cannot be evaluated exactly in the same way. The cement content also affects the properties of the concrete, such as strength, density, texture and deformation behaviour. The alkali content of the cement, on the other hand, hardly changes these concrete characteristics at all. So far our tests have shown that for both parameters there is a certain threshold value, above which damage may occur and that the influence of the alkali content of the cement is of somewhat greater importance than that of the cement content. Fig. 6 demonstrates this behaviour for concrete with a water-cement ratio of 0.45. Only alkali contents over 0.9 led to a more marked deterioration, that is damage exceeding degree 2. At the same time, the cement content was in these cases always at least  $400 \text{ kg}/m^3$ , with higher water-cement ratios at least  $350 \text{ kg}/m^3$ .

Some preliminary tests (Fig. 7) on concretes of cements with  $\text{Na}_2\text{O}$ -equivalents of over 1 and of cement contents slightly under  $400 \text{ kg}/m^3$  produced damage above degree 2 when the water-cement ratio exceeded 0.55. But these initial tests are to be followed up by further investigations.

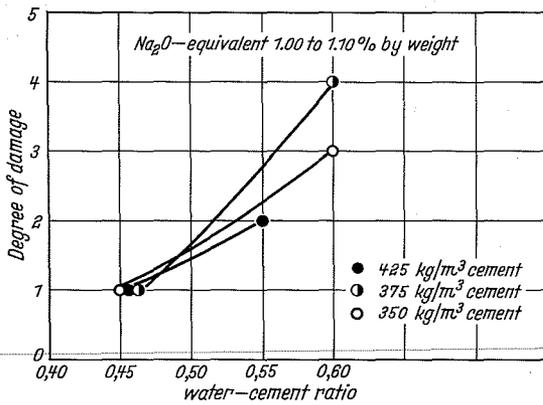
#### Conclusions

On the basis of the tests carried out at our institute and the investigations into the behaviour of concrete constructions the following can be said: A deleterious alkali-aggregate reaction could only be found on concretes of an unfavourable composition when the specimens had been subjected to wet storage or on



Degree of damage to concrete due to alkali-aggregate reaction versus the effective alkali-content of the concrete

FIG. 6



Influence of the water-cement ratio on alkali-aggregate reaction

FIG. 7

concrete constructions in wet environmental conditions. However, tests on concrete samples whose drying process had been inhibited also showed that in massive constructions the moisture inherent in the concrete is sufficient to cause deleterious alkali-aggregate reaction.

The degree of damage was mainly dependent on the composition of the total aggregate. As especially unfavourable were those which contained very alkali-reactive aggregate in an amount of approximately 15 to 25 % by weight of the total aggregate in the size range 2/8 mm.

Marked deterioration occurred on wet stored concrete specimens with very alkali-reactive aggregate ("critical") when the cement content in the case of a cement with an effective alkali content of approximately 0.90 % by weight  $\text{Na}_2\text{O}$ -equivalent was  $500 \text{ kg/m}^3$  and in the case of a cement with an effective alkali content of approximately 1 % by weight  $\text{Na}_2\text{O}$ -equivalent  $400 \text{ kg/m}^3$ . In general, the damage increased with higher water-cement ratios.

When the deterioration as a result of alkali-aggregate reaction was assessed, it became clear that this damage on concrete constructions can easily be confused with damage due to other causes. For the study of unknown aspects of the alkali-aggregate reaction it is not enough to measure the expansions of the specimens when their behaviour is to be investigated, it is in fact also necessary to consider the deterioration on other specimens, for instance 30 cm sized cubes.

On the basis of the present state of knowledge the precautionary measures set out in table 3 were recommended in Germany as being on the safe side.

TABLE 3: Precautionary Measures against deleterious Alkali-Aggregate Reaction in Concrete

Alkali-reactivity of the aggregate	Environmental conditions		
	dry	wet	wet + alkali supply from outside
safe	none	none	none
conditionally useful	none	low-alkali cement <sup>1)</sup>	low-alkali cement
critical	none	low-alkali cement	exchange of aggregate <sup>2)</sup>

- 1) only with concrete of the strength classes Bn 350 and higher
- 2) only with concrete of the strength classes Bn 350 and higher, otherwise low-alkali cement

References

1. J. Bonzel and J. Dahms, beton 23, 495 and 547 (1973).

CONTRIBUTIONS TO DISCUSSION

Dr. D. Hirche

I wish to comment on the statement of B. Mather and Dolor-Mantuani<sup>a</sup> "the reactive part of flint is the  $\text{CaCO}_3$  -  $\text{SiO}_2$  impurity in flint or the leached  $\text{CaCO}_3$ ":

- 1) There are no reactive parts in the flint. IR spectroscopy of fine grains shows that flint has very large numbers of silica groups like opal or pyrex glass. This is because of the high proportion of lattice defects all over the flint grains. We shall suggest that alkalies can react with the whole grain.
- 2) Alkali reactions start on the outer surface of a silica grain because there are more defects arising from crystal growth or from the crushing process. However, the reaction occurs on internal interfaces too.