Influences on the alkali-aggregate reaction in concrete

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1. Introduction

American, Australian and Danish investigations [1-4] on concrete deterioration as a result of alkali-aggregate reaction show among other factors that the type of the reactive aggregate, its grain size and quantity, the alkali content of the cement and the conditions during storage and use of concrete are of special importance. In the last few years there has also been evidence of an alkali-aggregate reaction in Germany which could be attributed to the Eozän opal containing sandstone occurring to a limited extent in North Germany. Consequently the main objective of the investigations was to describe the influences, to evaluate their significance for the building sector, particularly in North Germany, and to derive on the basis of gained knowledge guiding directives for the constructing with aggregate materials which may contain alkali-reactive constituents [5-11].

2. Influences on the alkali-aggregate reaction

2.1 Investigation methods

At the Research Institute of the German Cement Industry the behaviour of aggregate in mortar and concrete test specimens was investigated and critically examined in addition to petrographic and other physical and chemical investigations. As a measure the length change resulting from the alkali-aggregate reaction was used. For the tests to be carried out the ASTM procedure C 227 was slightly modified. As test specimens 2.5 x 2.5 x 28.5 cm and 4 x 4 x 16 cm prisms were used which were stored at 40 °C in air with more than 95 % relative humidity. The concretes tested had a composition according to figure 1.

AGGREGATE					
SIZE	SAND I DIN 1164 (OLD)	SAND II DIN 1164 (OLD)	1/3 MM	3/7 MM	7/15 MM
QUANTITY W.-%	10	30	20	20	20

CONCRETE						
CEMENT CONTENT KG/M^3	300	350	400	450	500	606
AGGREGATE CONTENT KG/M^3	1723	1662	1608	1545	1472	1348
WATER/CEMENT RATIO	0.55	0.50	0.45	0.43	0.43	0.43

Fig. 1: Composition of the concrete used for the test specimens

A peculiarity was the use of unbroken aggregate with a maximum size of 15 mm whereby the sensitivity of the testing procedure could be greatly enhanced. As aggregates quartz sand and gravel were used which in some size ranges were exchanged entirely or in part for reactive minerals such as opal, flint or Duran® (Pyrex) glass. The composition of both kinds of glass shows almost no difference. The cement content varied between about 300 kg/m^3 and 600 kg/m^3 with water-cement ratios of 0.43 up to 0.55.

2.2 The influence of aggregate type, quantity and grain size

Characteristic for the behaviour of alkali-reactive aggregate in concrete is the known fact that each size range in dependence on the quantity proportion shows an expansion maximum, called pessimum. Figure 2 illustrates the pessima of opal. It demonstrates that with the chosen concrete composition of 606 kg cement/m^3 and a total alkali content in the Portland cement of about 1.2 w.-% of Na_2O-equivalent the pessimum shifts to higher proportions of opal as the opal grain size increases. At the same time the total expansion of the prisms is reduced, in this example from nearly 20 mm/m in the size range of 0/0.09 mm to about 3 mm/m in the size range of 7/15 mm.

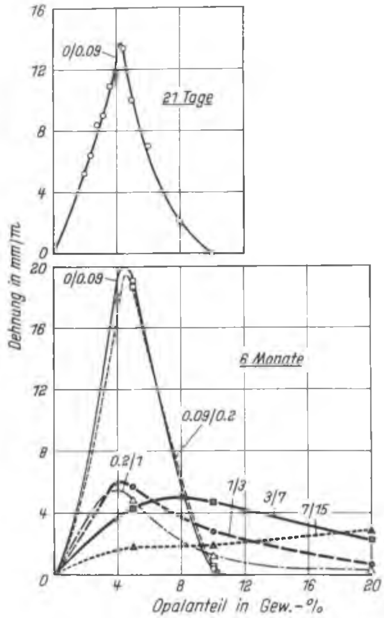

Fig. 2: Pessimum of pure opal (6)

In principle similar statements have also been the result of investigations on North German flints which with a suitable solution of high density (tetrabromäthan/acetone) were divided into four density classes between > 2.59 and < 2.53 g/cm^3. From the flints with different densities or porosities four aggregate grain size groups were produced by crushing. They were tested according to table 1 (fig. 1) with 606 kg cement/m^3. The results of the expansion measurements are presented in figure 3. They show that similar to opal, pessima occurred which with increasing flint grain size shifted to higher flint contents. The expansions reached at most about 2 mm/m, that is 3 to 10 times smaller than in concretes with opal as aggregate. The biggest expansion was found in a concrete with some 30 w.-% flint of the size range of 1/3 mm. It could furthermore be seen that the maximum expansion of about

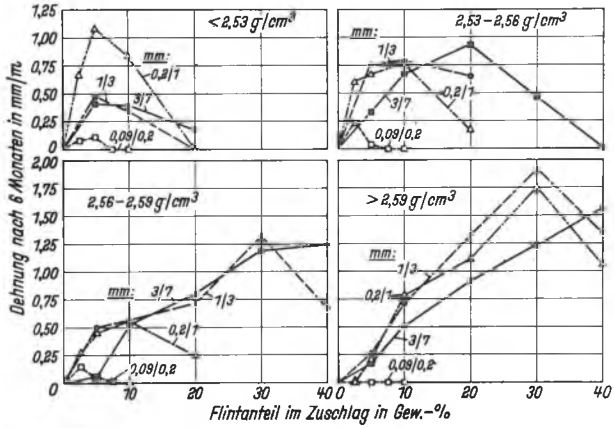

Fig. 3: Pessimum of dense flint (6)

1 mm/m in the case of the more porous flints increased to about 2 mm/m with denser flints.. Since the flint in the four density groups contained,according to x-ray defraction investigations, only quartz and no cristobalite, there was virtually no difference in the reactivity. However, a slightly higher porosity of the flint could have the result that smaller amounts of reaction products partly escape into the pore space thus causing a smaller expansion than in concrete with a denser flint. A precondition for a deleterious alkali-aggregate reaction or alkali expansion is therefore a sufficiently high reactivity of the aggregate and in addition, as for instance in the case of opal, a dense pore free structure.

A medium position with respect to alkali reactivity was found for Duran® glass which due to its homogeneous and uniform composition is particularly well suited as standard aggregate in comparative tests. As can be seen from figure 4 Duran® glass too has a pessimum in each grain size range. The highest expansion with probably about 5 mm/m occurred in a narrow pessimum region in the grain size range of 0.2/1 mm with Duran® glass quantities of 10 to 20 w.-%. In the size ranges of 1/3 and 3/7 mm, on the other hand, a very wide pessimum region was evident with Duran® glass contents of 25 to 30 w.-%.

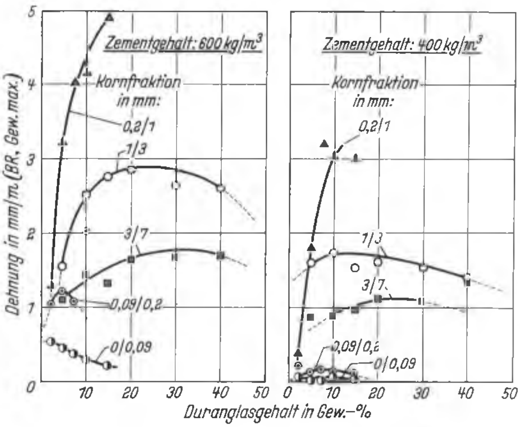

Fig. 4: Pessimum of Duran® glass

In concrete with 400 kg cement/m^3 a similar expansion occurred, although to an altogether smaller extent.

A comparison of the alkali-reactive aggregates allows among others the following conclusions: Opal, Duran® glass and flint have a typical pessimum in all grain size ranges. The amount of the aggregate to achieve the highest expansion is apparently the smaller, the more reactive the material ist. With increasing chemical reactivity of the aggregate the pessimum shifts to smaller grain size ranges, for instance from 1/3 mm in the case of flint down to 0/0.09 mm in the case of opal. On the basis of these results the differing reactivity of the aggregate has also been taken into account when the limiting values in the German directive were established.

2.3 The influence of the alkali-content in concrete

A deleterious alkali-aggregate reaction is only possible if besides reactive aggregates there are sufficiently high quantities of alkali in the pore solution of a moisture-penetrated concrete. The alkalies originate predominantly in the cement, but they may also reach the concrete from weathered aggregate constituents, concrete admixtures, sea-water or solutions of de-icing salts.

In Portland cements the total alkali content of the cement can be regarded as the effective alkali content for the alkali-aggregate reaction. In the case of Portland blast-furnace cements the effective alkali content comes primarily from the clinker proportion of the cement; but it might be possible that to a certain extent alkalies are introduced into the pore solution also by the slag or other additives such as trass in the case of trass-cement.

The information on the limit value for the effective alkali conten of Portland cements in the literature is rather contradictory with quotations ranging from 0.6 w.-% down to 0.09 w.-% Na_2O-equivalent (1; 2-12). But of greater importance to the building sector are those findings (2, 12, 17, 22, 23) which indicate that a deterioration of the concrete no longer takes place, if the cement contains less than 0.6 w.-% Na_2O-equivalent. On the basis of this experience and recent tests the limit values for cements with a low effective alkali content are at present fixed in Germany at 0.6 w.-% Na_2O-equivalent for Portland cement and 0.9 w.-% Na_2O-equivalent for Portland blast-furnace cement with at least 50 w.-% slag (11).

However, some investigations also demonstrated that it could be more advantageous for the assessment of the extent of an alkali-aggregate reaction to use the effective amount of alkali present in a certain volume of concrete instead of a single value for the alkali content of the cement.

For these investigations cements with different alkali contents and concretes with differing cement contents of 300 to 600 kg/m^3 were therefore chosen. In addition Duran® glass, in the size range of 1/3 and 3/7 mm, was used.

The test results of cement-rich concretes which are presented in figure 5 showed that the wide Duran® glass pessimum region of the grain size range of 1/3 and 3/7 mm remained virtually unchang in its position when Portland cement or Portland blast-furnace

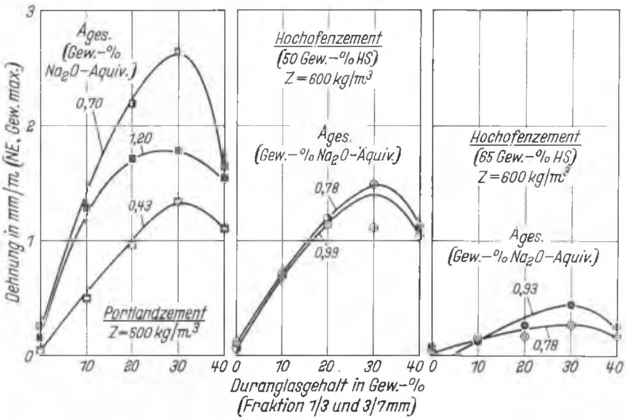

Fig. 5: Pessimum of Duran® glass with Portland and Portland blast-furnace cements

cement was used. The left part of the figure also demonstrates that it is not the Portland cement with the highest alkali content of 1.20 w.-% Na_2O-equivalent which caused the largest expansion, but the cement with an average total alkali content of 0.70 w.-% Na_2O-equivalent. This phenomenon was quite frequently observed in other tests too and could indicate that with greater length changes the measured expansion value for several reasons fails to serve as a clear measure for the extent of the alkali-aggregate reaction. The low alkali cement with 0.43 w.-% Na_2O-equivalent in this mixture with 600 kg cement/m^3 still caused an expansion of about 1.3 mm/m. The prisms containing Portland blast-furnace cement with 50 w.-% slag and a total alkali content of 0.78 and 0.99 w.-% led to similarly high expansion values of 1.4 to 1.5 mm/m.

Portland blast-furnace cements with 65 w.-% slag caused maximum expansions of 0.3 to 0.5 mm/m. The results show that the behaviour of Portland blast-furnace cement with more than 50 w.-% slag and total alkali contents of about 0.8 to 1.0 w.-% Na_2O-equivalent equals Portland cement with less than 0.6 w.-% Na_2O-equivalent. Thus the test result complies with the preliminary German specification for low alkali cement. For the final directives the results of comparative tests of the VDZ on some 50 cements are at present statistically evaluated.

The influence of the cement quantity on the extent of the alkali-aggregate reaction is indicated by figure 6. These diagrams show the Duran® glass pessimum of the size ranges 1/3 and 3/7 mm with the use of Portland cement with low (right) and with medium-high effective alkali contents (left). Whereas the pessimum with decreasing cement content seems to shift to somewhat lower glass contents, the maximum expansion determined with this highly sensitive test falls down to values of less than 1 mm/m as soon as the content of low alkali cement in the concrete is reduced from 600 to 500 kg/m^3 or in the case of the normal Portland cement to contents below 400 kg cement/m^3. This, together with many field observations, allows the conclusion that the use of low alkali cement with the quite common cement contents is a safe measure against a deleterious alkali-aggregate reaction in concrete structures.

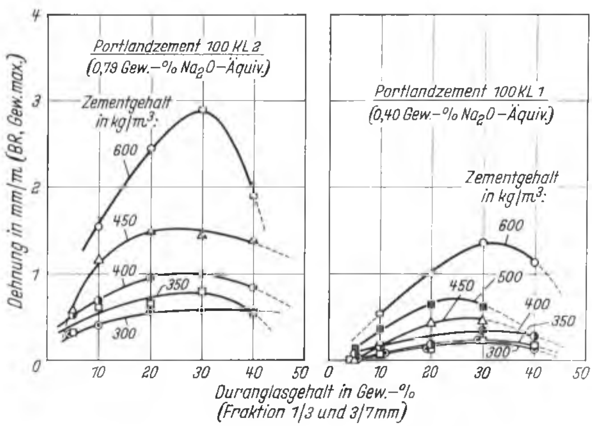

Fig. 6: Pessimum of Duran® glass with changing cement contents

From this and a number of other test results it therefore follows that it is above all the effective alkali amount in the concrete in kg Na_2O/m^3, that under the existing aggregate conditions permits a comprehensive assessment of the effects of the alkali-aggregate reaction in concrete. To prevent a deleterious alkali-aggregate reaction in concrete it was therefore necessary that in establishing limit values, not only the alkali content of the cement should be taken into consideration but also the respective cement content of the concrete.

With the help of existing test data which are within a 95 %-tolerance region such a limiting curve was calculated unter the assumption that mortar bar-expansions of maximum 1 mm/m in agreement with the ASTM specification C 227 do not cause expansions in concrete of similar composition used in practice. In figure 7 the cement content of such concretes was calculated and plotted in relation to the effective alkali content of the used cement. The continuous line refers to these tests with Duran ® glass with maximum expansion of 1 mm/m. The dotted line represents a similar relation which has been derived for opal in the aggregate and an expansion of mortar bars of 0 mm/m. The curves B and C enclose the regions in which according to Bonzel and Dahms (24) a slight (B) or more severe (C) deterioration of concrete under more practical conditions occur.

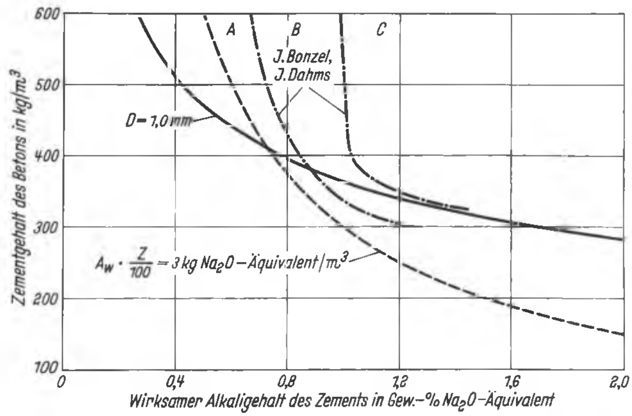

Fig. 7: Cement content in concrete and the effective alkali content of the cement (8)

The diagram illustrates that up to cement contents of about 350 kg/m^3 and with alkali contents of maximum 1.3 w.-% Na_2O-equivalent the results of tests in the laboratory are in agreement with results found on field concrete.

This would for instance mean that a concrete containing approximate 320 kg cement/m^3 with an alkali content of 1.30 w.-% Na_2O-equivalen and in the case of a highly reactive aggregate with pessimum composition would still not show deleterious alkali-aggregate reaction With the dotted line referring to opal, the cement content would be limited to values which are very far on the safe side. In the range of higher cement contents the various results still differ. An explanation for this may be the difference of alkali reactivity of aggregates such as Duran® glass, opal or opal-containing sandstone. Additional reasons are perhaps non-comparable pessimum conditions, when Duran® glass and opal are used at different cement contents. Furthermore, the not yet fully examined influence of the dimensions of the test specimen and the influence of the aggregate grain size in relation to the cross section of the test specimen could also play a role.

3. Summary

The alkali-aggregate reaction (AAR), which only in special cases leads to a damaging expansion, will be influenced by several factors. Investigations carried out with highly sensitive concrete prisms 2.5 x 2.5 x 28.5 cm have shown that the reactivity of opal, Duran® glass and flint can obviously be classified according to that pessimum, which leads to the maximum expansion. Opal has the maximum, Duran® glass a somewhat lower and flint with a bulk density of > 2.53 g/cm^3 the lowest reactivity. Reactive aggregates with a small porosity may cause a higher expansion than more porous aggregates of the same kind.

Portland cement with less than 0.6 and Portland blast-furnace cements with a minimum content of 50 w.-% slag and of about 0.8 to 1.0 w.-% total alkali content (Na_2O+0.658 K_2O) were according to

the test results equivalent as cements with low effective alkali content. In full accordance with practical experience the utilization of such cements is one of the important precautions to avoid damaging expansion in concrete structures.

With the aid of the effective alkali content of the cement and the cement content of concrete it was possible to estimate that quantity of alkalis, which is responsible for the extent of AAR. The investigations have shown that up to cement contents of 350 kg/m^3 and effective alkali contents of 1.3 w.-% (Na_2O+0.658 K_2O) the results of the Duran® glass test agree with the practical behaviour of concrete. A judgement on the influence of higher cement contents with the test method will not be possible before further test results are known. Because of the fact that the Duran® glass test generally leads to higher, but in no instance to lower expansions compared with concrete of similar composition, the conclusions for practice are still far on the safe side. It should therefore be one of the aims of further investigations, to diminish the safety-factor to a necessary measure with regard to economic construction.

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