The Alkali Aggregate Reaction with Opaline Sandstone from Schleswig-Holstein

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Abstract:

A report of the research work on the alkali-aggregate reaction with opaline sandstone from Schleswig-Holstein, North-Germany is given. The influence of different parameters such as the grain size of the reactive aggregate and the storage conditions, and the effects of a surface impregnation and of puzzuolanic and latent hydraulic additions is investigated. A reaction starting at later ages and thus proceeding in a more stiffened structure may cause severer damages. Whether coarser reactive aggregate or puzzuolanic additions, reduce or only delay the consequences of the alkali-aggregate reaction can only be determined with prolonged test series.
The pressures, producing the observed expansions were roughly estimated with a simple device which allowes humidity exchange with the surroundings during the measurement.

Introduction

In spite of nearly 40 years of research work, a uniform, generally accepted theory of the alkali silica reaction (ASR) and a clear explanation of the mechanisms which influence it does not exist. The heterogenity and the complexity of the system cement - aggregate is the origin of this situation and the reason for so many reaction-determining parameters. Further effects are the poor comparability of the results of different authors and the low reproducibility of laboratory tests, already mentioned by Vivian in 1948 (1). Nevertheless, the numerous published research works is the basis for today's understanding of the ASR.

Among others, the models of Hirche et.al. (2) and Ludwig and Sideris (3) contributed to the understanding of the reaction. The experimental works presented in the following is based on these models.

The parameters investigated are the grain size of the reactive aggregate, the curing conditions and the effects of a surface impregnation and of puzzolanic and latent-hydraulic additions. Furthermore, some results obtained with a simple device to determine the expansive pressure due to the ASR are presented, and efforts are made to apply the experience of laboratory work to the investigation of construction damages.

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(1) H.E. Vivian, Journ. Coun. Sci. Ind. Res. 21 (1948), 148-159

(2) H.W. Nürnberg, G. Wolff, D. Hirche, U. Ludwig, Sprechsaal106 (1973) 24, 982-992; 107 (1974) 3, 83-92 and 5, 187-206

(3) U. Ludwig, K. Sideris, Sprechsaal 108 (1975) 5, 128

to have a porosity of about 20 %. It contains 2 wt.-% - 6 wt.-% calcite. It's surface area determined by nitrogen adsorption amounts to 19 $m^2 .g^{-1}$.

Influence of the grain size of the reactive aggregate

The influence of the grain size of the reactive aggregate was investigated in four test series with grain sizes ranging from 0.09 mm to 5 mm. Figure 1 shows the expansion and the natural frequency of the specimens containing opaline sandstone with 4 granulometric fractions: 0.09 to 0.5 mm, 0.5 to 1 mm, 1 to 3.15 mm, and 3.15 to 5 mm.

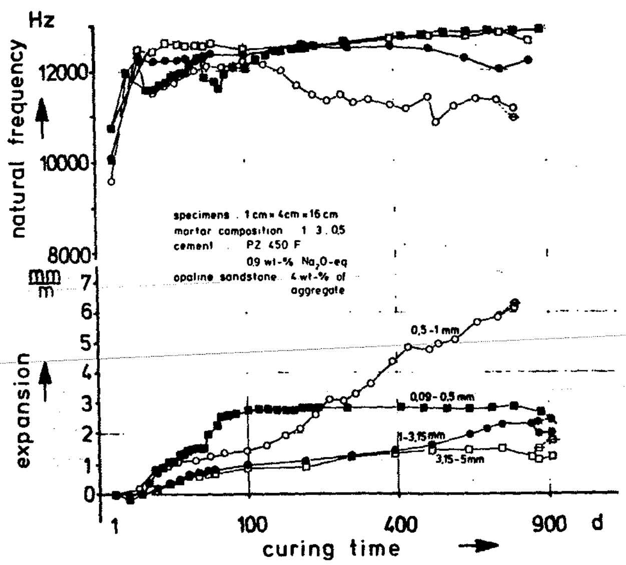

Fig. 1 Influence of the grain size of the reactive aggregate on the ASR

Each point is the mean of 6 different specimens.

The specimens containing the finest reactive aggregate (0.09 - 0.5 mm) attained their ultimate expansion after about 100 days humid storage. Then their natural frequency increased continuously.

The fraction 0.5 - 1 mm seems to be near the pessimal grain size. The corresponding specimens exceed the expansion of the former after 225 days and do not seem to have reached their ultimate expansion even after 770 days.

The mortars containing the coarser reactive aggregate fraction expand more slowly in agreement with published experiments by other authors (1, 2). The expansion of these specimens seems to be finished after about 700 days. The decreasing natural frequency, however, indicates that the expansion could increase again.

The acceleration of the reaction by raising temperature confirms this presumption.

Determination of minimum humidity

In order to determine the minimum atmospheric humidity required for the ASR, 6 specimens at a time were cured at different humidities (see 3). The dimensions of the specimens are 1 cm x 4 cm x 16 cm. They contain opaline sandstone of the fraction 0.09 mm to 0.5 mm.

To adjust the atmospheric humidity, sulphuric acid of different concentrations is used. In the first instance, the humidities are adjusted to about 40 % rh, 60 % rh, 80 % rh, 90 % rh, and more than 95 % rh.

The specimens stored at more than 95 % rh already expand clearly before 15 days and after about 100 days, they reach their final expansion of 2.8 mm/m. At the lower humidity of 90 % rh the ASR cannot be observed before at least about 50 days. The expansion increases more slowly due to the lower water supply. The specimens stored at humidities of 80 % rh and less only show drying shrinkage. Therefore,

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(1) H.E. Vivian, Austr. Journ. Appl. Sci. 2 (1951), 488-494
(2) F.W. Locher, S. Sprung, Beton 23 (1973) 7, 303-306 and 8, 349-353
(3) U. Ludwig, W. Bauer, loc. cit.

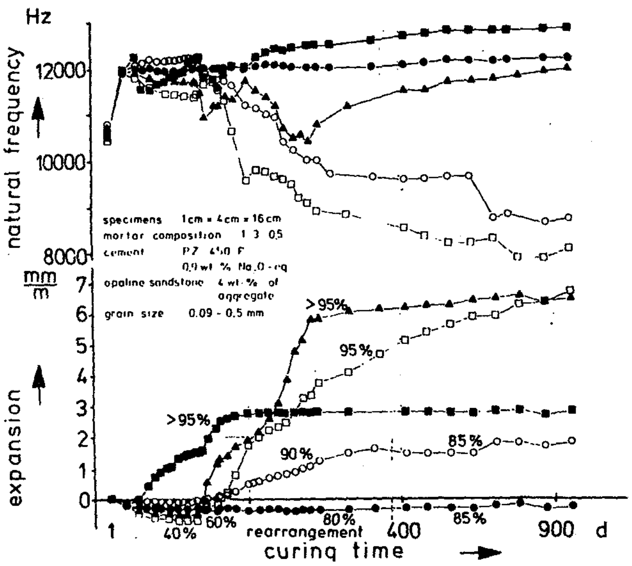

Fig. 2 Effect of atmospheric humidity on the ASR

after 42 days, these specimens were rearranged from 60 % rh and 40 % rh to > 95 % rh and 95 % rh respectively. Then these specimens expanded rapidly and their natural frequency decreased considerably. Again, the specimens stored at the higher humidity > 95 % rh expanded faster and reached their final expansion earlier than those stored at the lower humidity of 95 % rh.

The originally dried specimens have a lower natural frequency, corresponding to a lower Young's modulus because of the hindered hydration. The slight increase of the natural frequency of the specimens originally stored at 40 % rh after the rearrangement is due to recovery through hydration. As soon as the shrinkage is neutralised, the natural frequency decreases with increasing expansion. After about 100 days, the expansion slows down and a slight increase of the natural frequency indicates a short recovery. Then the expansion is accelerated again and the natural frequency continues to decrease. The specimens rearranged from 60 % rh to more than 95 % rh show the same sequence of reactions. However because of better water supply, they react and expand faster. These specimens have reacted completely after about 200 days. The subsequent small expansion is due to a non reactive swelling.

The comparison of these two series shows that within the limits of these experiments, a poorer water supply does not diminish but only delays the damages due to the ASR. Because of the prolonged expansion, the deterioration marked by lower natural frequencies is severer at lower atmospheric humidities.

The same is true for the specimens stored at high humidities from the beginning.

The specimens stored at more than 95 % rh reach after about 100 days their final expansion. As the reaction already starts at an early stage of cement hardening, part of the swelling pressure is cancelled by plastic deformation within the concrete structure. Therefore, the final expansion only amounts to 50 % of the expansion of the specimens rearranged later on. After the end of the expansion, autogeneous healing takes place. The natural frequency almost reaches the values of undamaged mortar prisms of this age, beeing about 13.5 kHz.

The poorer water supply when storing at 90 % rh, causes a prolonged reaction and a prolonged expansion which results in severer damages to the structure.

Storing the specimens at 80 % rh does not cause expansions or a decrease of the natural frequency.

Therefore, in order to determine the minimum humidity needed for the ASR, the specimens stored initially at 80 % rh,and 90 % rh were rearranged to about 85 % rh after 360 days.

Thereafter, the specimens formerly stored at 80 % rh do not show effects of the ASR. The inferior shrinkage decrease is accompanied by a slight increase of the natural frequency and is caused by the water uptake of the mortar.

The rearrangement from 90 % rh to 85 % rh results in a delay of the expansion reaction. After a dormant period of about 200 days, the specimens expand a little. This inferior expansion is accompanied by a distinct decrease of the natural frequency, a clear indication of the recommencing ASR.

Effect of temperature

The investigation of the effect of raised temperatures on the ASR leads to similar conclusions as already stated.

Specimens of different series were stored at 25°C and 40°C. An example is shown in figure 3.

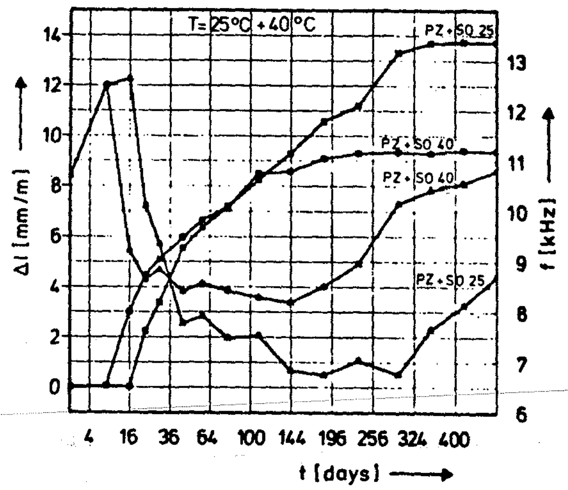

Fig. 3 Effect of curing at 25°C and 40°C on the ASR

A higher temperature accelerates the ASR and consequently the expansion of all the specimens. Because of the higher reaction rate, a considerable amount of the swelling pressure is developed during the plastic stage of the mortar, and that is why the damages are less severe.

Effect of an impregnation

Earlier investigations (1) of the effect of a surface impregnation showed a delay of the ASR even when immersing the specimens three times a week into water and interim storage at 80 % rh or when storing continuously at more than 95 % rh. However, this delay causes increased damages to the specimens later on. The influence of an effective water repellent agent on the ASR was reinvestigated. In this case 4 cm x 4 cm x 16 cm prisms were used which had been impregnated with an average uptake of 115 g/m^2 alkyl-alkoxy-silane solution. The grain size of the reactive aggregate ranges from 0.5 mm to 1 mm. Contrary to the above tests, these specimens were stored at 20°C and 60 % rh. Three days after the demolding, half of the specimens were impregnated. Afterwards, all specimens were immersed into water of 20°C three times three hours per week. The expansion of the comparative specimens not impregnated are smaller than the expansions of specimens of other series which are stored at high humidities due to the limited water supply. Nevertheless the protective influence of the impregnation can clearly be recognized (fig. 4).

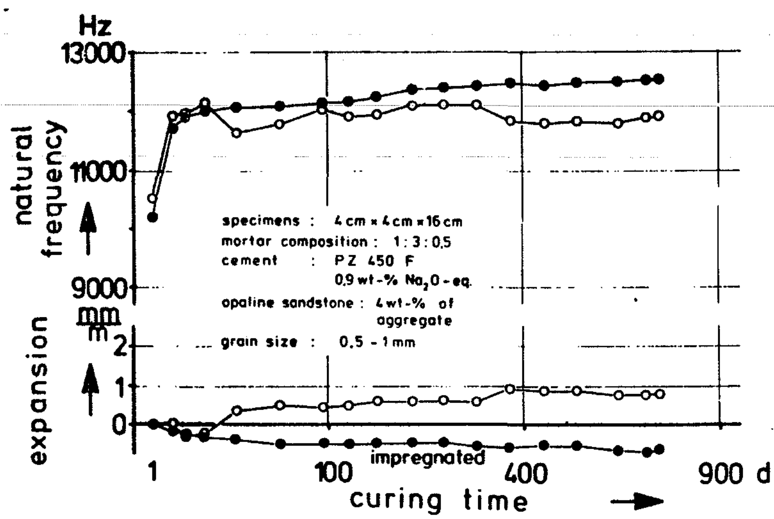

Fig. 4 Effect of an impregnation on the ASR

(1) U. Ludwig, Cem. Concr. Res. 6 (1976), 765-772

At the initial storage at about 60 % rh, a water loss is measured. The specimens shrink uniformly. About 10 days after the beginning of the water treatment, the ASR becomes noticeable by a clear expansion and a decrease of the natural frequency. It only starts in the non impregnated specimens. The impregnated specimens have not shown any expansion up to now (700 days). However, their strength, measured by their natural frequency, remains below the strength of the non damaged and non impregnated reference specimens because of the minor water uptake.

These specimens are currently being examined by rearrangement to high humidities whether there is still activity left after the testing time of 720 days or not.

Influence of additions of puzzolanas and of granulated blast furnace slags

The favourable influence of puzzolanic additions on the ASR has been known for some time (1, 2). Generally, the action of the puzzolanas is attributed to the rapid alkali adsorption due to their large surface areas (1, 3). On the other hand, this finely grained addition alters the concrete structure. And especially the exchange of a part of the cement by a puzzolana affects the strength development of the concrete. Both factors also influence the ASR.

First results of our examinations of the influence of puzzolanic additions on the ASR were already published (4). There it was stated that an addition of fly ash decreases the mortar damage caused by the ASR. It was assumed that alkali adsorption by the fly ash or a changed pore structure or both explained these effects. To get more information about the influence of different puzzolanas and granulated blast furnace slags on the ASR, the mortar mixtures shown in table 1 were prepared.

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(1) T.C. Powers, H.H. Steinour, Journ. Amer. Concr. Inst. 51 (1955), 497-516, 785-812

(2) J.C. Bennett, H.E. Vivian, Austr. Journ. Appl. Sci. 6 (1955), 88-93

(3) C.S. Forum, Beton u. Stahlbetonbau 7 (1965), 163-168

(4) U. Ludwig, loc. cit.

cement PZ 450 F	puzzolana	finely grained sand	standard sand	water
1	-	0,2	3	0,5
1	0,2	-	3	0,5
0,8	0,2	0,2	3	0,5
	blast furnace slag			
0,65	0,35	0,2	3	0,5
0,35	0,65	0,2	3	0,5

Table 1 Mortars used to examine the influence of puzzolanas and blast furnace slags

Using these mortars, several series of six 1 cm x 4 cm x 16 cm prisms were formed. Eight days later, and for each series, three specimens were stored at 25°C and three at 40°C in evacuated desiccators above water.

These tests differ from those already published by the fact, that equivalent weight ratios and a similar grain structure is achieved in all mortars by the addition of a corresponding quantity of fine sand to the reference mortars without puzzolanic addition and to the mortars in which the addition replaces a part of the cement. Table 2 shows part of the chemical analysis of the additions and their specific surface areas determined by nitrogen adsorption.

	SiO_2 wt-%	CaO wt-%	Na_2O-eq. wt-%	surface area m^2g^{-1}
PZ 450 F (PZ)	19,9	63,0	0,90	-
fly ash (F)	46,1	3,0	3,40	0,49
lava (L)	42,2	12,6	2,99	15,5
B. trass (T_b)	60,7	4,8	3.27	16,7
R. trass (T_r)	54,6	6,8	5,39	10,1
slag 1	32,7	39,5	1,80	0,65
slag 3	32,7	39,6	1,12	0.64
slag 5	32,2	45,0	0,92	0,50

Table 2 Alkali, silica-, and lime content and surface area of the additions

As shown in fig. 5, the addition of fly ash accelerates the beginning of the expansion probably due to the supplementary amount of alkali but it reduces the final expansion more than the addition of lava.

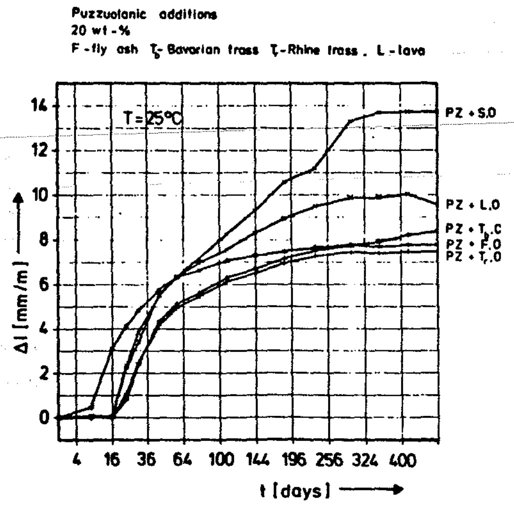

Fig. 5 Influence of puzzolanic additions on the expansion of mortar bars

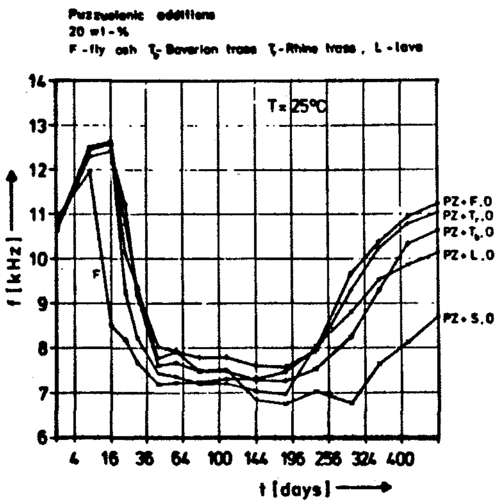

Fig. 6 Natural frequencies of the mortar bars containing puzzolanas

The comparison of the natural frequencies shows again that an earlier expansion is accompanied by an earlier beginning of the autogeneous healing thus resulting in minor damages.

When replacing part of the cement by the puzzolanas, the differences in the effects are more pronounced (fig. 7).

The trasses delay the beginning of the expansion more than the glass containing puzzolanas, the respective addition with the larger surface area being more effective.

The puzzolanas not only delay the beginning of the expansion; this effect alone should lead to severer damages; but they diminish the final expansion partly to more than 50 %. Here in both groups the addition with the higher content of SiO_2 is more effective.

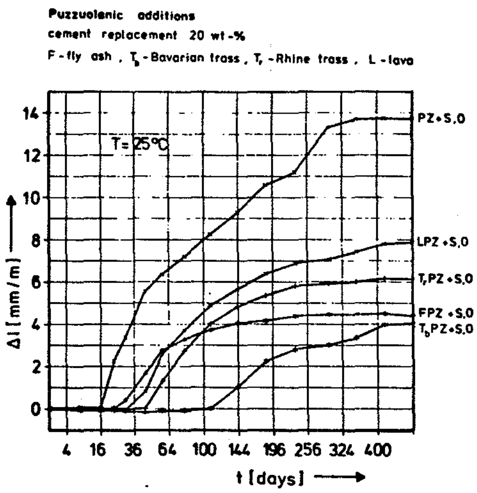

Fig. 7 Expansions of mortars containing the puzzolanas as cement replacement

Fig. 8 shows the expansions and fig 9 the natural frequencies of the slag cement mortars with 35 % blast furnace slag.

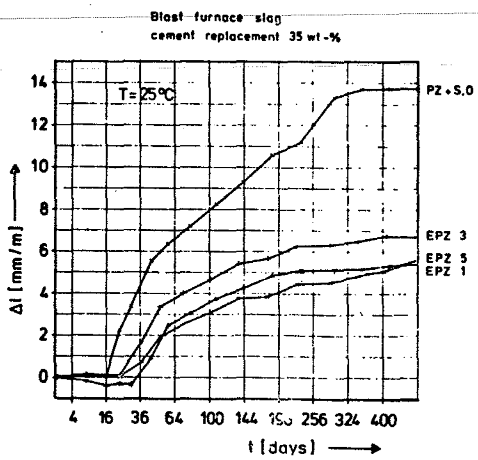

Fig. 8 Expansions of the mortar bars containing blast furnace slag

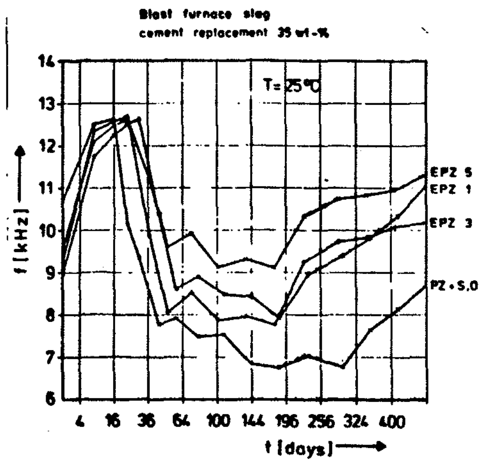

Fig. 9 Natural frequencies of the mortar bars containing blast furnace slag

The reduction of the final expansion amounts to about 50 % for all 3 blast furnace slags tested.

Continuous expansion measurements

In order to investigate the mechanism of the expansion reaction more accurately, the expansion of a specimen of 4 cm x 4 cm x 16 cm containing opaline sandstone of 0.09 mm to 0.5 mm was measured with high resolution quasi-continuously with an inductive strain gauge.

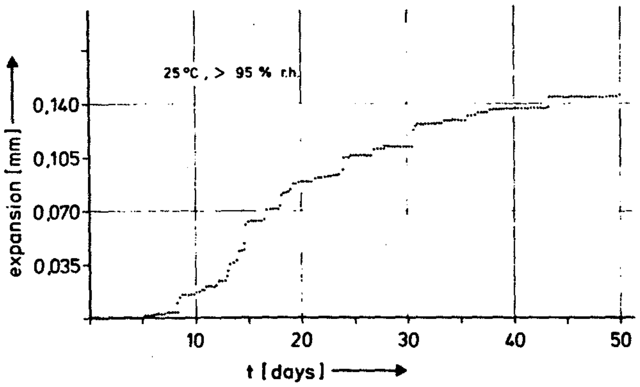

Fig. 10 Quasi-continuous expansion measurement

Readings were taken automatically every six hours.

Figure 10 shows the beginning of the expansion. This clearly shows that the length changes are discontinuous, which means that the expansion of mortar, which is damaged by the ASR, results from crack development.

Pressure determination

In order to obtain information about the swelling pressures leading to the observed expansions, a simple device described earlier (1) is employed which does not hinder the curing of the mortar.

The equipment consists of a threaded steel rod, at the ends of which rigid steel plates are screwed on to transmit the forces. It is embedded axially as a reinforcement within the prismatic specimens which are prepared and treated by the methods described earlier.

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(1) J. Kuhlmann, D. Lenzner, U. Ludwig, P. Zitzen, Zement-Kalk-Gips 28 (1975) 12, 526-530

From the elastic deformation of these elements which were calibrated individually, the axial component of the swelling pressure within the specimen is calculated.

The pressure caused by the ASR are decreased by the expansion of the structure. Therefore, in order to determine the maximum forces, the expansion should be prevented completely. But then, the measurement would be impossible as the force is calculated from the elastic deformation of the measuring element. Therefore, various rigid reinforcements were used to get an estimation of the maximum pressure by extrapolation.

The reinforcement diminishes the expansion of the specimens down to 30 % of the non-hindered expansion. That is why the resolution of the dial gauge used for the tests named above was unsufficient. The expansion measurements are performed either with an inductive dilatometric gauge or with a dial gauge having a sensitivity of 0.001 mm.

The axial reinforcement results in an increased lateral expansion, signifying that only a part of the actual pressures is determined by this method.

Up to now, the swelling pressures of mortars containing opaline sandstone of the fractions 0.09 - 0.5 mm and 0.5 - 1 mm were examined. The reinforcement does not alter the lapse of the expansion. The expansion is reduced proportionally to the rigidity of the reinforcement.

In figure 11 the pressures calculated from the expansions of the reinforced specimens are plotted versus the expansions.

As already stated, the pressure increases with decreasing expansion. An estimation of the maximum pressure can be achieved by extrapolating to zero expansion.

The specimens containing the coarser fraction of the opaline sandstone have not yet reached the end of the reaction. From the results obtained so far, however, a maximum pressure of about 2.5 N/mm^2 may be expected.

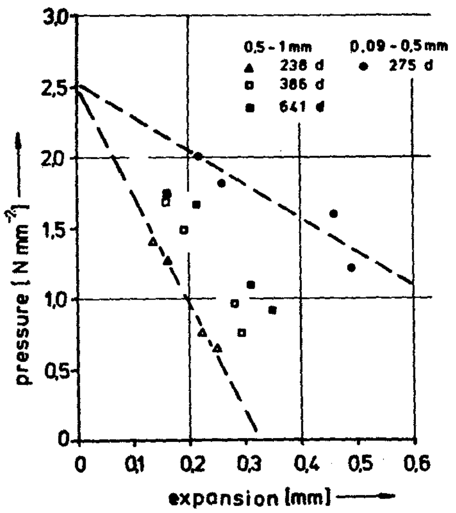

Fig. 11 Pressure measurement with different reinforcements

Examination of construction damages

Besides the laboratory tests described above, damaged constructions in Schleswig-Holstein were examined (1, 2).

If the damage is caused by the ASR the content of reactive aggregate and the potentially remaining risk have to be estimated. Reliable data can only be obtained by examining drill cores. For this purpose, the drill cores are equipped with gauge points for expansion measurements immediately after the drilling and stored in sealed containers.

The expansion of the drill cores during the first few days after drilling is an indication of the degree of tensions within the concrete which are now released.

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(1) U. Ludwig, Schlußbericht zum Forschungsvorhaben I/70 (HV)/10.1.50 (DBV) March 1976

(2) D. Lenzner, U. Ludwig, Schlußbericht zum Forschungsvorhaben BMV, Nov. 1977

Because of the hygroscopicity of the alkali silica hydrates, the reactive grains near the surface of the drill cores become clearly visible after about one day and can be counted. This count furnishes an estimation of the content of reactive aggregate within the concrete.

By storing the drill cores under high humidities, the potentially remaining risk of the construction can be determined with the aid of expansion measurements and measurements of the natural frequency.

Discussion

The damage of the specimens due to the ASR is marked by expansion, and by decrease of the natural frequency.

Within the examined grain size range of 0.09 to 5 mm, after 900 days curing time, the damage to the specimens containing opaline sandstone of 0.5 to 1 mm is evidently severer than that to the specimens with finer or coarser reactive aggregate. The damage to the specimens containing the fraction 0.09 - 0.5 mm proceeds faster and is already terminated after about 100 days, whereas the damage to the specimens with coarser reactive aggregate (> 1 mm) proceeds so slowly that their expansion remains less than 2.5 mm/m after 900 days.

The existence of a pessimal grain size in the range of 0.5 - 1 mm for the opaline sandstone can be explained as follows:

If the amount of reactive aggregate within the mortar remains constant, the mean distance of the aggregate grains decreases with decreasing grain size and the boundary surface area between aggregate and mortar related to the weight of aggregate increases. The adsorption of ions out of the pore solution by the reactive aggregate is limited by this boundary surface area and by the concentration of the ions in its vicinity. At the beginning of the ASR, the concentration of alkali within the pore solution is high, and thus the concentration of lime is low.

For equal volumes and equal times, small grains absorb a larger amount of ions than bigger ones because of their larger specific boundary area. Through the absorption, the alkali concentration in the vicinity of the grains decreases, and further alkali ions diffuse out of the mortar to the reactive grains. As long as this diffusion gradient maintains a sufficiently high alkali concentration in the solution, the concentration of lime remains low.

If the mean distance of the reactive grains is small, the alkali supply is soon exhausted. Then the lime concentration rises, and with the transformation of the swelling alkali silicate into stable lime alkali silicate, the ASR comes to an end. With finely grained aggregate, this stage may be reached before the mortar is completely hardened, and then no damages are observed (1, 2).

Coarse grains quickly exhaust the alkali supply in their vicinity. Because of the growing diffusion distances of the ions, the alkali concentration near the grains decreases and thus the lime concentration rises. An increasing amount of lime is absorbed. The transformation rate from alkali silicate into stable lime alkali silicate grows. Thus the increment of damage decreases.

Within the range of the pessimal grain size, the mean distance of the grains is such that the alkali supply to each grain is sufficient for the ASR. Whereas the ratio of outer surface to grain volume is such that the stabilizing reaction with lime remains behind the formation of the swelling alkali silicates.

Moreover, the pressures proceeding from the reactive grains overlap when the distance of the grains is small, resulting in enlarged stresses. For this effect, there is a pessimal grain size too. If the aggregate is so finely divided i.e. grain sizes in the range of the capillary pore diameters of the hardened cement, only part of the pressure is transmitted to the structure. If the aggregate is coarsely grained, the mean distances are respectively large. Then the pressures don't overlap any more and the resulting stresses decrease.

The influence of the grain size cannot be estimated quantitatively until the effect of distance and boundary surface area of the reactive grains is investigated more thoroughly by varying simultaneously the grain size and the amount of the reactive aggregate.

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(1) W.C. Hansen, Proceedings 4. Intern. Sym. Chem. Cem. Washington (1960) 784-788

(2) T.C. Powers, Proceedings 4. Intern. Sym. Chem. Cem. Washington (1960) 788-794

After 50 to 100 days curing, a step in the graph of the expansion is observed (see 1) connected with a rehealing of the mortar. This step is the more pronounced when the range of the grain size fraction of the reactive aggregate is narrower. An explanation for this discontinuity may be that during the time corresponding to the step observed the pressures proceeding from all the reactive grains contribute to the expansion by crack formation. Thereby, the pressures are decomposed and the alkali silicate flows out into the crack. Only a new alkali supply makes possible a renewed pressure development and therewith renewed expansion.

After the termination of the ASR, the structure consolidates as stable hydration products are formed when the humidity is sufficient. Stable hydration products are formed through the reaction of lime with the alkali silicate as well as through the hydration of till then unhydrated parts of the cement.

The expansion of the mortar bars containing opaline sandstone results in fact from crack formation (2), as is shown by a quasi-continuous expansion measurement. The nearly exclusive step-wise length change is a clear evidence of the crack formation. The reason thereof is not the mechanism of the pressure set up but the poor elasticity of the structure of the cement stone which allows only small plastic deformations.

The tests with storage at different relative humidities bring new refinements to previous conclusions (3, 4) about the least humidity for the ASR. The least humidity lies between 80 and 85 % rh, but nearer to 85 % rh. The storage at 80 % rh prevents any expansion up to at least 1000 days curing time. Therefore, the knowledge of the equilibrium humidity within affected concrete constructions could tell if an active reaction is to be expected.

Furthermore, these tests show that expansion measurements are not always sufficient to estimate the damage. A slow expansion caused by the low water supply when storing at 90 % rh leads to lower natural frequencies than a rapid expansion when storing at higher humidities. The reason for this is the further

(1) S. Diamond, Cem. Concr. Res. 4 (1974) 591-607

(2) J.K. McGowan, H.E. Vivian, Austr. Journ. Appl. Sci 3 (1952) 228-232

(3) U. Ludwig, W. Bauer, loc. cit.

(4) U. Ludwig, loc. cit.

reduced elasticity of the structure and the limited possibility of rehealing due to the lower water supply.

The excessive expansion after the rearrangement from low to high humidities shows, that the ASR begins right after the mortar preparation. The rapid onset of the reaction is promoted by the imbibition of pore solution by the dry aggregate during the preparation. The subsequent drying of the specimens interrupts the ASR. If the water supply is raised later on, the already present alkali silicates swell. This results in severer damages, because, 1.) at the time of swelling, the cement structure is more stiffened and a decomposition of the swelling pressures by plastic deformation is only possible to a minor degree; and 2.) because the velocity of the swelling is higher since at the time of the water uptake, a larger amount of swelling products is already formed.

Raising the storage temperature from 25°C to 40°C generally results in an acceleration of the expansion but also in lower ultimate expansion. The acceleration is caused by a higher reaction rate, the lower ultimate expansion being the result of an altered reaction mechanism.

The investigation of the effect of an impregnation demonstrates that a suitable impregnation can diminish or prevent the ASR.

In the test series with puzzolanic and latent hydraulic additions, the expansions of the reference specimens exceed the expansions of mortar bars of the same composition but of other test series. This increased expansion could not be explained yet. All the puzzolanic and latent hydraulic additions investigated lead to a decrease of the damage recognizable by diminished expansions and higher natural frequencies. As expected, the exchange of a part of the cement by a puzzolana is more effective than a mere addition.

When interpreting the effect of the puzzolanic additions, one may distinguish between additions containing glassy material (these are lava and fly ash), and the trasses which do not contain glass. Within these two groups respectively, the addition with the higher surface area is more effective in retarding the onset of the expansion. In reducing the ultimate expansion, the addition with the higher silica content is more effective. A correlation between efficacy and alkali content is not evident.

A more extensive explanation of the effect of puzzolanic additions will only be possible when the participation of the puzzolanas in the hydraulic hardening of cement is better understood.

In the case of the slag cements containing 35 % blast furnace slag, a correlation between efficacy and alkali content is also not observed. The reduction of the ultimate expansion through the addition of the blast furnace slags is approximately the same as in the case of the puzzolanic additions. However, taking into account the larger amount of slags in the mortar, they are less effective than the puzzolanas.

The mortars containing 65 % blast furnace slag as cement replacement do not show any expansion or decrease of the natural frequency up to at least 600 days in agreement wiht other investigations (1).

With the aid of calibrated reinforcements, without obstruction of the lateral expansion, maximum swelling pressures due to the ASR of 2 N/mm^2 are measured. The extrapolation of the values to zero expansion leads to 2.5 N/mm^2. This value agrees well with the results of theoretical calculations (2). For further investigation of the maximum swelling pressures, tests with tri-axial obstructed expansion are in preparation.

In order to estimate reliably constructions affected by the ASR, drill cores have to be taken. Immediate expansion measurements give important indications concerning the stage of the ASR. Counting the reactive grains allows an estimation of the amount of reactive aggregate within the concrete. An estimation of the potentially residual risk of the construction can be obtained by appropriate storage of the drill cores and measurement of weight, expansion and natural frequency.

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(1) S. Sprung, Schriftenreihe der Zementindustrie 40 (1973)

(2) U. Ludwig, K. Sideris, loc. cit.

Conclusions

The following general conclusions can be drawn concerning the ASR: Immediately after the addition of the dry aggregate to the mortar mixture, the porous opaline sandstone imbibes the solution which is already enriched with lime and alkalis (1). The ASR already begins during the preparation of the mortar.
With progressing ASR, the alkali ions dissolved in the pore solution of the mortar diffuse to the reactive grains until the soluble silicate is consumed completely. Simultaneously, the lime which is also present within the solution reacts with the alkali silicates to form stable lime alkali silicates. However, this stabilizing reaction progresses more slowly than the formation of the swelling alkali silicate (2, 3). And the already formed layers of lime alkali silicate strongly hinder the diffusion of lime to the core of the reactive grains. Therefore, the remaining amount of alkali silicate in the interior of (not too small) grains is sufficient to produce osmotic pressures by continuous imbibition of water (4, 5).

The hardened cement structure does not permit elastic deformations. The swelling pressures due to the ASR produce only small plastic deformations but mostly cracks.

An acceleration of the ASR results in minor damages, whereas a retardation causes severer deteriorations.

The expansion is only terminated after the reactive silica is completely consumed by reacting with alkali and lime. According to the preliminary results, with opaline sandstone and a storage temperature of 25^{o}C, this is only possible with aggregate grains smaller than 0.5 mm within three years.

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(1) U. Ludwig, W. Bauer, loc. cit.
(2) T.C. Powers, H.H. Steinauer, loc. cit.
(3) H.W. Nürnberg, G. Wolff, D. Hirche, U. Ludwig, loc. cit.
(4) T.C. Hansen, Proc. Am. Concr. Inst. 40 (1944) 213-227
(5) U. Ludwig, K. Sideris, loc. cit.

Puzzolanic or latent hydraulic additions reduce the damage due to the ASR.

With non-restrained lateral expansion, the maximum swelling pressure transmitted through the mortar structure is at least 2 N/mm^2.

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