

PREVENTION OF ASR WITH SUPPLEMENTARY CEMENTITIOUS MATERIALS - LONG TERM PORE SOLUTION INVESTIGATIONS

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Abstract

In this study, the effect of the supplementary cementitious materials (SCM) fly ash and ground granulated blast furnace slag (GGBS) on the damaging alkali-silica reaction (ASR) in concrete was investigated. Finely ground limestone was used as inert material for some mixes. The external manifestation of ASR – expansion and crack formation – was followed over three years and the compositions of expressed pore solutions analyzed chemically. All three concrete additions delayed or prevented ASR damage. For limestone and GGBS this could be attributed mainly to the dilution of the hydroxyl and alkali concentrations of the pore solution. Furthermore, the addition of fly ash or GGBS results ultimately in a denser microstructure which reduces the flux of ions in the pore solution. At similar Portland cement replacement levels to limestone or GGBS, fly ash was found to be more effective in inhibiting ASR. This can be explained by alkali incorporation during the pozzolanic reaction. In addition it is suggested that the release of aluminium from fly ash promotes the formation of non-swelling aluminosilicates which inhibit damaging ASR.

Keywords: ASR, fly ash, porosity, alkalis, aluminium

1 INTRODUCTION

The avoidance of damaging alkali-aggregate reactions by the use of latent hydraulic or pozzolanic mineral additions such as GGBS or fly ash is commonly attributed to the reduction in alkali and hydroxyl ion concentration of the pore solution of concrete. This could partly be explained by dilution of the alkali concentration of the pore solution when Portland cement is replaced by, for example, GGBS. In addition, it is possible that alkalis are immobilised in the reaction products of the SCM - as occurs with fly ash [1, 2, 3]. Furthermore, the addition of fly ash or GGBS results ultimately in a denser microstructure which reduces the flux of ions in the pore solution.

In the following, results are presented on the effect of GGBS and fly ash on the development of damaging ASR in concrete made with precambrian greywacke as the reactive aggregate fraction. The results of investigations with concrete - expansion of prisms and crack formation in cubes - are compared with porosity and changes in the concentrations of sodium, potassium and hydroxyl ions as well as silicon and aluminium ions in the pore solution. Attention is focused on the question as to whether the occurrence of the alkali-aggregate reaction is reflected by changes in the composition of the pore solution. In addition, specific characteristics of the mineral additions were investigated regarding the formation, perhaps delay or even complete prevention of damaging ASR.

2 CONCRETE COMPOSITIONS AND MATERIALS

Different concrete compositions with precambrian greywacke as reactive aggregate were produced in the laboratory [4]. Binder contents of 400 and 500 kg/m³ were used with w/b ratios of 0.45 and 0.5, respectively. The greywacke was used in the 2/16 mm fraction making 70% of the total aggregate graded at A16/B16 according to DIN 1045. The cement was replaced by weight with different quantities of SCM at constant w/b ratio; b is the total amount of cement and SCM. Starting from compositions with pure Portland cement, the mass ratio of binder paste to greywacke was kept constant. This was achieved by adjusting the amount of 0/2 mm inert quartz sand in the mixes. The composition of the concretes is listed in Table 1. In addition, binder pastes (P) were produced having the same composition as the pastes in the concretes. The different concretes are labelled according to the amount of SCM or the alkali equivalent of the cement and the composition of the concrete, e.g. GW2/1.0 denotes concrete composition GW2 made with cement Z2 having 1.02 wt.% Na₂O_e.

The Portland cements CEM I 32.5 R (Z1 to Z4) have alkali equivalents between 0.65 and 1.21 wt.%, Table 2. The cements containing GGBS, CEM II/A-S and CEM III/A, are in the same strength class 32.5 and originate from the same plant as the Portland cement Z1 with 1.21 wt.%

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Na₂O_e. They contain 13 and 42 % GGBS, respectively. The fly ash (F) fulfils the requirements of DIN EN 450-1 [5] and is, with an alkali content of 3.6 wt.%, in the upper region of the range of permitted alkali equivalent (maximum 5.0 wt.% Na₂O_e). The finely ground limestone (GL) serves as an inert SCM for comparison, see Table 2 and Table 3.

3 INVESTIGATIONS

In order to investigate expansion and crack formation behaviour, concrete prisms 500 mm × 100 mm × 100 mm and 300 mm × 300 mm × 300 mm cubes were stored in a fog chamber at 40°C and 100%RH according to Part 3 of the Alkali Guideline published by the German Commission for Reinforced Concrete (DAfStb) [6]. The effect of alkali leaching during storage in the fog chamber at 40°C on the results of the investigations with concrete is unknown, but is assumed to be similar for all specimens investigated. Pore solution were expressed under high pressure from concrete specimens also stored at 40°C, but sealed to prevent moisture exchange with the surroundings. The concentration of cations in the pore solutions was analysed by ICP OES and the concentration of hydroxyl ion determined by titration with neutral red as indicator. Pore size distributions were recorded for hardened binder paste specimens with mercury intrusion porosity.

4 RESULTS AND DISCUSSION

4.1 Expansion and Cracking of Concrete

Table 4 and Figure 1 show the progression of expansion and crack formation of selected concretes during storage at 40°C in the fog chamber. The precise definition of the time at which damage begins is difficult. A further difficulty is the estimation of the time at which damage begins in concrete under field conditions based on the results of fog chamber observations. A direct comparison between the present fog chamber results and the behaviour of parallel specimens stored under natural weather conditions is planned for the future. In the present study, the onset of damage was defined as the time at which expansion of concrete prisms exceeded 0.4 mm/m or cracking was first apparent.

Regarding the onset and degree of damaging ASR, the concretes GW1, GW2 and GW2/1.0 made with pure Portland cement proved insensitive to variation of the alkali content between 4.1 and 6.0 kg/m³ and changes in w/c ratio between 0.45 and 0.5. At an age of 2 months, a large increase in length occurred over a period of 5 months. Afterwards the expansion slowed down reaching terminal values between 1.55 and 1.62 mm/m at ages between 7 and 12 months. Opposed to this, small changes in the amount of SCM resulted in a significant delay of damage onset compared with pure Portland cement. For concretes GW2 made with 13% GGBS, 20% GL and 10 or 20% fly ash, the onset was delayed from 3 months to 5, 6, 13 and 21 months, respectively, Table 4. This occurred even though the alkali contents of the concretes (3.9 to 4.4 kg/m³) were similar to those of the concretes made with Portland cement only, Table 1.

To gain insight in the degree of acceleration of ASR produced by storage in the 40°C fog chamber, the fog chamber results were used to estimate roughly the onset of damage for the concrete specimens stored outdoors, [7]. It was found that 3, 12 and 36 months until damage onset in the fog chamber corresponds to 3, 13 and 40 years under natural weather conditions, respectively.

After approximately twelve months expansion sets in for concrete GW1 made with 20% fly ash as well as concrete GW2 with 10% fly ash. However, the concrete containing more fly ash expands more slowly. The replacement of 20% of the Portland cement in concretes GW1 and GW2 by fly ash does not lead to identical behaviour. After 12 months the onset of expansion was observed for concrete GW1 made with 20% fly ash. Opposed to this, the expansion of concrete GW2 with 20% fly ash reaches 0.4 mm/m after 21 months. The different onsets of expansion and expansion rates of the concretes GW1 with 20% fly ash and GW2 with 10 and 20% fly ash may be explained by the different total alkali contents of these concretes, 4.8, 4.4 and 3.9 wt.%, respectively, Table 1. This means that the specification of the proportion of SCM in the binder is alone an insufficient measure to avoid damaging ASR in concrete. It is necessary to take the alkali content of the Portland cement into account as well. However, on comparing the onset of damage for concretes GW2 made with 20% ground lime stone or 20% fly ash (both binder compositions with an alkali content of 3.9 wt.% calculated from the Portland cement content) which occurs after 6 and 21 months, respectively, it is obvious that other factors beside the calculated alkali content must be considered regarding the effect of fly ash on the avoidance of ASR.

The concretes made with 42% GGBS or 30 to 35% fly ash or made with low-alkali equivalent cement only (0.76 or 0.65 wt.% Na₂O_e) still show no signs of damage after 36 months (concretes

GW1/35F, GW2/0.7 and GW2/0.6 are not listed in Table 4). It is not expected that ASR damage will occur in these concretes after longer storage periods.

4.2 Porosity of Concrete

The type of SCM has a considerable effect on the porosity and denseness of the concrete microstructure. This is demonstrated by the pore size distributions of the hardened binder pastes corresponding to concretes GW2 made with cement Z1, Table 5.

Compared with the pure Portland cement binder paste P2, the use of 20% ground lime stone increases the binder paste porosity by about 24%. This corresponds to the increase in w/c ratio of 0.45 to 0.56 when Portland cement is replaced by ground lime stone. Despite the increase in w/c ratio (c = Portland cement) from 0.45 to 0.52 and 0.56 for binder compositions containing 13 % GGBS and 20% fly ash, respectively, see Table 3, no significant change in total porosity is observed after hydration for 90 days at 40°C.

The transport of ions in concrete is governed by the volume fraction of capillary pores and not just total porosity, i.e. the pore size distribution is important. In general, the inclusion of ground lime stone in the binder results in a coarser pore structure, whereas fly ash leads to a significantly finer structure. The pore size distributions measured for hardened pastes made with Portland or Portland blast furnace cement with 13 % slag were found to be similar.

Since the diffusion flux of ions in concrete is approximately proportional to capillary porosity, the transport properties of the binder compositions can be estimated from the contribution of pore sizes above 40 nm to porosity. Compared with pure Portland cement pastes, the diffusion flux is increased by 40% when Portland cement is replaced by 20% ground lime stone. By contrast, the effectiveness of transport is reduced by 8% for binders with 13% slag. The use of 20% fly ash results in a large reduction of 25%.

Quantification of the effect of the transport properties of the hardened binder matrix on damaging ASR has, up to now, not been undertaken. Obviously, a reduction in the diffusion flux of ions in the binder matrix will slow down the supply of dissolved alkalis to the aggregate and thus the rate of the alkali-silica reaction. This may partly explain the different expansion rates for concretes with different amounts of fly ash, see Figure 1.

4.3 Changes in Pore Solution Composition with Time

In principle, the chemical reactions of the binder (hydration) and/or the aggregate (ASR) simultaneously affect the composition of the pore solution of concrete. However, it may be assumed that the hydration process in concrete made with Portland cement or Portland cement with GGBS has virtually ceased at an age of 90 d at 40°C. Thus for these concretes essentially only the slower ASR is observed. The pozzolanic reaction of the fly ash is also slow and leads to consumption of alkalis and calcium. It is therefore difficult to distinguish between changes due to the reaction of the aggregate and the fly ash. NMR investigations with a mixture of Portland cement and fly ash F showed that 50% of the fly ash has reacted after 180 d at 40°C [3]. It therefore appears permissible to attribute changes in the pore solution of concrete at high ages to ASR - including concrete made with fly ash.

Although ASR presumably affects the composition of the pore solution of young concrete, the comparison of the effects of different supplementary cementitious materials appears permissible at an age of 90 d. It was thus concluded in [3] that the replacement of Portland cement by ground limestone or GGBS, in the concrete compositions used in the present investigations, results in a proportional dilution of the concentrations of hydroxyl and alkali ions. In the case of fly ash, alkalis are also removed bonding in the products of the pozzolanic reaction.

In the case of concrete mixed with Portland cement or Portland cement combined with GGBS or ground lime stone, a reduction in the concentration of hydroxyl and alkali ions in the pore solution occurs with time which does not depend on the alkali content of the concrete or the initial concentrations of hydroxyl ions or dissolved alkalis in the pore solution. This effect is due to chemical reactions between the alkali-sensitive greywacke aggregate with the alkaline pore solution. Nevertheless, it is not possible to correlate generally ASR damage with a particular consumption of alkalis or hydroxyl ions. For example, after 36 months, expansion or cracks are not observed for concrete GW2 with 100% Portland cement Z3 ($\text{Na}_2\text{O}_e = 0.76 \text{ wt.}\%$) or GW2 with 42% GGBS ($\text{Na}_2\text{O}_e = 1.2 \text{ wt.}\%$) in spite of a relatively high consumption of alkalis, see Figures 1 and 2. As expected, no signs of macroscopic gel formation were found on freshly fractured surfaces of concrete GW2 with 42% GGBS whereas abundant gel deposits were still present in the pores of concrete made with 13 % GGBS. This shows that the consumption of alkalis is not generally related to the amount of gel and thus the degree of ASR damage. Up to now, it has not been possible to determine the

particular reactions or localise the place at which the reaction products are deposited in these concretes.

However, the rate of alkali removal from the pore solution is smaller for lower initial concentrations. In general, two reaction phases may be assumed. At the beginning a rapid reaction occurs between the reactive components on the surface of the aggregate particles and the pore solution which subsequently slows down. As expected for reactions governed by kinetics, low initial alkali concentrations lead to lower initial rates of removal of alkalis from the concrete pore solution. An additional factor is the transport of ions from the paste matrix to the surface of the aggregate particles. In view of their similar capillary porosity, similar transport effects are expected for the concretes made with Portland cement and Portland blast furnace cement. In contrast the rapid drop in the concentrations of OH⁻ and alkalis observed for concrete with 20% ground limestone in the binder supplies evidence for the effect of transport since, based on capillary porosity, the diffusion flux in this concrete is about 40% higher than for the equivalent Portland cement concrete, see Table 5. Following the reaction of aggregate surface material, the ions diffuse deeper into the aggregate itself – a process which is limited by the relatively low diffusivity of greywacke. Apparently, this process and the reduction in concentration gradient caused by the removal of OH⁻ and alkalis from the pore solution cause the alkali consumption to slow down.

It should be pointed out that the behaviour of the concretes made with fly ash does not conform to the above arguments, compare Figures 2 and 3.

There is much evidence that there is no significant release or even binding of alkalis from fly ash with moderate alkali and CaO contents (up to 5 wt.% or 10wt.%, respectively) according to the requirements of DIN EN 450 [2, 3, 8]. However, the concretes with 20 to 30% fly ash exhibit a relatively low consumption of OH⁻ over one year and virtually no reduction in alkali content of the pore solution see Figure 3. At first sight, this could be interpreted as the release of additional alkalis from the fly ash during the first year. However, this would be accompanied by a parallel increase in OH⁻ concentration.

Only the concrete made with 10% fly ash in the binder behaves in a similar manner to a Portland cement concrete, i.e. a similarly high consumption of alkalis like concrete GW2 made with Portland cement Na₂O_e = 1.0 wt.% or concrete GW2 with 13% slag in the binder. This may just be due to the very low amount of fly ash.

After a short decrease in alkali content of the pore solution in the first 90 days, the reaction seems to remain virtually dormant over a period of twelve months, Figure 3. It should be pointed out that the different concrete mixes were produced over a period of two years so that storage and pore solution extraction were performed at different times; the pause in reaction observed for different specimens was found to be reproducible. At ages higher than 12 months, the alkali concentration of the pore solution in concretes with fly ash decreases slowly in a similar manner to concrete with 100% Portland cement. This decrease in concentration correlates with the increase in expansion of concretes made with 20 to 25% fly ash in the binder, cf. Figures 1 and 3.

Earlier investigations using NMR revealed enhanced C-A-S-H formation in hardened Portland cement / fly ash pastes together with large amounts of dissolved aluminium in the pore solution. However, a large proportion of the aluminium in the binder could not be accounted for by the amounts of aluminium in the C-A-S-H phases and calcoalumino sulphate phases. It is suggested that the remaining aluminium could be in a phase which acts as a buffer for reactions with silicon released from the aggregate. The solubility limit of aluminium in the highly alkaline pore solution appears to be between 2 and 3 mmol/l.

NMR investigations revealed additional evidence for the formation of small amounts of non-swelling aluminosilicates along with the ASR gel [3]. This suggests that only a small amount of aluminosilicates was found in ASR gel taken from the pore space of damaged concrete because, as opposed to the mobile ASR gel, the aluminosilicates (like C-S-H) remain at their location of formation.

The rapid decrease in alkali concentration in the first 90 days coincides with a pronounced decrease in the aluminium concentration of the pore solution, cf. Figures 3 and 4. This could indicate the formation of aluminosilicates. Two reactions involving Si dissolution and dissolved Al are postulated. The adsorption of aluminium on the surface of the silicates and the formation of aluminosilicates in the pore solution. The adsorption of aluminium will probably not prevent further Si dissolution, but will at least slow it down [9, 10]. This argument has already been used by other authors [9, 11] to explain the self-inhibiting effect of sandstone or greywacke with respect to alkali-silica dissolution, where it is necessary that the particles are able to release sufficient amounts of

aluminium into the alkaline solution. Obviously, aluminium can also be supplied for this reaction by fly ash in the binder paste matrix as well as from the aggregate.

Like the consumption of alkalis, an increase in silicon concentration of the pore solution does not necessarily indicate the beginning of damaging ASR, cf. Figures 1 and 4. Although in extremely damaged concretes the alkali reaction is accompanied by the release of large amounts of silicon into the pore solution (40 to 80 mmol/l) there is no evidence for a threshold in silicon concentration of any type. In fact, the region between 10 and 30 mmol/l in Figure 4 contains a mixture of damaged and undamaged concretes, cf. concretes with 13% GGBS, 10 to 30% fly ash and GW2 1.0.

It is apparent that up to an age of at least one year the concentrations of aluminium (1 to 2 mmol/l) and silicon (2 to 10 mmol/l) in the pore solution of concrete made with fly ash are similar, see Figure 4. It may be assumed that the aluminium comes from the fly ash. Larger amounts of fly ash in the binder are expected to result generally in higher aluminium concentrations which can be maintained for a longer period of time. Based on the present results, it is not possible to separate the contributions of fly ash and the alkali-silica reaction of the aggregate to the concentration of silicon. A silicon concentration of 2.4 mmol/l was measured for hardened cement paste P2 20% F at an age of 365 days which is similar to the concentration (3.7 mmol/l) measured for concrete GW2 0.7 made with 100% Portland cement. In contrast, the aluminium concentration for the hardened paste (1.5 mmol/l) was markedly higher than the concentration for the concrete (0.3 mmol/l). This provides evidence that the enhanced silicon concentration is due to the alkali-silica reaction of the aggregate.

The silicon to aluminium ratio in Figure 5 provides a much better correlation between pore solution composition and the beginning of expansion of concrete. It seems that ASR damage does not occur as long as the Si/Al ratio remains roughly under 20 to 30, cf. Figures 1 and 5, left. In Figure 5, right, the concentration of aluminium is plotted as a function of the silicon concentration of the pore solution. It can be seen that an increase in silicon concentration coincides with a reduction in aluminium concentration. Although not direct proof, this nevertheless provides evidence for an inhibiting effect of aluminium on the dissolution of silicon. This is supported by the concrete mixes with fly ash where the hydroxyl concentration was observed to remain around 400 mmol/l for a long period of time and nevertheless damage did not occur, Figure 1 and Figure 3, left. It is suggested that a competition exists between the release of aluminium from fly ash and the consumption of aluminium due to the formation of aluminosilicates with silicon from aggregate and/or binder constituents. When the supply of aluminium from the fly ash declines more damaging alkali silicate gel with swelling potential is formed at a faster rate.

5 CONCLUSIONS

The reaction of the alkali-active aggregate material results in a corresponding progressive decrease in the hydroxyl ion concentration of the pore solution. Nevertheless, a sufficient amount of damaging reaction products form only at high ASR active alkali contents in concrete.

At similar Portland cement replacement, levels fly ash delays the beginning of ASR damage much more than ground lime stone or GGBS.. This is caused by a decrease in alkali and hydroxyl concentration due to binding in reaction products and a reduction in ion diffusion flux due to a denser paste matrix. Furthermore, it is suggested that aluminium released by the fly ash has an inhibiting effect on ASR.

Changes in the concentrations of alkalis or silicon in the pore solution with time do not yield a distinct indication of the beginning of ASR damage in concrete. However, there is evidence that little ASR damage occurs while a low Si/Al molar concentration ratio is maintained in the pore solution. This can be achieved even when relatively low amounts of cement are replaced with fly ash. When the release of aluminium from fly ash into the pore solution decreases then damage can occur even after many years. To postpone ASR damage, the binder should contain sufficient fly ash - the amount depending on the effective alkali content of the cement. This way the hydroxyl ion concentration - as the main factor controlling ASR - has already reached a low value when the Si/Al ratio increases and thus no damaging ASR occurs.

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TABLE 1: Concrete composition and other characteristic values.

Component	GW1					GW2					GW2	GW2	GW2	
Cement	Z1(1.2)					Z1(1.2)					Z2(1.0)	Z1(1.2)	Z1(1.2)	
											Z3(0.7)	GGBS	GGBS	
											Z4(0.6)	13	42	
b = c + SCM [kg/m ³]	500					400					400	400	400	
w/b ratio	0.50					0.45					0.45	0.45	0.45	
Greywacke	70 wt.% of the aggregate; fraction 2/16 mm; grading A16/B16													
SCM [wt.%]	0	20 F	25 F	30 F	35 F	0	10 F	20 F	20 GL	25 F	30 F	0	0 (13)	0 (42)
Alkali content ¹⁾ of concrete [kg/m ³]	6.0	4.8	4.5	4.2	3.9	4.8	4.4	3.9	3.9	3.6	3.4	4.1/3.0 /2.6	4.4 (4.2 ²⁾)	4.0 (2.8 ²⁾)
w/c ratio	0.50	0.62	0.67	0.71	0.77	0.45	0.50	0.56	0.56	0.60	0.64	0.45	0.45 (0.52 ²⁾)	0.45 (0.78 ²⁾)
f _{cm28d} [N/mm ²]	45	38	36	36	31	52	47	47	45	41	42	~52	50	46

¹⁾ Alkali content = Na₂O_e of cement [wt.%] × cement content [kg/m³]

²⁾ Theoretical calculation for contribution of Portland cement clinker only

TABLE 2: Chemical composition of the cements used.

Cement:	Z1	Z2	Z3	Z4	Z1 GGBS13	Z1 GGBS42
Oxide [wt.%]	CEM I				CEM II/AS	CEM III/A
CaO	60.8	64.2	62.6	64.1	57.7	53.3
SiO ₂	19.7	19.3	21.8	21.5	22.1	25.8
Al ₂ O ₃	5.0	4.8	5.6	5.5	6.0	7.4
Fe ₂ O ₃	3.5	2.5	2.3	2.7	2.9	2.2
Na ₂ O	0.27	0.33	0.19	0.27	0.27	0.29
K ₂ O	1.43	1.05	0.87	0.58	1.24	1.08
Na ₂ O _e	1.21	1.02	0.76	0.65	1.09	1.00

TABLE 3: Properties of greywacke und binder materials used.

Oxide	Aggregate and binder materials [wt.%]		
	Greywacke	Ground limestone	Fly ash
CaO	1.1	--	3.6
SiO ₂	67.1	--	47.8
Al ₂ O ₃	16.5	--	26.6
Fe ₂ O ₃	4.9	--	9.1
Na ₂ O	2.78	0.13	1.36
K ₂ O	3.04	0.12	3.41
Na ₂ O _e	4.78	0.21	3.61
	Fineness [wt.-% > 45µm]		21.4
	Activity index 28d / 90d [%] [5]		84 / 98
	Glass content ¹⁾ [wt.-%]		80

¹⁾ XRD with Rietveld analysis

TABLE 4: Expansion values and crack widths in selected concretes at different times.

Concrete	GW1				GW2						GW2/ 1.0	GW2 13 GGBS	GW2 42 GGBS
	0	20F	25F	30F	0	10F	20F	20 GL	25F	30F			
SCM [wt.%]	0	20F	25F	30F	0	10F	20F	20 GL	25F	30F	0	0 (13)	0 (42)
[months]													
Prism expansion > 0.4 mm/m	3	15	29	--	3	13	21	9	36	--	4	5	--
Expansion 3 [mm/m] ⁹	0.42	0.08	0.00	0.06	0.43	0.17	0.08	0.24	0.08	0.13	0.36	0.22	0.10
12	1.60	0.15	0.09	0.13	1.50	0.22	0.16	0.41	0.14	0.13	1.55	1.30	0.15
24	--	0.27	0.17	0.18	1.55	0.35	0.20	0.45	0.20	0.17	1.58	1.30	0.20
36	--	0.75	0.32	0.25	--	¹⁾	0.43	0.37	0.30	0.20	--	--	0.24
	--	1.19	0.59	0.34	--	--	0.65	--	0.39	²⁾	--	--	0.26
Cubes start cracking	4	29	--	--	3	14	--	6	--	--	4	6	--
Crack width 3 [mm] ⁹	--	--	--	--	0.05	--	--	--	--	--	--	--	--
12	0.8	--	--	--	0.7	--	--	0.4	--	--	0.6	0.1	--
24	1.0	--	--	--	0.8	--	--	0.6	--	--	0.65	0.4	--
36	--	--	--	--	--	³⁾	--	1.2	--	--	--	--	--
	--	0.05	--	--	--	--	--	--	--	--	--	--	--
Beginning of damage ⁴⁾	3	15	29	--	3	13	21	6	36	--	4	5	--

¹⁾ 0.57 mm/m after 16 months

²⁾ 0.19 mm/m after 30 months

³⁾ 0.1 mm after 19 months

⁴⁾ Defined as expansion > 0.4 mm/m or beginning of cracking

TABLE 5: Porosity and contribution of different pore diameter ranges to porosity of hardened binder paste; 90d / 40°C; w/b = 0.45 = const.

Binder paste	Total	> 4 nm	> 10 nm	> 20 nm	> 40 nm	> 100 nm
P2 20GL	40.4	39.6	33.3	28.7	23.6	16.8
P2	32.7	31.9	26.4	22.0	16.6	5.5
P2 13GGBS	31.9	30.8	24.0	19.9	15.3	6.4
P2 20F	34.1	33.0	24.4	19.0	12.4	5.3

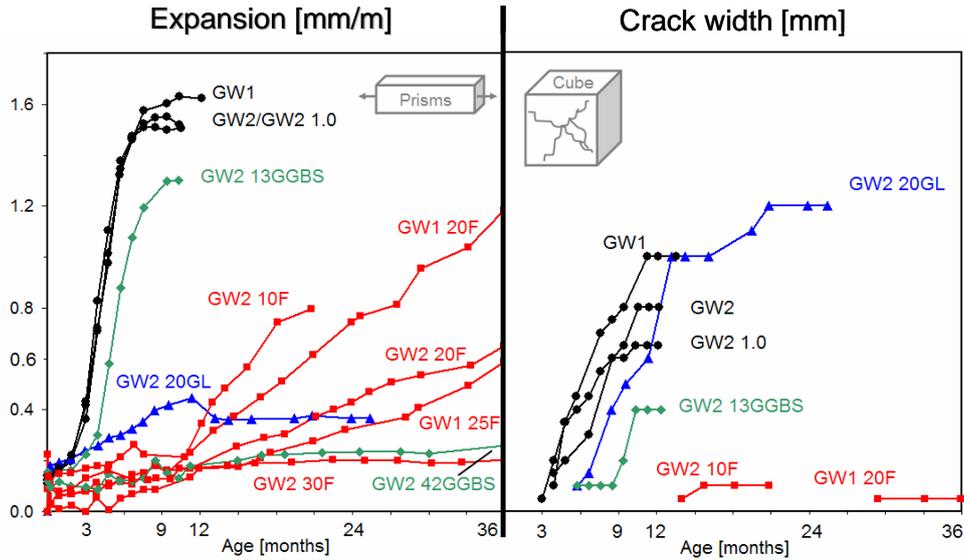


Figure 1: Development of expansion (left) and cracking (right) for concretes made with different binder compositions.

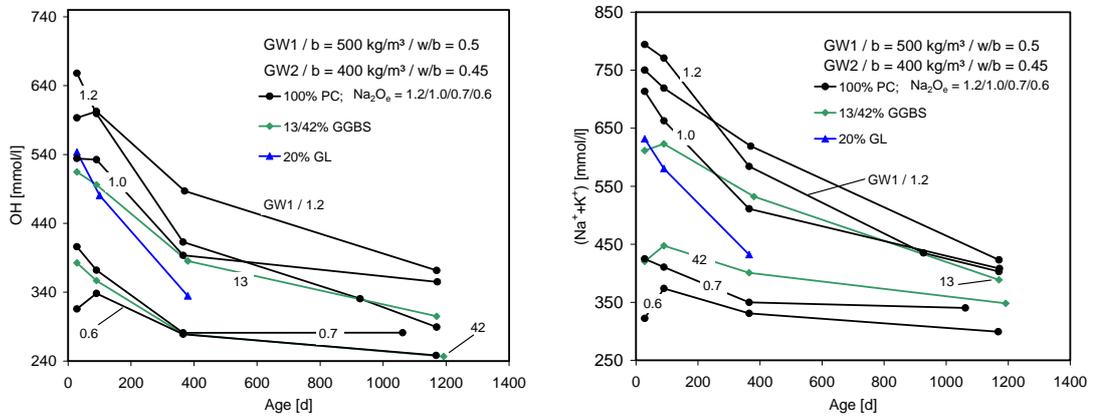


Figure 2: Effect of SCM on the hydroxyl (left) and sodium and potassium (right) ion concentration of the pore solution of concretes with 100% Portland cement, ground granulated blast furnace slag and ground limestone during storage at 40°C.

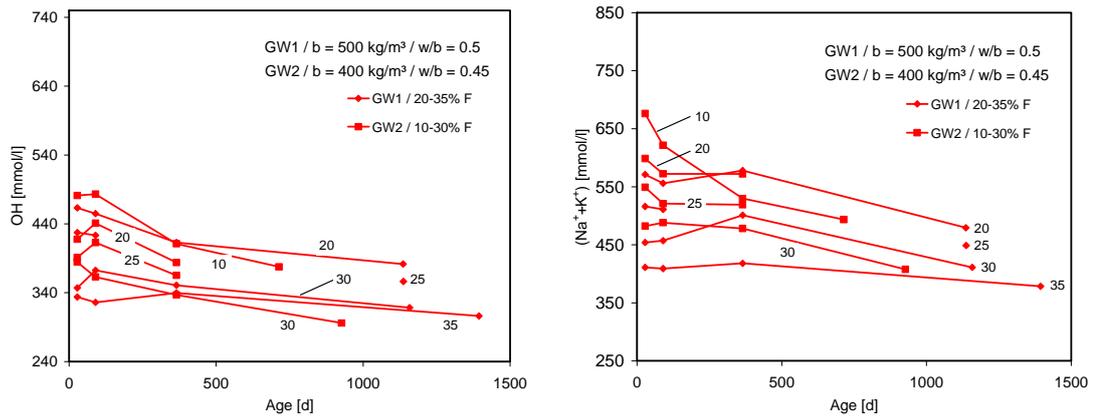


Figure 3: Effect of SCM on the hydroxyl ion (left) and sodium and potassium (right) ion concentration of the pore solution of concretes with fly ash during storage at 40°C.

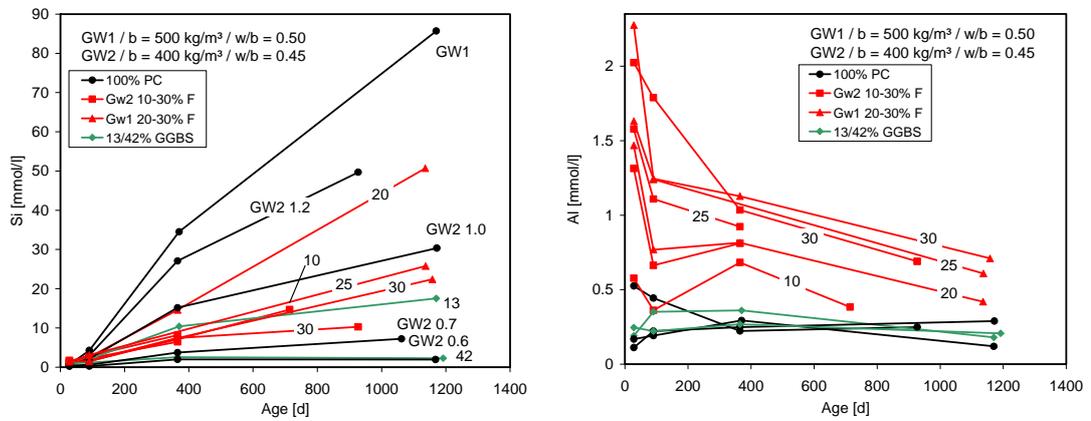


Figure 4: Effect of SCM on Si (left) and Al (right) concentration of the pore solution during storage at 40°C.

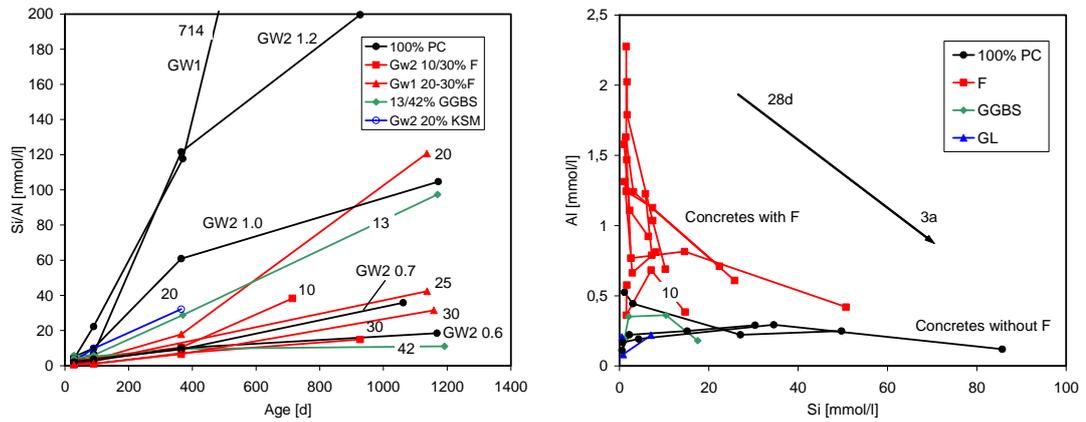


Figure 5: Relationship between the concentrations of Si and Al in the pore solution. Left) Si/Al with time. Right) Al as a function of Si.