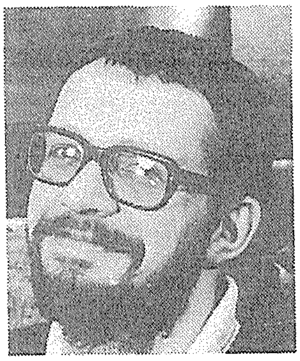

INFLUENCE OF THE CURING CONDITIONS ON THE FLEXURAL STRENGTH OF ALKALI ACTIVATED BLAST-FURNACE SLAG MORTAR

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Changes in compressive and flexural strength of alkali activated mortar due to different curing conditions have been investigated. Influence of water curing, air curing and alternating curing in water and air have been studied. Relations between flexural strength, changes in water content and deformations of alkali activated slag mortar at alternating curing conditions have been analyzed and compared with those of slag cement and portland cement mortars.

Keywords: Air and water curing, alternating curing, alkali activation, blast-furnace slag, compressive and flexural strength, dimensional changes, gel structure.

1 INTRODUCTION

Alkali activated blast-furnace slag as a rapid hardening cement has been reported in many research works and patents. In these investigations, mainly based on /1, 2/, slags of different origins and basicities have been activated by sodium hydroxide, soda, water glass and other alkalies and cured under various conditions, normal curing, heat curing and autoclaving. High strength at early and later age have been obtained. Industrial applications have been mentioned /3/. A short review of the literature is presented by the authors in /4/. - In Finland recently one type of AS-binder, so called F-cement, has been developed and applied in the precasting industry with promising results /5/.

In previous works by the authors /4, 6/ the high strength at normal curing and autoclaving was confirmed. At heat curing the strength was low. Furthermore, at normal curing a considerable decrease in flexural strength at drying after previous water curing was noted. This phenomenon is not mentioned in the literature on alkali activated slags studied. On the other hand a similar phenomenon in the case of portland cement mortars and the changes related to shrinkage stresses are reported in /7/. However, the course of the strength and the magnitudes of the changes were not the same as in the alkali activated slag mortars tested.

In the current work the changes in flexural strength of normal cured alkali activated slag (AS) mortar due to different treatments have been investigated. Influence of different periods of water curing, air curing as well as alternating curing conditions in water and air has been studied. The relations between flexural strength, changes in water content and deformations of the AS-mortar at alternating curing have been analyzed and compared with those of slag cement (SC) and ordinary portland cement (PC) mortars.

2 LABORATORY TESTS

2.1 Programme and materials

The investigations were divided into two parts. In part I the influence of the curing conditions on the flexural strength of the AS-mortar was tested. In part II the properties of the AS-mortar were compared with those of SC- and PC-mortars.

Part I

In this part only AS was used. The slag was produced at the steel plant of Domnarvet and activated in our laboratory by 3.5% NaOH (chemical pure). The properties of the slag are shown in Table I.

Table 1. Physical and chemical properties of the slag used.

True density kg/m^3	Blaine m^2/kg	Glass content %	Chemical composition, %						
			CaO	SiO_2	Al_2O_3	FeO	MgO	MnO	S
2860	530	95	42.6	32.5	8.7	1.4	7.0	1.1	1.2

The mortar was of plastic consistency. The binder/sand-ratio was 1/3 and the W/C-ratio 0.43. The specimens 4x4x16 cm were made by means of vibration on a vibrating table. During the first day after casting the specimens were treated in foil. After removing the moulds at the age of 24 hours different curing conditions were applied.

Series 1 - water curing in +20°C

- continuous water curing (series 11)
- water curing followed by air curing at day 7 (series 12)
- water curing followed by air curing at day 28 (series 13)

Series 2 - air curing in +20°C, RH = 50%

- continuous air curing (series 21)
- air curing followed by water curing at day 7 (series 22)
- air curing followed by water curing at day 28 (series 23)

Series 3 - alternating curing

- water/air curing finished in air (series 31)
- water/air curing finished in water (series 32)
- air/water curing finished in water (series 33)
- air/water curing finished in air (series 34)

In all series both the flexural and compressive strengths were tested.

Part II

In this part three different binders were used - AS, SC and PC. The materials of the AS were the same as in part I. The PC was ordinary portland cement (Blaine 360 m^2/kg) and the SC was mixed with the slag and ordinary portland cement in the proportions 1/1.

The mortars tested were all of plastic consistency. The binder/sand-ratio was kept constant 1/3. For the consistency applied the W/C-ratios of the AS-, SC- and PC-mortars were 0.43, 0.46 and 0.50 respectively.

The dimensions of the specimens, the compaction procedure, the curing conditions during the first day after casting and the stripping time were the same as in part I. After removing the moulds alternating water/air-curing was applied. In addition to the flexural strength, the changes in water content and the dimensional changes of the specimens during the water curing periods (wetting) and the air curing periods (drying) were measured.

2.2 Results and discussions

Part I

The test results concerning part I are presented in Figs. 1 and 2.

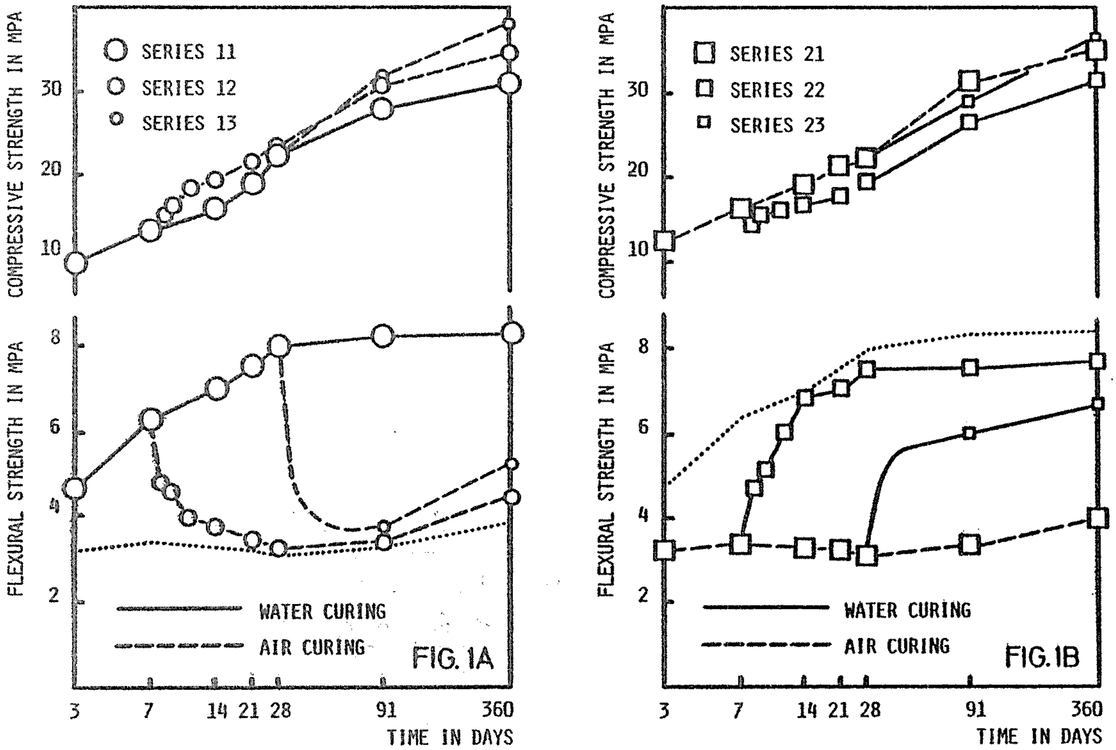

Fig. 1. Influence of water curing and air curing on the compressive and flexural strengths of the AS-mortar. W/C-ratio 0.43. Fig. 1A: Continuous water curing followed by air curing at two different times. Fig. 1B: Continuous air curing followed by water curing at two different times.

The Figures 1A (series 1) and 1B (series 2) show considerable differences in flexural strength between the water cured and air cured mortars. At continuous water curing (series 11) the strength was about 100% higher than that at continuous air curing (series 21) in which only insignificant changes in strength were noted. - Air curing after 6 days of water curing (series 12) resulted in a rapid and considerable decrease in strength. Up to the age of 91 days the strength approached asymptotically to that obtained at continuous air curing. At further curing in air some increase in strength was observed. At air curing after 27 days of water curing (series 13) a similar tendency was observed. However, the final strength seemed to be higher than that in series 12.

Water curing after 6 days of air curing (series 21) resulted in a rapid and considerable increase in strength. The graph of the strength development approached asymptotically to that obtained at continuous water curing. A week after immersion in water the strength achieved 90% of that in series 11. Water curing after a longer period of air curing (series 23) resulted in lower strength.

Regarding the compressive strength, the influence of the curing conditions was not substantial. In spite of the curing conditions applied the strength increased in general.

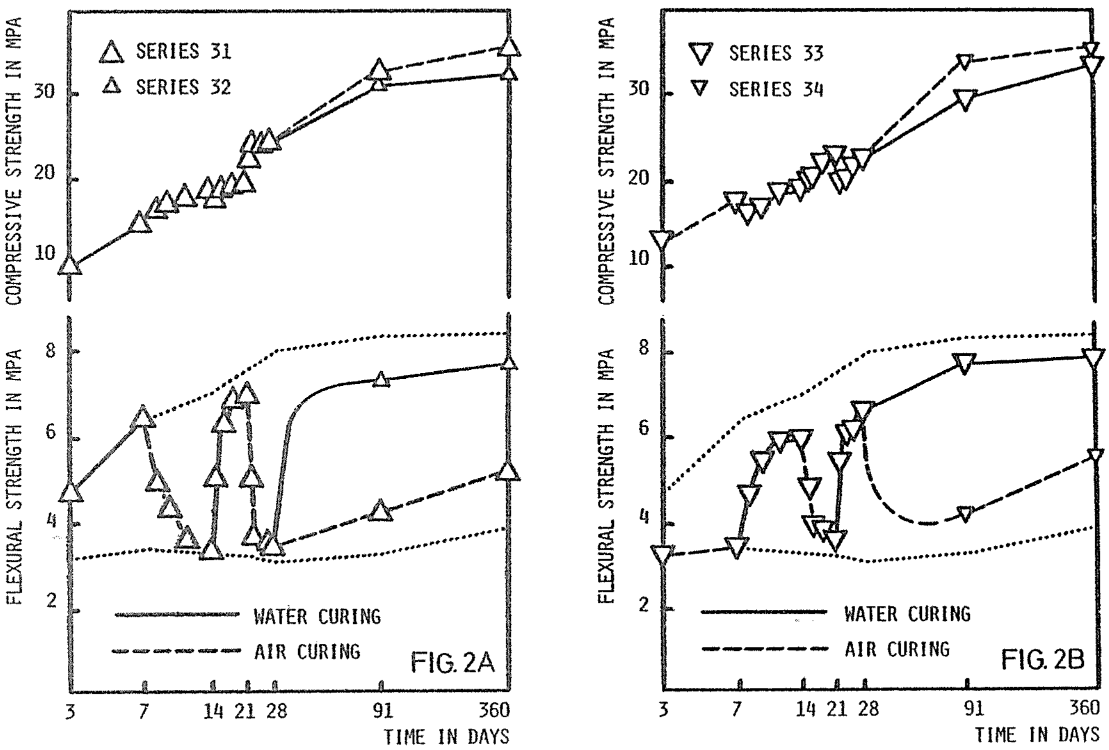

Fig. 2. Influence of alternating curing conditions on the compressive and flexural strengths of the AS-mortar. W/C-ratio 0.43.
Fig. 2A: Alternating curing in water and air.
Fig. 2B: Alternating curing in air and water.

At alternating water/air-curing (series 31 and 32) in Fig. 2A and alternating air/water-curing (series 33 and 34) in Fig. 2B the similar tendencies as in series 1 and 2 respectively can be seen. In both cases the changes in flexural strength were of approximately reversible character. The course of the strength approached asymptotically to those obtained at continuous water curing and air curing respectively. The final strength of the mortars where the curing was finished in water (series 32 and 33) was about 10% lower than that obtained at continuous water curing. For the mortars where the curing was finished in air (series 31 and 34) the final strength was 40% higher than that obtained at continuous air curing. - Regarding the compressive strength in series 3, insignificant influence of the curing conditions as in the series 1 and 2 was noted.

Part II

The test results concerning part II are presented in Fig. 3.

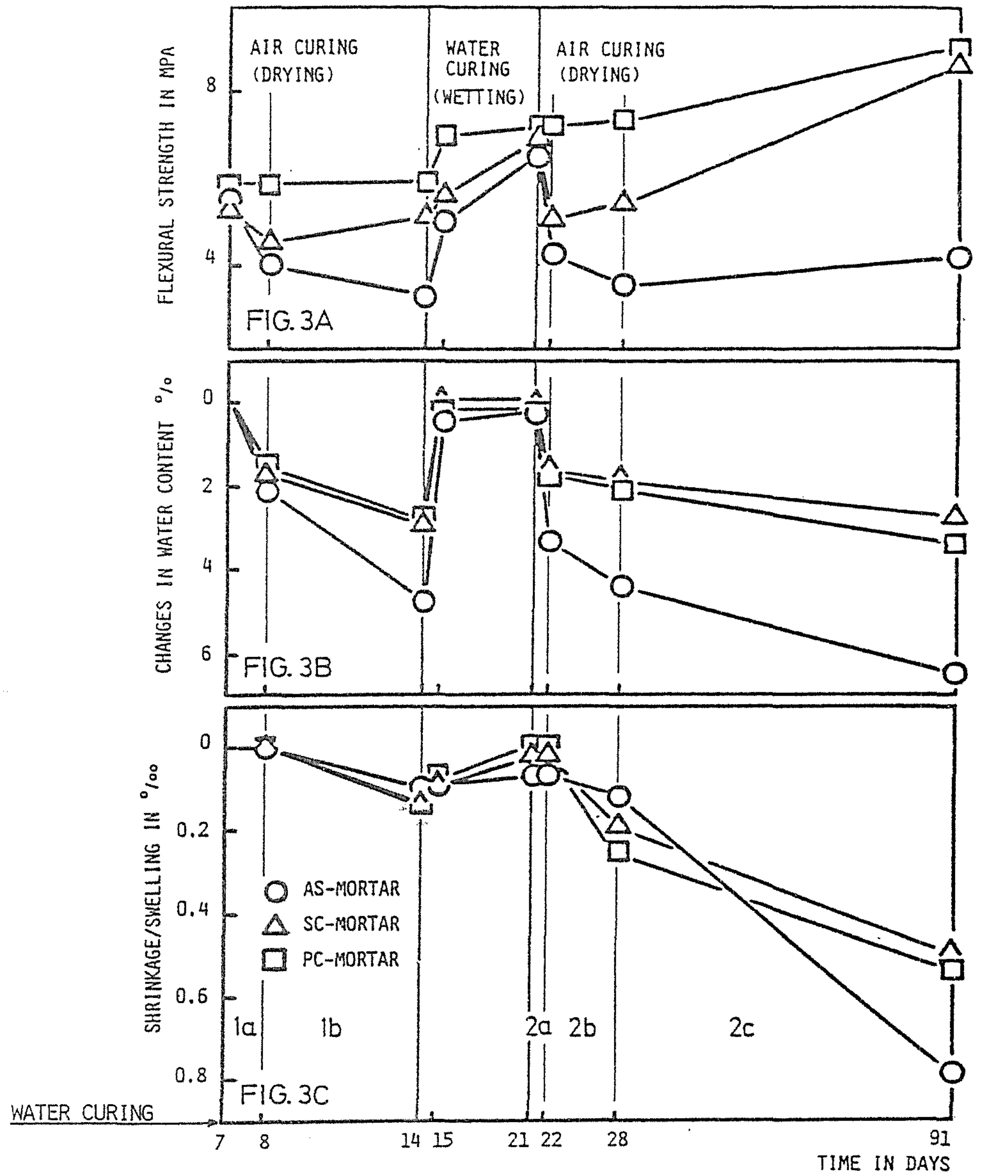

Fig. 3. Changes in flexural strength, water content and dimensional changes of AS-, SC- and PC-mortars due to drying and wetting. The W/C-ratios of the AS-, SC- and PC-mortars were 0.43, 0.46 and 0.50 respectively. 1a, 1b, 2a, 2b and 2c are characteristic stages of the two periods of drying.

Fig. 3A shows that the tendency of changes in flexural strength of the AS-mortar due to the alternating curing conditions was similar to those obtained in the tests in part I. For the SC-mortar a similar tendency of decrease in strength at drying and increase at wetting was observed. However, the changes were less pronounced and the strength recovered unlike that of the AS-mortar at further air curing. In the case of PC-mortar no significant changes at drying could be noted.

Fig. 3B shows that the loss in water content during the two drying periods was of exponential character in all mortars tested and significantly larger for the AS-mortar. The loss of water of the SC- and PC-mortars was almost alike. - At wetting a similar character of the changes in water content was observed.

Fig. 3C shows that the shrinkage during the first period of drying was insignificant in all mortars tested. At the following wetting period the deformations of the AS- and SC-mortars seemed to be partly irreversible, while in the case of the PC-mortar it was totally reversible. At the beginning of the second period of drying (stages 2a and 2b) the shrinkage of the AS-mortar still was insignificant but later on (stage 2c) considerable deformations were noted. In comparison with the SC- and PC-mortars the shrinkage was lesser at early age but considerably larger two months later.

The course of the changes in flexural strength of the AS-mortar showed distinct similarities to that of the changes in the water content until stage 2c - decrease at drying and increase at wetting (Figures 3A and 3B). In stage 2c the strength increased, while the water content still decreased. For the SC-mortar the similarities were evident just at the very beginning of each drying period (stages 1a and 2a) and at wetting, while for the PC-mortar only at wetting.

The deformations showed correlations to the changes in the water content in all the mortars tested (Figures 3B and 3C). However, their magnitudes were different. The relation between the two phenomena in different stages of the drying periods is shown in Table 2.

Table 2. The ratios between shrinkage and water loss of AS-, SC- and PC-mortars at different stages of the drying periods.

Mortars	$\Delta\varepsilon/\Delta W$					
	First period of drying, days 7-14		Second period of drying, days 21-91			
	Stage 1a (1 day)	Stage 1b (6 days)	Stage 2a (1 day)	Stage 2b (6 days)	Stage 2c (63 days)	Total (70 days)
AS	0	0.04	0	0.05	0.32	0.11
SC	0	0.11	0	0.57	0.34	0.17
PC	0	0.10	0	0.65	0.22	0.17

The shrinkage/water loss-ratio at the very beginning of each drying period (stages 1a and 2a) was equal to zero in all mortars tested (Table 2). No shrinkage even at considerable water loss could be observed. In stage 1b this ratio of the AS-mortar was significantly lower and in stage 2b considerably lower than those of the SC- and PC-mortars. However, at further drying (stage 2c) the ratio of the AS-mortar increased, while the ratios of the SC- and PC-mortars decreased. Considering the whole second period of drying the total shrinkage/water loss-ratio of the AS-mortar was lower than those of the other mortars in spite of much larger total shrinkage.

The relations between the deformations and the changes in water content of the SC- and PC-mortars are in full agreement with the thermo-dynamic theory, while the relation between the two phenomena in the case of the AS-mortar showed some irregularities. In the case of the SC- and PC-mortars the capillary structure of the materials has predominant influence on the relations discussed. The loss of water from larger pores and capillaries at the beginning of the drying period (stages 1a and 2a) is not causing volume changes, while later on the water loss from capillaries of smaller radius is resulting in significant deformations. In the case of the AS-mortar another additional factor is probably of significance and that seems to be the gel structure of the AS-binder causing large loss of water at drying without significant dimensional changes. A similar phenomenon is clarified in the theory of hardening of the gel structure of binders based on magnesium hydroxide /8/.

The relation between the flexural strength and the deformations at wetting was similar for all mortars tested - increase in strength accompanied with swelling (Figures 3A and 3C). At drying this relation was different in all materials tested. The relations during the first period of drying (stage 1a and 1b) were of the same nature as in the stages 2a and 2b. For the AS-mortar in the stages 2a and 2b considerable decrease in strength without any significant deformations was noted, while later on, in stage 2c, insignificant increase in strength accompanied with considerable deformations was observed. For the PC-mortar in stage 2a no changes in strength and deformations were noted. At further drying (stage 2b) the strength increased insignificantly with relatively large deformation, while in stage 2c the strength increased substantially with lesser deformations. For the SC-mortar the relation between the two phenomena was similar to that of the AS-mortar in stage 2a and similar to that of the PC-mortar in the stages 2b and 2c. Consequently, the relation between the changes in flexural strength and deformations was clear in the case of PC-mortar but less pronounced for the other mortars, especially for the AS-mortar.

3 CONCLUSIONS AND REMARKS

The investigations confirmed the test results obtained by the authors in the previous works /4, 6/ concerning the flexural strength of the AS-mortar.

- Considerably higher strength at continuous water curing than at continuous air curing.

- Considerable decrease in strength at air curing after previous water curing.

The results show that the strength is approaching asymptotically to that obtained at continuous air curing. At water curing after previous air curing the strength is increasing and in the same way approaching asymptotically to that obtained at continuous water curing. Some increase in final strength (in comparison with continuously air cured mortar) and some decrease in final strength (in comparison with continuously water cured mortar) are noted. The curing conditions at early age seem to be important. Longer water curing period is favourable. At alternating curing the changes in strength are almost of reversible character. - Concerning the compressive strength the influence of curing conditions was insignificant.

Comparative tests showed a similar but less pronounced tendency of changes in flexural strength of the SC-mortar than for the AS-mortar. In the case of the PC-mortar tested insignificant changes in strength were observed. With the decrease in strength of the AS- and SC-mortars no shrinkage could be observed. The deformations of the AS-mortar were delayed in comparison with the SC- and PC-mortars, while the total deformations were considerably larger. The relation between the changes in flexural strength and the deformations, being depending on the changes in water content, was clear in the case of the PC-mortar but less pronounced for the other mortars. The differences are due to the capillary structure of the materials and especially in the case of AS-binder due to the larger amount of gel component in the hydration products /9/. This gel component, causing large loss of water at drying and large gain at wetting without any significant volume changes, seems to be responsible for the changes in strength in both the AS- and SC-mortars tested.

These investigations reveal the need for further research before AS-binder could be used industrially. Special consideration is to be given to prevent the decrease in flexural strength at drying and to reduce the deformations. Overcoming these two drawbacks the material can be useful for industrial applications.

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