PROPERTIES OF ALKALI ACTIVATED SLAG CONCRETE

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Granulated blast furnace slag is a latent hydraulic binder which can be alkali-activated. Properties as flexural and compressive strength, porosity, shrinkage and structure have been studied on slag mortar activated with NaOH, Na_2CO_3 and Na_2SiO_3. The specimens have been either steam cured (up to +80°C during 8 hours) or submitted to normal curing conditions (+20°C and 80% RH).

The results indicate that slag activated by alkalies can have good mechanical properties. However a large number of micro cracks develops in the material and the shrinkage is larger than for ordinary Portland cement mortar.

Keywords: blast furnace slag, alkali activation, flexural and compressive strength, porosity, shrinkage, structure.

1. INTRODUCTION

Granulated blast furnace slag is used extensively in many parts of the world to supplement ordinary Portland cement (OPC) as a binder. Since the slag in itself is only a latent hydraulic binder it needs to be activated to achieve any notable strength.

Normally slag is activated with lime, directly or through OPC, or with gypsum. Activation of slag with lime (OPC) gives a concrete with a low heat of hydration, which is beneficial for mass concrete structures. Blended cements containing both OPC and slag are widely used in many countries /1/. Activation of slag with gypsum results in a rapid increase in strength, as well as high strength levels and excellent sulphate resistance. However, other kinds of durability are affected in a negative way and for this reason such activation is rare.

Awareness of and interest in a third type of activation, alkali activation, grew during the seventies, although the possibility has been known since at least 1940 /2/. Alkali activation refers to activation mainly by caustic alkali ROH, nonsilicate salts of weak acids R_2CO_3, R_2SO_3, R_2S, RF and silicate salts type $R_2O(n)SiO_2$ where R stands for alkali metal ions such as Na^+, K^+, Li^+ etc. Concrete produced with alkali activated cement has been used in numerous applications in the USSR and in a number of applications in Poland /3/. This kind of concrete is mainly used for concrete products such as in the precast industry where curing at elevated temperatures ensures a rapid strength development.

In Finland an activator named F-admixture was developed in the late seventies. It holds a combination of NaOH, Na_2CO_3 and a lignosulphonate (superplasticizer).

Concrete made with F-admixture - known as F-concrete - is characterized by a rapid strength development. Its properties have been thoroughly studied /4/ and they are reported elsewhere in the present publication /5/.

The Swedish Cement and Concrete Research Institute (CBI) has investigated the properties of alkali-activated slags in a more general manner. Some significant results are presented in this paper.

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2. MATERIALS USED

Slag from Oxelösund (Sweden) with a chemical composition shown in Table 1 was used. The slag was ground to three different specific surfaces, 350, 530 and 670 m^2/kg (Blaine).

Table 1 Chemical Composition of the slag and OPC used in the experiments

	Compound %								
	CaO	SiO_2	Al_2O_3	MgO	FeO	MnO	S	K_2O	Residue
Slag	38	35	10	12	0.5	0.8	1.2	0.8	1.7
OPC	63	21	4.2	3.4	2.1	-	3.2	1.1	2.0

The activators used were NaOH, Na_2CO_3 and sodium water glass (Na_2OnSiO_2) and the addition varied between 3 and 11 percentage by weight of the slag. The dry content of the water glass was 37% and the n-modulus (weight ratio between SiO_2 and Na_2O) was 3.35, 1.80 and 0.90 (changed by addition of NaOH). Ordinary Portland cement from Slite was used for comparison, Table 1. Fine sand (quartz), 0-2 mm, was used as aggregate.

3. PREPARATION OF SPECIMENS

Mortar specimens were manufactured of slag, aggregate and water with a weight ratio of 1:3:0.43. The activator addition is not included in this ratio. The mortar made with ordinary Portland cement had a water-to-cement ratio of 0.50.

Mortar prisms measuring 40x40x160 mm were prepared in accordance with ASTM C 305-82. The specimens were stored in a climate chamber with a temperature of +20°C and a relative air humidity of 80% up to the time of testing. Some mortar prisms were heat treated with steam beginning 15 minutes after they had been cast. The temperature was then raised from +20°C to +80°C in 2.5 hours and was kept constant for 3.5 hours before it was reduced to +20°C in 2 hours. Thus the steam curing cycle was 8 hours. If not tested immediately after the curing and demoulding (within 30 minutes) the specimens were stored until testing under the same conditions as the air cured ones.

Small specimens of slag and Portland cement pastes were cast into Teflon moulds with a height of 74 mm and a diameter of 19 mm. The water-to-slag ratio was 0.23, 0.26 and 0.32 while the water-to-cement ratio was 0.32. The specimens were cured for three weeks at +20°C and 80% RH, vacuum treated for one week and then tested.

Mortar specimens for shrinkage tests, measuring 40x40x160 mm, have been prepared. (Three specimens for each composition). The specimens were stored at +20°C and 80% relative humidity during the whole test period.

Mortar specimens for the preparation of thin sections have been stored at +20°C and 80% relative humidity for 1.5 years.

4 PROPERTIES IN THE FRESH STATE

The setting time has been determined in accordance with ASTM C 807-83 and the results are shown in Fig 1. The setting time decreases with increasing amounts of NaOH or water glass and when the fineness of the slag goes beyond some 550 m^2/kg. With Na_2CO_3 the dosage does not change the length of the setting time. The setting time of the ordinary portland cement used in the investigation was 160 minutes.

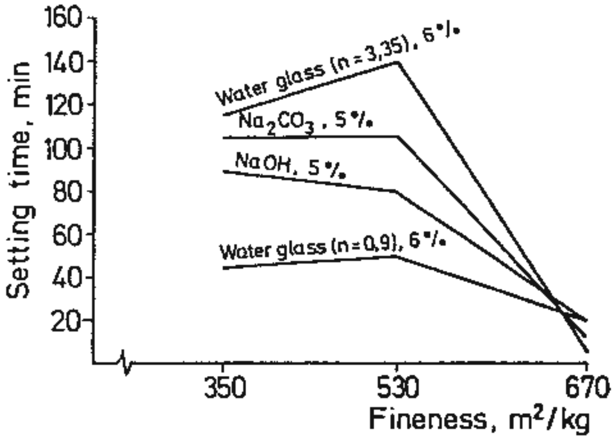


Fig 1 Time of setting as a function of slag fineness (Blaine) and type of activator

The workability of the mortar with slag as binder is much better than that of the mortar with ordinary Portland cement. A mortar with a water-to-slag ratio of 0.43 has approximately the same workability as a mortar with a water-to-cement ratio of 0.50.

5 PROPERTIES IN THE HARDENED STATE

5.1 Flexural and compressive strength

The flexural strength has been determined according to ASTM C 348-86. Each result is based on a test of two specimens. The compressive strength has been determined in accordance with ASTM C 349-82 and each result is based on a test of four specimens. The test results are presented in Tables 2-4.

Table 2 Flexural and compressive strengths of mortar made of slag with a fineness (Blaine) of 530 m^2/kg. Water-to-slag ratio 0.43. Specimens cured at room temperature. Reference test with OPC.

Activator	Addition	Flexural strength/Compressive strength in MPa. Age			
	%	1 day	7 days	28 days	91 days
NaOH	3	3/9	4/23	5/31	7/37
	5	3/11	4/22	4/32	8/39
	7	3/10	4/23	5/31	9/38
	11	5/16	5/27	7/31	-
Water glass n=0.90	4	0/0	6/31	7/42	7/47
	6	0/0	7/45	7/55	9/56
	8	0/0	7/38	8/55	10/63
	11	1/3	8/43	8/48	-
Water glass n=3.35	4	0/1	2/8	3/14	5/15
	6	0/1	2/7	3/14	4/19
	8	1/2	1/5	4/14	3/20
Na_2CO_3	3	0/0	5/27	5/29	5/39
	5	0/1	6/32	5/35	6/41
	7	2/6	6/33	7/42	8/53
	11	0/1	2/8	3/14	5/15
OPC	w/c = 0.50	5/24	6/39	6/39	7/42

From table 2 can be seen that NaOH is the only activator which gives a reasonable 1 day strength for air cured specimens. At later ages slag activated with water glass (n=0.90) gives the highest strengths. The strength development of slag mortar activated with NaOH seems to be little affected by the amount of added activator.

Table 3 Flexural and compressive strengths of mortar made of slag with a fineness (Blaine) of 530 m^2/kg. Water-to-slag ratio 0.43. Specimens steam cured. Reference test with OPC

Activator	Addition	Flexural strength/Compressive strength in MPa			
		Age			
	%	8 hours	7 days	28 days	91 days
NaOH	3	5/14	4/20	3/1	3/19
	5	5/17	4/17	3/18	4/23
	7	4/14	3/15	4/23	7/30
	11	6/24	8/24	5/30	-
Water glass n=0.90	4	4/19	4/19	4/24	5/27
	6	9/41	9/40	7/41	6/44
	8	11/51	10/50	9/57	10/60
	11	11/56	10/55	8/59	-
Water glass n=3.35	4	0/1	1/7	2/7	3/8
	6	2/11	4/25	5/45	7/49
	8	4/26	5/35	7/53	8/62
Na_2CO_3	3	6/24	5/27	5/25	6/32
	5	7/38	8/39	7/44	8/52
	7	9/43	8/44	8/48	9/53
	11	9/44	8/47	8/52	-
OPC	w/c = 0.50	5/29	7/37	5/31	6/32

From Table 3 it can be seen that the amount of added activator has a marked influence on the strength of steam cured specimens. The higher the amount of activator, the higher the strength.

The steam curing leads to very high strength at early ages (as high as 11/56 MPa already after eight hours). However, further strength development decreases and this is the reason why air cured specimens have a higher strength at later ages.

Table 4 Flexural and compressive strengths of mortar made of slag with different finenesses. Water to slag ratio 0.43. Activator: 5% Na_2CO_3

Specific surface (m^2/kg)	Flexural strength/Compressive strength (MPa)				
	Age				
	8 hours	1 day	7 days	28 days	91 days
air cured					
350	-	0/1	4/15	3/6	3/12
530	-	0/2	6/33	5/36	6/41
670	-	2/10	6/38	8/48	9/58
steam cured					
350	6/27	-	5/29	6/34	6/39
530	7/39	-	8/39	7/44	8/52
670	10/44	-	10/47	7/48	9/49

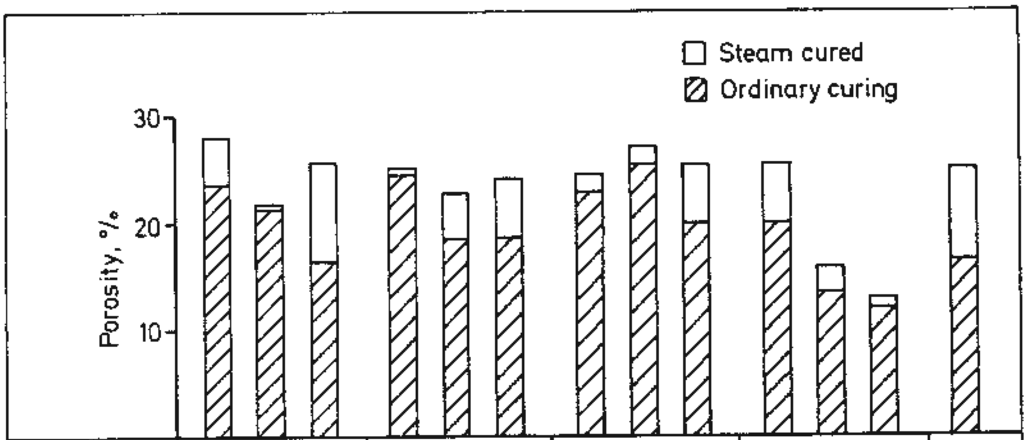
From Table 4 can be seen that the finer the slag is ground, the higher is the strength for air cured specimens. This difference is less significant in the case of steam curing.

5.2 Porosity

The appearance of the capillary pore system in slag paste specimens was investigated with the aid of a Micrometrics 910 mercury porosimeter. This unit works within a pressure interval of 1 psi to 50 000 psi, in other words 0.0069-346 N/mm^2.

Four thin sheets of mortar with a total volume of 4 000 mm^3 were placed in a glass container with a volume of $23 \cdot 10^3 mm^3$. The air in the glass container was evacuated to a residual pressure of less than 50 mm Hg. The glass container was then filled with mercury so that the specimen was completely surrounded by mercury.

In evaluating the experimental results it was assumed that the pores in the specimens are cylindrical, that the edge angle between the pore wall and the mercury meniscus is 130° and that the surface tension between mercury and air is 0.474 N/m. The measurement results were corrected with respect to the compression of the mercury and the expansion of the glass container. Pore sizes within the range 3.44 nm to 0.177 mm can be measured with the pressure interval of the mercury porosimeter. The results from the experiments are presented in Fig 2-4.



Activator	NaOH	Na_2CO_3	Na_2SiO_3	Na_2SiO_3	OPC
Amount	5%	5%	6%	6%	
Water to binder ratio	0.32	0.32	0.32	0.32 0.26 0.23	0.32
Fineness (Blaine)	350 530 670	350 530 670	530	530	
n = ratio of SiO_2/Na_2O			3.35 1.80 0.90	0.90	

Fig 2 Total pore volume determined by mercury porosimetry on slag paste activated with different activators, different slag finenesses and, in the case of water glass, different n-moduluses. Specimens made of ordinary Portland cement were tested for reference. The specimens were 3 weeks old at vacuum treatment and 4 weeks old at testing.

For air-cured specimens the porosity which is detectable with the mercury porosimeter decreases for increasing fineness of slag or decreasing water-to-slag ratio. Steam curing always results in a higher porosity. Aircured slag paste has a higher porosity than ordinary Portland cement paste, steam-cured in the same range as the OPC-paste.

The pore size distribution is shown in Fig 3 and 4.

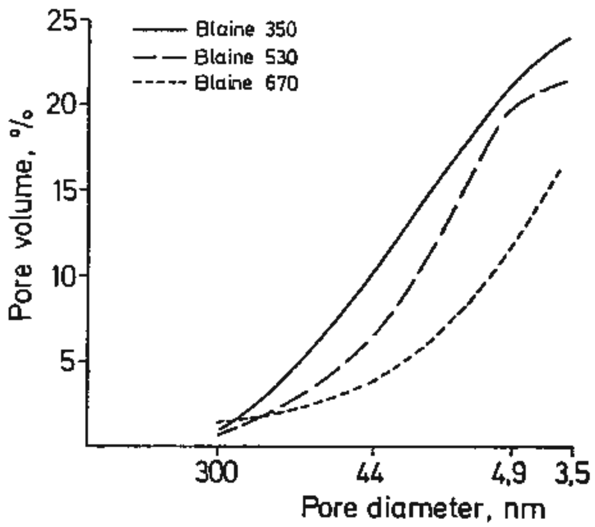


Fig 3 Pore size distribution for slag paste with a water-to-slag ratio of 0.32 activated with 5% by weight of the slag with NaOH. Specimens were air-cured.

As can be seen from Fig 3 the pore system is finer and the total porosity lower when the slag is finer.

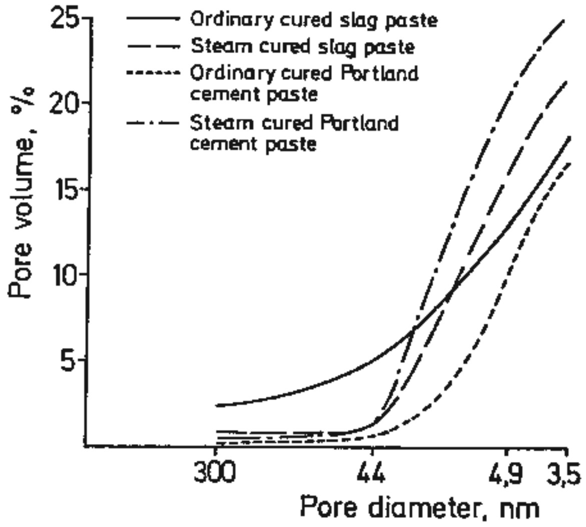


Fig 4 Pore size distribution for slag with a fineness of 530 m^2/kg activated with 5% by weight of Na_2CO_3 and for OPC. Water-to-binder ratio is 0.32

Steam curing leads to a higher pore volume.

The pore volumes for slag paste found in this investigation are generally much higher than expected. One reason for this might be the curing in air with 80% relative humidity instead of curing in water.

5.3 Shrinkage

Immediately after demoulding at the age of 1-3 days (depending on the strength of the specimens) the length of the specimens was measured. Table 5 shows shrinkage values after 231 days of storing at +20°C and 80% relative humidity.

Table 5 Shrinkage measured on specimens with a water-to-slag ratio of 0.43. The slag fineness is 530 m^2/kg. Reference test with OPC.

		Shrinkage (o/oo)	
Binder	Activator	Air cured	Steam cured
Slag	5% NaOH	0.93	0.67
	5% Na_2CO_3	1.11	0.45
	6% Water glass, n=3.35	2.29	1.76
	6% Water glass, n=1.80	1.33	0.35
	6% Water glass, n=0.90	1.46	0.42
OPC, w/c = 0.50		0.68	0.48

The shrinkage of air-cured mortar of alkali-activated slag is higher, often more than twice that of ordinary Portland cement mortar. Steam curing reduces the shrinkage to values lower than those for air cured OPC with the exception of slag activated with water glass with n=3.35.

For steam-cured slag mortar the shrinkage is reduced with increased additions of Na_2CO_3 or water glass. The slag fineness has no influence on the shrinkage of steam-cured slag activated by NaOH or water glass, but the shrinkage is reduced for finer ground slags when Na_2CO_3 is used.

5.4 Structure

The structure of mortar has been studied on thin sections in a microscope (fluorescence) with 35 times magnification, see Fig 5 and 6.

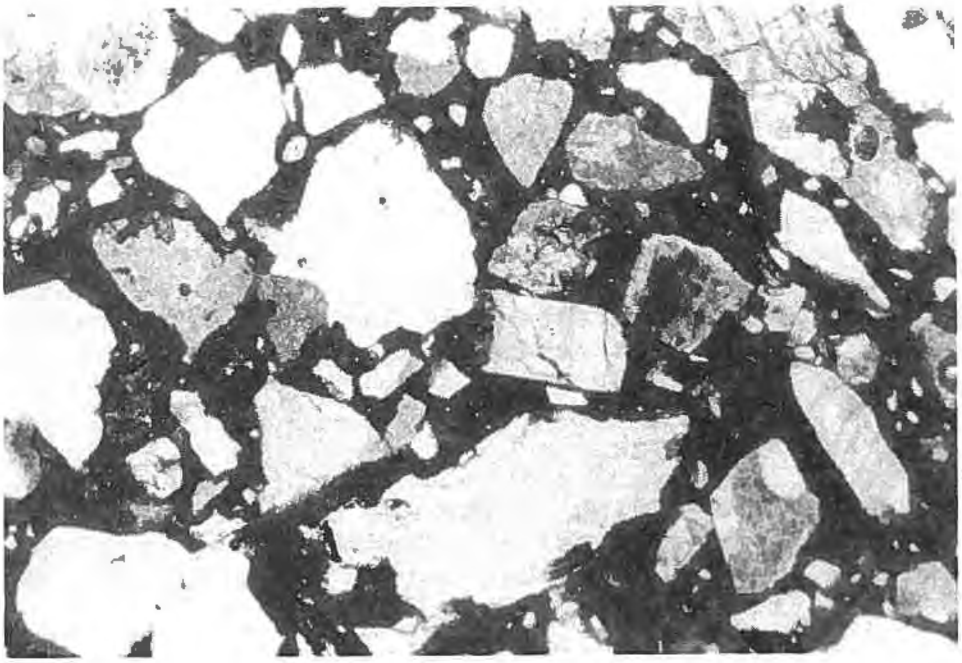


Fig 5 Air-cured OPC-mortar with a water to cement ratio of 0.50.

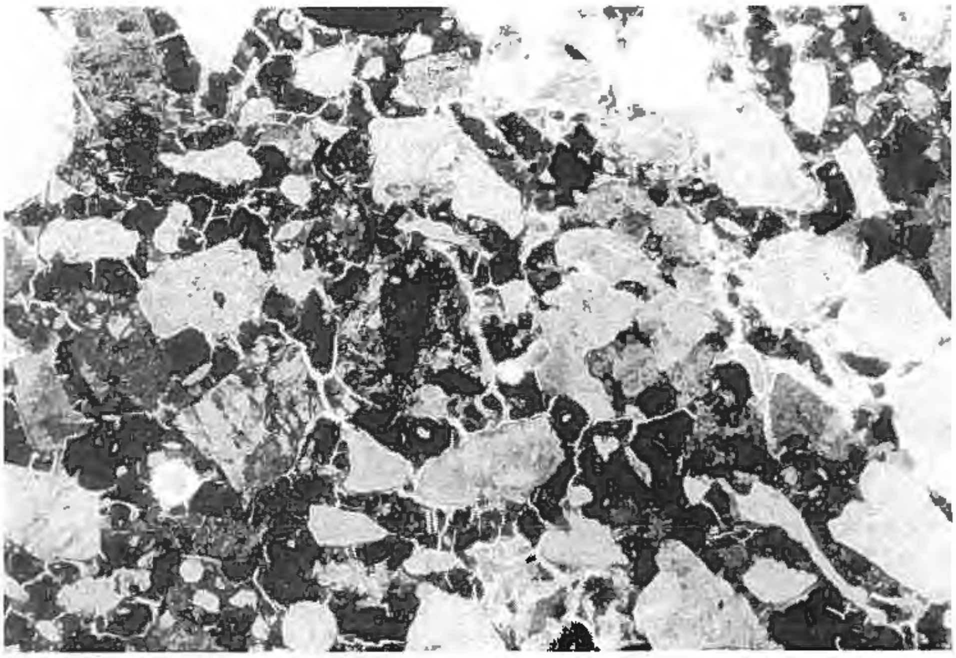


Fig 6 Air-cured slag mortar with a water-to-slag ratio of 0.43 and a slag fineness (Blaine) of 530 m^2/kg. 7% Na_2CO_3 was used as activator.

The figures show a difference in structure between OPC-mortar and alkali-activated slag mortar. The main difference between the two binder systems is the large number of micro cracks in the slag paste. This is probably due to an amorphous structure sensitive to changes in moisture.

The tendency to micro cracking is somewhat lower for specimens with finer ground slag. In general steam-cured and air-cured slag mortar specimens show the same crack pattern.

6 CONCLUSIONS

Alkali-activation is a very efficient way to activate granulated blast furnace slags especially in combination with steam curing. A steam-cured activated slag mortar can achieve a flexural strength above 10 MPa and a compressive strength above 50 MPa after no more than 8 hours.

The setting time for slags with a fineness (Blaine) up to 530 m^2/kg is of the same magnitude as for ordinary Portland cement.

The shrinkage of air-cured slag mortars is much higher than (often twice as high as) the shrinkage of air-cured OPC mortars.

Steam curing reduces the shrinkage to levels comparable with OPC mortars.

Studies of thin sections have shown that alkali-activated slag develops an extensive number of micro cracks. These micro cracks may influence the durability of the material in a negative way. Further research activities should be concentrated on finding countermeasures against the development of micro cracks.

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