

## THE PERMEABILITY OF HIGH STRENGTH BLAST FURNACE SLAG CONCRETE



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### ABSTRACT

The permeability properties of the high strength slag concrete were studied by means of carbonation tests, water suction and gas penetration. The permeability of the blended cement concrete was compared to that of the alkali activated slag concrete and Portland cement concrete.

According to the results the high strength slag concrete activated by cement is very dense. The carbonation results indicated that in high strength concrete the dense structure of the paste compensates for the lack of calcium in blended cement concrete. In the alkali activated slag concrete the structure contains microcracks at the microscopic level. The rate of carbonation was significantly higher in alkali activated slag concrete than in other concretes. The gas permeability results revealed the same tendencies as the carbonation tests. Water suction values were very low in the all high strength concrete samples.

Key words: permeability, carbonation, blast furnace slag, high strength, microcracks.

### 1 INTRODUCTION

The influence of the binder type on the permeability and microstructural properties of high strength concrete was studied. High strength Portland cement concrete, blended cement concrete and alkali activated slag concrete were compared with each other. Especially the effect of microcracks in alkali activated slag concrete on the permeability properties were considered. The reasons for the cracking tendency in alkali activated slag concrete were discussed on the basis of the

microstructural studies. The results of the microstructural studies are presented in the second part of the study (Häkkinen 1992).

## 2 MATERIALS

The chemical compositions of the cementitious materials are presented in Table 1. The surface area of the granulated blast furnace slag (GS) was 680 m<sup>2</sup>/kg (Blaine).

Table 1 The oxide composition of the cementitious materials.

	OXIDE COMPOSITION (% by weight).	
	Ground granulated slag (GS)	Rapid hardening Portland cement (PC)
CaO	37.7	60.1
SiO <sub>2</sub>	37.0	20.4
Al <sub>2</sub> O <sub>3</sub>	8.4	4.9
MgO	10.8	3.5
Fe <sub>2</sub> O <sub>3</sub>	2.6	2.6
SO <sub>3</sub>	0.10	3.4
Insoluble	0.85	0.87
Ignition loss (950°C)	0.0	0.0

## 3 PROPORTIONING OF CONCRETE

Two test series were performed in order to study the permeability properties of high strength concrete. The compositions and the strength values of the concrete samples are listed in Tables 2 and 3. The maximum aggregate size was 10 mm. All the specimens were moist cured for 7 days and kept thereafter at RH 70%. In the first test series (Table 2) the flow (Haegerman) of fresh concrete was 10 - 12 cm.

Table 2 The compositions of the concrete samples.  
Specimen size 40 x 40 x 160 mm. Compressive strength results are given as a mean of 6 values.

	Concrete						
	A *	B *	C	D	E	F	G
<b>BINDER (%)</b>							
GS A	100	100		87	87	70	70
PC			100	13	13	30	30
<b>WATER BINDER RATIO</b>							
	0.25	0.30	0.30	0.25	0.30	0.25	0.30
<b>AGGREGATE BINDER RATIO</b>							
	3	3.5	3.5	3	3.5	3	3.5
<b>CONTENT OF WATER REDUCING AGENT ** (w.% of binder)</b>							
	3	1	4	2	1	3	1
<b>COMPRESSIVE STRENGTH MPa (<math>\pm</math> SD)</b>							
Mean of 6 values							
1 day							
N7 ***	28.3 (0.49)	25.6 (0.68)	53.3 (1.06)	7.4 (0.38)	7.5 (0.26)	19.2 (0.54)	14.8 (0.33)
H7 ***	47.3 (1.02)	36.5 (0.16)	57.4 (1.21)	34.2 (0.65)	22.7 (0.20)	55.0 (1.57)	31.0 (0.68)
7 days							
N7	52.6 (0.24)	48.0 (0.59)	65.7 (1.16)	55.1 (0.87)	37.5 (0.87)	70.8 (2.15)	52.4 (0.88)
H7	55.4 (0.94)	47.0 (1.35)	68.6 (1.47)	57.7 (1.10)	41.1 (0.58)	84.3 (2.35)	52.0 (0.69)
28 days							
N7	70.1 (0.94)	61.90 (1.90)	76.0 (1.68)	74.2 (1.79)	57.7 (1.45)	92.0 (2.49)	70.6 (1.94)
H7	72.9 (1.03)	63.8 (0.82)	78.7 (2.58)	78.8 (1.73)	59.0 (1.74)	99.0 (2.36)	72.0 (1.33)
91 days							
N7	79.8 (1.73)	73.4 (3.02)	78.9 (2.26)	84.5 (3.51)	65.1 (2.45)	96.1 (2.08)	-
22 months ****							
N7	104.4 (4.32)	109.7 (3.55)	113.8 (6.01)	110.8 (1.00)	99.9 (5.62)	123.1 (3.30)	104.5 (2.43)

\* Alkaline activator 5% NaOH of the weight of GS.

\*\* Peramin F

\*\*\* Curing of the specimens:

N7 = 7 days at RH>95%, where after at RH 70%.

H7 = Heat treatment at 40°C for 24 h, 6 days at RH>95%, where after at RH 70%.

\*\*\*\* From the age of one month onwards curing at CO<sub>2</sub>≈3%, RH≈70%.

Table 3 The compositions of the concrete samples in the the second test series.  
Specimen size 100 x 100 x 100 mm.  
Compressive strength results are given as a mean of 6 values.

	Concrete		III	IV	V	VI	VII
	I	II					
<hr/>							
BINDER (%)							
PC	100	100	30	30	13	13	13
GS A			70	70	87	87	87
<hr/>							
WATER- BINDER RATIO	0.28	0.32	0.28	0.32	0.24	0.28	0.32
<hr/>							
AGGREGATE- BINDER RATIO	3.5	4	3.5	4	3	3.5	4
<hr/>							
CONTENT OF WATER REDUCING AGENT* (w.% of binder) 4.5	3.0	3.0	1.5	4.5	3.0	1.5	
<hr/>							
COMPRESSIVE STRENGTH MPa ± SD							
1 day	62.3 (0.7)	45.6 (0.2)	22.5 (0.1)	15.6 (0.4)	2.2 (0.2)	5.7 (1.0)	5.8 (0.2)
7 days	63.5 (4.1)	55.2 (1.5)	66.9 (3.3)	43.1 (0.9)	56.1 (1.3)	43.0 (3.5)	36.4 (1.1)
28 days	79.5 (6.3)	67.0 (2.2)	84.6 (0.9)	58.5 (0.5)	72.0 (4.4)	65.9 (1.7)	47.5 (1.1)
91 days	87.6 (9.0)	75.9 (0.5)	87.5 (4.3)	69.6 (0.1)	84.0 (2.8)	74.9 (3.1)	51.7 (0.4)
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## 4 CARBONATION

The effect of the binder type on the carbonation of high strength concrete was studied. The concrete specimens were moist cured for 7 days and kept there after at RH 70%. At the age of one month some of the specimens were placed in a carbonation chamber with a CO<sub>2</sub> content of about 3% (RH≈70%). The depth of carbonation was measured by dyeing with using phenolphthalein solution and thin section analysis. The results are shown in Table 4. The carbonation depth of high strength alkali activated GS concrete was almost impossible to determine by means of dying because the colour of the paste was too dark. Thin sections measuring 30 x 50 mm x 25 μm impregnated by fluorescent resin were prepared and studied by polarising and fluorescent microscopy.

The appearance of microcracks was studied using fluorescence microscope (Table 5). The age of the samples was 6 months. Number of microcracks occurred in the alkali activated slag (AA GS) concrete samples, but the number of cracks was small in other samples. On the basis of the carbonation studies by means of thin section analysis it could be concluded that the microcracks in the AA GS samples were not generated in the course of drying during the thin section preparation. Typically, the carbonation had proceeded along the cracks and also penetrated deeper into the sample than the main carbonation zone.

After curing nearly 2 years at accelerated carbonation conditions also the strength properties of the specimens were tested. In those slag concrete samples where the carbonation had proceeded most of all (samples B and E in Table 4) the compression strength had increased by about 75% compared to the 28 d strength and by about 50% compared to the 91 d strength (Table 2).

Table 4 Carbonation depth.  
Compositions of the concrete samples in Table 2.

CARBONATION DEPTH (mm)							
	Concrete		C	D	E	F	G
	A	B					
Accelerated conditions. Determination by dyeing.							
1 month							
N7	*	0.5	0.5	2.5	7.0	2.0	2.5
H7	*	0	0.5	-	4.0	0.0	1.0
2 months							
N7	*	0.5 **	2.0	4.5	8.0	2.0	3.5
H7	*	0.5**	1.5	-	6.0	1.0	3.5
4 months							
N7	*	*	3.4	4.5	8.5	3.0	4.5
6 months							
N7	8.0 **	6.0 **	3.5	3.5	10.5	2.5	5.0
H7	*	6.0 **	3.0	-	8.0	*	3.5
22 months							
N7	-	9.0	6.5	6.0	8.5	-	6.5
Accelerated conditions. Determination by thin section analysis.							
4 months							
N7	2-8	$\frac{1}{2}$ -10	1-4	$\frac{1}{2}$ -2	2-4	$\frac{1}{2}$ -2	$\frac{1}{2}$ -4
6 months							
N7	5-8	2-4	1-3	1-2	4-6	$\frac{1}{2}$ -1	$\frac{1}{2}$ -2
H7	1-2	3-5	1-3	-	2-4	$\frac{1}{2}$	$\frac{1}{2}$ -2
Normal conditions. Determination by dyeing.							
2 months							
N7	*	*	0.0	1.5	1.5	0.0	1.0
6 months							
N7	*	*	0.0	2.0	4.0	0.0	2.0
22 months							
N7	-	4.0	3.0	-	4.0	-	3.0
Normal conditions. Determination by thin section analysis.							
6 months							
N7	1-2	$\frac{1}{2}$ -1 $\frac{1}{2}$	$\frac{1}{2}$ -1 $\frac{1}{2}$	1	$\frac{1}{2}$ -1 $\frac{1}{2}$	0-1	$\frac{1}{2}$ -1 $\frac{1}{2}$

\* The carbonated layer could not be distinguished.

\*\* The carbonated layer was hard to be distinguished.

Table 5 Crack classification of the samples by means of thin section analysis.  
The samples were vacuumed and impregnated by fluorescent epoxy. Thin sections measuring 30 x 50 mm x 25  $\mu$ m.  
Classification 0 - 3 ( 0 = no microcracks ).

Curing *	Concrete						
	A	B	C	D	E	F	G
N7 RH70%	3	2	0.5	0.5	0.5	0.5	0.5
H7 RH70%	2	3	0.5	-	1.5	1	0.5
N7 CO <sub>2</sub>	2	2	0	0.5	1	0.5	0.5

\* Curing of the specimens:  
N7 = 7 days at RH>95%, where after at RH 70%.  
H7 = Heat treatment at 40°C for 24 h, 6 days at RH>95%, where after at RH 70%.  
N7 CO<sub>2</sub> = From the age of one month onwards curing at CO<sub>2</sub>≈3%, RH≈70%.

## 5 WATER PERMEABILITY

The water permeability of concrete samples was studied by means of capillary suction test. The capillary suction test was performed on concrete sections (100 x 100 x 25 mm) taken from specimens measuring 100 x 100 x 100 mm. The samples were dried at 50°C and placed on a grating to absorb water from below by capillary suction. The weight of the specimens was measured intermittently for about 3 weeks. Subsequently, the specimens were saturated at a water pressure of 15 MPa in order to determine the total pore volume. Finally, the samples were dried at 105°C. The absorption results were calculated as a function of the square root of time. The resistance coefficient (m) and the capillary index (k) were calculated from the test results as follows:

$$m = 3600 t_{np} / h^2 \quad (s/mm^2) \quad (1)$$

$$k = P_{cap} / (1000 \sqrt{m}) \quad (kg/m^2/s) \quad (2)$$

$$P_{cap} = (S_{np} - S_0) P_{tot} \quad (-) \quad (3)$$

where  $t_{np}$  = time point at the nick point (h)  
 $h$  = thickness of the specimen (mm)  
 $P_{cap}$  = capillary porosity (kg/m<sup>3</sup>)  
 $S_{np}$  = water suction degree at the nick point (-)  
 $S_0$  = water suction degree at beginning of the test (-)  
 $P_{tot}$  = total porosity (kg/m<sup>3</sup>).

The water permeability values were determined. In addition the effect of carbonation was investigated. The specimens were placed at the age of 28 days for 6 months in a carbonation chamber with a  $\text{CO}_2$  content of about 3%. The results are presented in Table 6.

The capillary indexes of all the concretes were very low. The capillary indexes of the PC concretes were a little smaller than those of the slag concretes. But the resistance coefficients were greater in the slag concretes than in the PC concretes. The capillary indexes measured from the surface samples of the slag concretes were higher than those measured from the inner samples. The capillary porosity ( $P_{\text{cap}}$  in eq. 3) was greater and the microporosity ( $P_0 = S_0 P_{\text{tot}}$  eq. 3) was smaller in the slag concretes than in the PC concretes. Possibly the reaction degree was lower in the slag concretes than in the PC concretes. It is also possible that the microporosity is difficult to measure correctly in the slag concrete by water suction test because of the typically very small pore dimensions. The greater number of capillary pores in the slag concretes could also be due to microcracking. But on the basis of the microscopy studies no microcracks appeared either in the PC concrete or the GS70 concrete (slag content 70% by w. of binder). In those samples in which the slag content was 87% of the binder (GS87) there were a few microcracks.

In the GS87 concretes the capillary pore volume was remarkably greater than in the PC concrete. As a result of this the capillary indexes measured from the GS87 concrete were higher than those measured from the PC concrete. In spite of that the resistance coefficients were very high in the GS87 concrete. It seems that the average pore size in capillary area must have been significantly smaller in the GS 87 concrete than in the PC concrete.

Carbonation in accelerated conditions considerably reduced the capillary suction in all the concrete samples. During the 6 months' accelerated curing the capillary porosity decreased and the microporosity ( $P_0$ ) increased significantly in the PC activated GS concrete samples.



Table 6 Water permeability of the concrete samples.  
Composition of concrete in Table 3.

	Concrete						
	I	II	III	IV	V	VI	VII
<b>k (kg/m<sup>2</sup>/s)</b>							
S 1 month *	0.003	0.005	0.005	0.008	0.005	0.006	0.008
I 1 month **	0.005	0.005	0.004	0.006	0.004	0.005	0.007
S 7 months ***	0.002	0.002	0.002	0.003	0.002	0.003	0.004
<b>m (s/mm<sup>2</sup>)</b>							
S 1 month	21.3	22.9	38.7	31.6	47.1	48.2	52.5
I 1 month	14.1	18.1	40.5	30.3	40.2	50.8	63.1
S 7 months	80.1	90.0	82.0	105.1	96.8	99.2	117.6
<b>P<sub>tot</sub> (l/m<sup>3</sup>)</b>							
S 1 month	102	112	76	108	111	126	116
I 1 month	104	115	80	115	111	126	121
S 7 months	95	109	78	103	107	113	115
<b>P<sub>cap</sub> (l/m<sup>3</sup>)</b>							
S 1 month	15	22	31	36	32	44	54
I 1 month	18	23	23	33	25	37	53
S 7 months	16	25	21	33	19	31	39
<b>P<sub>0</sub> (l/m<sup>3</sup>)</b>							
S 1 month	60	56	23	27	40	45	40
I 1 month	58	57	37	44	46	48	44
S 7 months	58	56	37	37	46	46	42

- \* S 1 month = surface layer of the sample, age 1 month, curing 7d at RH>95%, 21 d at RH≈70%.
- \*\* I 1 month = inner layer of the sample, age 1 month, curing 7d at RH>95%, 21 d at RH≈70%.
- \*\*\* S 7 months = surface layer of the sample, age 1 month, curing 7d at RH>95%, 21 d at RH≈70%, 6 months at CO<sub>2</sub>≈3%, RH≈70%.

## 6 GAS PERMEABILITY

The gas permeability was determined at the age of 1 month. The samples were prepared by cutting a slice 50 mm thick from the surface layer of a normal cylinder (height 300 mm, diameter 150 mm). During the test the ambient air pressure was directed onto the other surface of the sample and a nitrogen gas pressure was applied to create a pressure difference of 1, 2, 5, 10, 5, 2 and 1 bar. The gas flow through the specimen was determined and the gas permeability was calculated according to formula (4). The results are presented in Table 8 as the mean of two samples.

$$Q/A = (K/n) \times (P/p_2) \times (p_1 - p_2) \times (1/l) \quad (4)$$

where Q is gas flow ( $m^3/s$ )  
 A surface area of the sample ( $m^2$ )  
 K gas permeability ( $m^2$ )  
 n dynamic viscosity of gas ( $Ns/m^2$ ). At  $20^\circ C$   
 $n = 0.000018 Ns/m^2$  for nitrogen  
 P  $(p_1 + p_2)/2$  ( $N/m^2$ )  
 p1 gas pressure on one side of sample ( $N/m^2$ )  
 p2 gas pressure on the other side of sample  
 ( $N/m^2$ ) = 100,000 ( $N/m^2$ ), and  
 l thickness of the sample (m).

Table 8 Gas permeability.

Concrete	Water binder ratio	GAS PERMEABILITY ( $10^{-18} m^2$ ) over pressure				
		1 bar	5 bar	10 bar	5 bar	1 bar
I	0.28	<0.001	0.005	0.002	0.03	0.4
II	0.30	<0.001	0.003	0.001	0.004	0.12
III	0.28	<0.001	<0.001	<0.002	<0.002	<0.003
IV	0.32	1.4	1.7	1.6	1.9	3.0
V	0.24	0.09	0.16	0.16	0.38	1.2
VI	0.28	57	47	44	51	64
VII	0.32	14	12	11	12	14

The gas permeabilities of the samples I - IV were very low and the values were reasonably proportional to the strength values. But if the concretes II and VI, having about the same strength, are compared, one can notice that the permeability of the GS87 concrete is significantly greater than that of the PC concrete.

## 7 DURABILITY IN ACIDIC SOLUTION

The concrete specimens were cured in turn for 1 week half immersed in acidic solution and for 1 week in normal air. Parallel specimens were cured in turn for 1 week half immersed in water and for 1 week in normal air. The test was stopped after six months' curing. The acidic solution was copper sulphate at pH 3 - 5. Before immersing, the samples were moist cured for 1 week and cured at RH 70% for 3 weeks. The composition and the strength of the specimens are shown in Table 3. When the test specimens were stored for 6 months alternately either in an acidic solution and dry or wet and dry, they were given a visual examination. The test specimens had remained in what appeared to be reasonable good condition. In the PC concretes the paste had dissolved the most from the surfaces. There were no visibly observable cracks on the surfaces. In the GS70 concretes the paste had dissolved the most from the surfaces in the samples prepared with the water

binder ratio of 0.32, but only in minor amounts in the samples prepared with the water binder ratio of 0.28. No cracks were visible. In the GS87 specimens the paste had dissolved only in small amounts from some of the surfaces. Few surface cracks were observable. Samples of the concrete specimens made with the water cement ratio of 0.28 were also studied with fluorescent and polarising microscopy. In all samples there was a chemically modified surface layer of 0.0 - 0.2 mm. Below this layer there was a carbonated zone. Only few microcracks were observable in all the samples. In air pores there appeared no corrosion products or other crystallizations (Table 9). In those specimens cured alternately wet and dry, no visible damage was observable.

Table 9 Summary of the microscopy examination.

Concrete	MODIFIED LAYER (mm)	CARBONATED ZONE (mm)	MICRO- CRACKS (0-3) 0 = no cracks	CRYSTALLIZATIONS
I	0.1-0.2	0.1-0.5	0.5	no
III	0.0-0.1	0.1-0.3	0	no
V	0.1-0.2	0.2-1.2	0	no

## 8 SUMMARY

The rate of carbonation was higher in the alkali activated slag concrete than in the other concretes. In addition, the carbonation zone as observed by optical studies was quite uneven in such a way that carbonation had proceeded along the microcracks. During the two years' curing in the accelerated conditions the carbonation zone proceeded deep into the concrete, but at the same time the strength of alkali activated slag concrete increased by about 50% compared to the strength at the age of three months.

The carbonation differences were quite small in the high strength concretes made of PC or GS with slag content 70% (by w. of binder). The dense structure of the cement activated slag concrete probably compensates for the lack of calcium compounds. In GS87 concrete carbonation proceeded faster than in GS70 concrete. The gas permeability results revealed the same tendencies as the carbonation tests. The gas permeabilities of the high strength PC and GS70 concretes were very low and the values were reasonably proportional to the strength values. But the permeability of GS87 concrete was significantly greater than that of the PC concrete having about the same strength.

Water suction was very low in all the Portland cement activated high strength slag concretes. In addition, carbonation in

accelerated conditions further reduced the capillary suction in the all concrete samples. However, in the GS87 concretes the capillary pore volume was remarkably greater than in the PC concretes. As a result of this the capillary indexes measured from the GS87 concretes were higher than those measured from the PC concretes. In spite of that the resistance coefficients were very high in the GS87 concretes. It seems that the average pore size in capillary area must have been significantly smaller in the GS87 concretes than in the PC concretes.

Durability in the acidic solution appeared to be good in the GS concretes.

#### REFERENCES

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