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Chloride Penetration into Alkali-Activated Slag Concrete under Uniaxial Compression

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ABSTRACT: *Durability, service life, and sustainability of alkali-activated slag concrete (AASC) in aggressive environment depend, among other influences, on transport of water and ions dissolved in water. The influence of different concentration and type of activators was investigated in particular. It could be shown that transport of both, water and ions dissolved in water, are more important in concrete, which is activated by water glass, although this type of AASC has higher compressive strength. These findings are attributed to the formation of micro-cracks in the composite structure, due to higher shrinkage. The concentration of Na_2O in the alkaline solution and the modulus of water glass have a strong influence on water and chloride transport in AASC. Partial substitution of slag by fly ash in AASC enhances mass transport while mechanical strength decreases.*

KEYWORDS: *Alkali activator; Alkali activated concrete; Uniaxial compression; Chloride penetration; Micro-cracks.*

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I. INTRODUCTION

Service life of reinforced concrete structures and structural elements in marine environment is limited very often by steel bar corrosion, which depends in addition to existing cracks on chloride penetration and the acting stress. Transport properties of concrete prepared with ordinary Portland cement (OPC) under tension and compression have been studied intensively in recent years [1-3]. Applied tensile stress widens the pore structure and leads to formation of new cracks. As a consequence, water and chloride penetration are intensified. Compressive load below 50 % of the ultimate load leads to decreased water transport. Under higher compressive load, however, existing cracks are enlarged and new cracks are formed in the composite structure of concrete, forming new flow channels for water and ions dissolved in water [1]. This leads to an increased water transport under hydrostatic pressure or by capillary action. Until now the influence of an applied load on moisture movement on durability of alkali-activated slag materials (AASM) has not been studied in detail. This paper is meant to close this gap. It will be of interest to compare results obtained on AASM with results obtained on ordinary concrete.

Transport properties measured under low load can be related directly to the undamaged structure of alkali activated materials (AAM). Permeability of undamaged samples was investigated intensively, and results obtained can be explained by the characteristic microstructure and the different hydration products. Shi [4] has studied the pore structure of granulated blast furnace slag (GBFS) based mortar. Häkkinen T. [5] obtained similar results. Binder activated with water glass shows serious shrinkage [6] resulting in early crack formation, which may lead to increased penetration of water and salt solutions. The type of hydration products determines the pore size distribution. Addition of slag reduces porosity and increases tortuosity of slag and FA blended materials [7].

It could be observed that AAM generally leads to higher strength as compared to strength of OPC, and first cracks are formed at higher applied stress [8]. As a consequence, the limit of linear elastic behavior is shifted to higher stress [9]. Thomas [10] presented results of his investigations on the elastic modulus, the Poisson`s ratio and the stress-strain relation of concrete prepared with slag and FA respectively. The influence of the ratio fly ash/slag and of the amount and type of activator on mechanical properties was also studied in the past. In terms of strength, water glass is generally considered to be the best activator, followed by NaOH and Na_2CO_3 [11]. Strength can be increased by increasing the amount of activator within certain limits [12]. Puertas et al. [13] found that substitution of slag by FA increases porosity and reduces strength when cured at room temperature.

Although a considerable number of papers on different properties of AASC exists, the influence of an applied load on transport mechanisms still needs further investigations. Therefore, the main objective of this paper is to investigate engineering properties under the influence of compressive stress and the effect of an applied load on chloride transport in particular. The influence of three parameters were studied in particular: type, and concentration of two activators and partial substitution by fly ash were studied experimentally. The influence of an applied uniaxial compressive stress on chloride transport was investigated in particular.

II. PREPARATION OF SPECIMENS

Six types of concrete with alkali activated blast furnace slag and fly ash respectively were prepared for this project. The composition of the six different cement-based materials is given in Table 1. The chemical composition of the slag and fly ash used in this project are shown in Table 2. Locally available river sand and broken basalt with a maximum grain size of 25 mm were used as aggregates. Analytical reagents of sodium hydroxide and water glass with a modulus n of 1.8 were used as activators. The water glass modulus n stands for the ratio SiO_2/Na_2O.

Cubes with an edge length of 100 mm and prisms with the following dimensions 100 × 100 × 400 mm were cast in steel molds. The molds of all specimens were removed after 24 h, and the young specimens were further stored in a curing room with a relative humidity of at least 95 % and a temperature of 20 ± 2 °C until an age of 14 and 28 days respectively. Then the specimens were ready for being tested.

Table 1: Composition of six types of AAS concrete, which were tested in this project.

Mix	Type of Activator	Na_2O in Alkaline solution, wt.%	Alkaline solution, kg/m^3	Coarse aggregate, kg/m^3	Sand, kg/m^3	Slag, kg/m^3	Fly ash, kg/m^3
1	NaOH	7%	184	1074	716	400	0
2	NaOH	9%	184	1074	716	400	0
3	NaOH	9%	184	1074	716	320	80
4	Water glass	7%	184	1074	716	400	0
5	Water glass	9%	184	1074	716	400	0
6	Water glass	9%	184	1074	716	320	80

Table 2: Chemical composition of slag and fly ash, mass %

	CaO	SiO_2	Al_2O_3	MgO	SO_3	Fe_2O_3	K_2O	Na_2O	TiO_2	MnO
Slag	41.60	26.81	17.79	0.48	2.03	9.28	0.39	0.31	0.72	0.34
Fly ash	5.79	66.8	17.93	1.50	0.50	4.03	1.32	0.26	1.07	0.06

III. RESULTS

3.1 Compressive strength

At an age of 14 and 28 days, compressive strength of both cubes and prisms was determined. Results are shown in Table 3 as the average value of at least three test results and an average standard deviation of 7 %. It can be seen that specimens activated with water glass have higher compressive strength of cubes and prisms after 14 days and 28 days as compared to specimens prepared with NaOH. As expected strength increases with increasing amount of activator added. It is of interest that addition of fly ash reduces compressive strength significantly. As expected, compressive strength of prisms is significantly lower than compressive strength of cubes because of the different stress distributions in the two geometrically different types of specimens.

Table 3: Compressive strength of cubes and prisms prepared with the six different types of concrete as

determined at an age of 14 and 28 days.

Concrete type	Compressive strength, MPa		
	Cubes, age of 14d	Cubes, age of 28d	Prisms, age of 28d
1	35.1	37.8	24.6
2	39.3	42.1	26.2
3	36.5	40.0	30.6
4	37.6	40.5	26.1
5	54.3	60.1	42.6
6	44.1	50.3	38.5

3.2 Stress-strain relations

Stress-strain relations up to different predefined stress levels and subsequent unloading were determined on all six types of concrete and results are shown in Fig. 2. The compressive strength has also been determined and can also be seen from Fig. 2. The load was applied by a universal testing machine with a constant rate up to 35, 50, 65, 80, and 100 % of the compressive strength. The selected maximum load was kept constant for 15 minutes before unloading. From Fig. 2 it can be seen that under an applied compressive load of 30 % of the ultimate load, creep deformation during the first 15 minutes of loading is very small. At higher applied load early creep deformation becomes more and more important as expected. On specimens made with concrete type 4 and 6 most important creep could be observed. After unloading part of the observed early creep deformation is recovered.

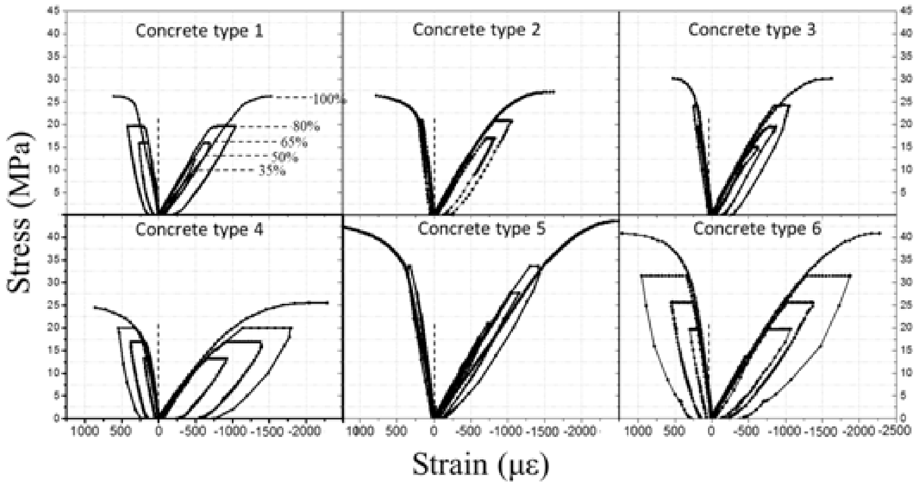


Fig. 2: Stress-strain diagrams as obtained on prisms of all six types of concrete. The negative strain corresponds to deformation in the direction parallel to the applied load (shortening), while the positive strain corresponds to the lateral deformation (extension). Five different stress levels, namely 35%, 50%, 65%, 80%, and 100%, were applied on all concrete prisms, as indicated in this figure for concrete type 1.

3.3 Volumetric strain and volume change under different stress levels

Similar tests as described in section 3.2 were carried out on cubes. The volume changes after unloading cubes with a volume V_c can be calculated approximately with Eq. (1):

$$V_c = 2\varepsilon_x - \varepsilon_y \quad (1)$$

ε_x stands for the horizontal strain normal to the applied load and ε_y stands for the vertical strain. The cubes with an edge length of 100 mm were chosen in this case. Results obtained are shown in Fig. 3. There is an obvious difference between results obtained from specimens prepared with NaOH (Type 1 to 3) as compared with results obtained from specimens prepared with water-glass (Type 4 to 6). Specimens prepared with NaOH show negligible or small volume change only up to about 50 % of the ultimate load. At higher applied load the volume increases. Specimens prepared with water-glass, however, show a different behavior. If compressed under low and medium stress the volume decreases and increases again at a stress level higher than 50 %. The observed volume change can be attributed to a change of the pore space.

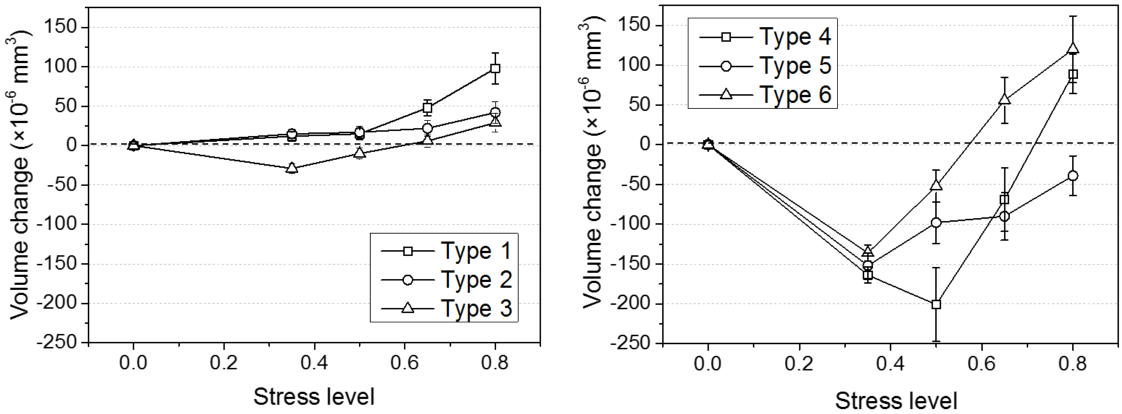


Fig. 3: Volumetric change as observed after unloading of preloaded cubes as function of the applied stress level for concrete activated with NaOH (left) and with water-glass (right).

3.5 Chloride penetration into concrete under different stress levels

One side surface of the concrete cubes was put in contact with an aqueous solution containing 5 % NaCl. After exposure for 60 and 90 days, chloride profiles as built up in the concrete cubes were determined by grinding stepwise thin layers, starting at the exposed surface. The chloride content of the powder obtained was determined by titration. Results obtained are shown in Figs. 4 and 5.

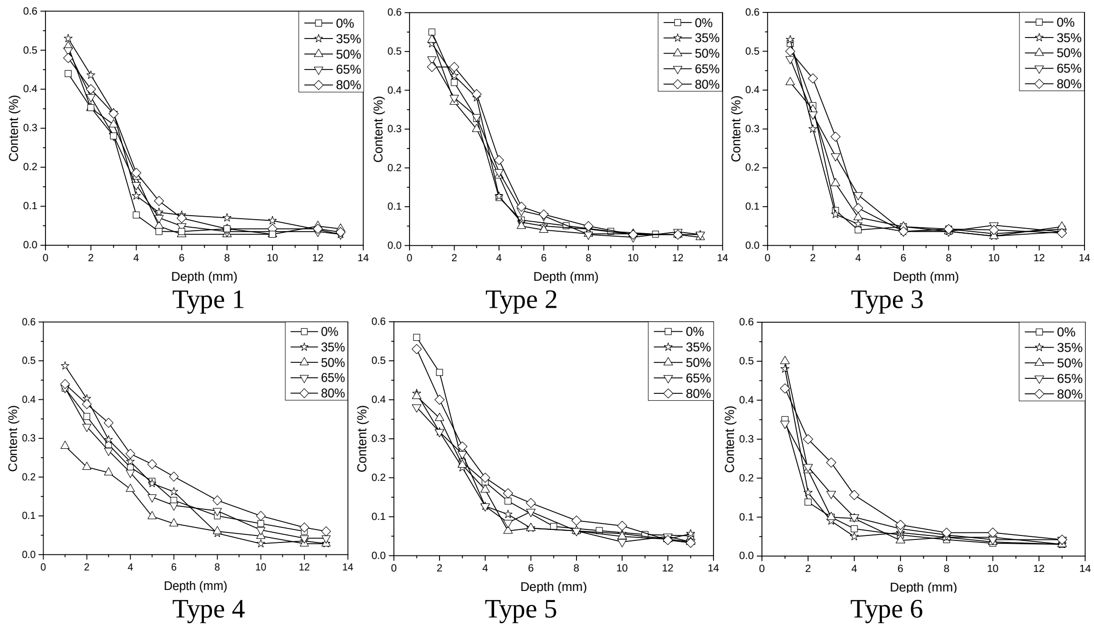
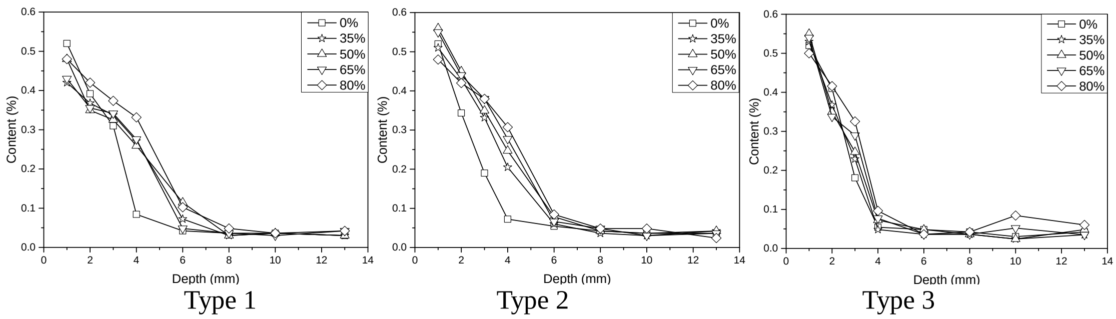


Fig. 4: Chloride profiles as determined in concrete exposed to 5 % NaCl solution for 60 days



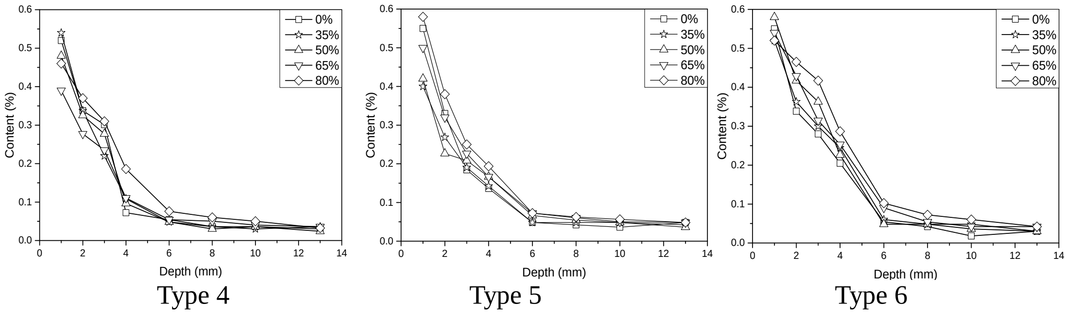


Fig. 5: Chloride profiles as determined in concrete exposed to 5 % NaCl solution for 90 days

From the chloride profiles C(x,t) shown in Figs. 4 and 5, an apparent diffusion coefficient D can be determined by applying Fick's second law:

$$C(x,t) = C_0 + (C_s - C_0) \cdot [1 - erf(\frac{x}{2\sqrt{Dt}})] \quad (2)$$

In eq. (2) x stands for the distance of a point in the concrete cube from the exposed surface, t represents the duration of exposure, C_0 is the initial chloride content before contact with the salt solution, C_s is the chloride concentration near the surface, and D is the apparent chloride diffusion coefficient, while erf(z) stands for the error function.

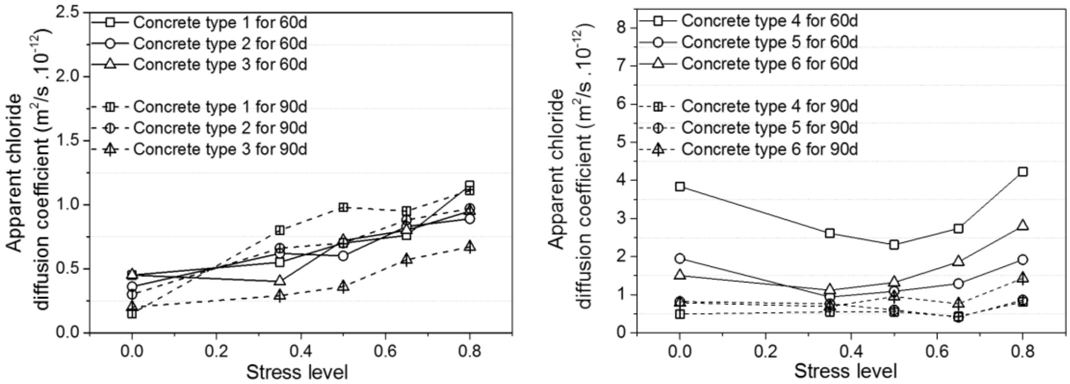


Fig. 6: Apparent chloride diffusion coefficient D(x) at different stress levels for slag concrete activated by NaOH (left) and water-glass (right).

As can be seen from Figure 6, the apparent chloride diffusion coefficients D(x) of concretes type 1 to 3 (activated with NaOH) increase slightly with increasing applied load, while the diffusion coefficient of concretes type 4 to 6 decreases first and then increases again as function of an applied load. This observation could be expected. It corresponds with the volume changes as shown in Fig. 3. In concretes type 1 to 3 the pores space increases steadily as function of an applied load, while in concretes types 4 to 6 the pore space is reduced until an applied stress of 50 % of the ultimate stress. This characteristic behavior of the different types of concrete has to be taken into consideration in service life design of structures exposed to aggressive environment.

IV. CONCLUSIONS

Based on the results described above the following conclusions can be drawn:

– Compressive strength of slag concrete activated with NaOH is lower than compressive strength of concrete activated with water glass. If part of the slag is replaced by fly ash, compressive strength is decreased.
– The apparent chloride diffusion coefficient of slag concrete activated with NaOH is considerably lower than the apparent chloride diffusion coefficient of slag concrete activated with water glass.
– The pore space of slag concrete activated with NaOH increases steadily with increasing applied compressive load. As a consequence, the apparent chloride diffusion coefficient also increases steadily under an increasing applied load.
– The pore space of slag concrete activated with water glass first decreases but increases again at an applied load higher than 50 % of the ultimate load. As a consequence, the apparent chloride diffusion coefficient

also decreases under an applied compressive load and increases again under an applied compressive load higher than 50 % of the ultimate load.

– The influence of an applied load on chloride penetration into slag concrete has to be taken into consideration in realistic service life design.

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