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MECHANICAL PROPERTIES OF CONCRETES WITH SLOWLY REACTING ALKALI SENSITIVE AGGREGATES

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Abstract

Concretes with three types of slow/late aggregates have been exposed in a fog room at 40°C for 560 days. The aggregates were greywacke, quartz porphyry, and crushed gravel from the Upper Rhine valley. The Portland cement had a Na_2O equivalent of 1.24% by mass. Compressive strength, tensile strength, static and dynamic modulus of elasticity were measured at fixed intervals. It is shown that tensile strength and static modulus of elasticity were significantly more affected by alkali-silica reaction than compressive strength and dynamic modulus of elasticity.

Keywords: aggregates, alkali-silica reaction, concrete, durability, mechanical properties

1 INTRODUCTION

Slowly reacting alkali sensitive grains, also known as slow/late aggregates, show the signs of alkali silica reaction (ASR) after 10 to 20 years of natural exposure. Typical aggregates are greywacke, quartz porphyry, quartzite, granite, and some type of andesite. The focus of previous investigations was on the chemical and mineralogical reactions and the expansion due to ASR and not on the mechanical aspects. There are some publications which can be mentioned and which were devoted to mechanical properties. Giaccio et al. [1] prepared four concretes with reactive and non-reactive aggregates which were stored at 38°C up to two years. They found a considerable reduction of elastic properties. Kubo et al. [2] found a gradual reduction of compressive strength after storage in NaCl solution at 40°C and a significant reduction of elastic modulus. Copuroglu [3] studied three types of rock in 80°C warm NaCl solution and found a reduction of elastic modulus up to 81% which was supposedly due to silica dissolution. Batic et al. [4] noted a reduction of compressive strength of 25% and of tensile strength of 40% after 75 days storage at 38°C. The literature review leads to the conclusion that tensile strength and Young's modulus are more sensitive to ASR than compressive strength. It should be investigated whether the findings can be transferred to slow/late aggregates.

2 EXPERIMENTAL PROGRAM

2.1 Aggregates used

Three crushed aggregates are used which are greywacke from the lower Harz, quartz porphyry from Halle and crushed gravel (boulders) from the Upper Rhine valley. The mineralogical composition of the aggregates has been described in [5].

2.2 Concrete composition

The cement used is a Portland cement CEM I 32.5 R [6] with 1.24% by mass Na_2O equivalent. Table 1 shows the composition of the three concrete mixes.

The cement content is always 400 kg/m^3, the water-cement ratio amounts to 0.45, and the grading curve follows almost the Fuller curve with 16 mm maximum grain size. It is designated as AB 16 according to the German DIN 1045-2 [7]. 30% by vol. of the aggregates consist of non-reactive sand up to 2 mm and 40% stem from reactive rock with grain size 2/8 and 30% 8/16 mm.

2.3 Specimens and storage conditions

Beams with the dimensions of 100 mm x 100 mm x 500 mm are used for the determination of the dynamic elastic modulus with the resonance frequency method. Cylinders with 300 mm height and 150 mm diameter are tested in compression for the static modulus of elasticity and in splitting to get the tensile strength. Cubes with 150 mm edge length serve for the determination of the compressive strength.

The specimens are stored after casting at 20°C and 95% RH for one day. Thereafter they are placed in a fog room at (40 ± 2.0) °C during 560 days. Measurements of the expansion and the dynamic modulus of elasticity are taken at 2, 7, 28, 35, 70, 140, 280, and 560 days. At the same dates, the specimens are visually inspected. Compressive strength, tensile strength, and the static modulus of elasticity are determined at 35, 70, 140, 280, and 560 days.

3 RESULTS

3.1 Dynamic modulus of elasticity

The dynamic modulus of elasticity has been measured with a Grindo-Sonic instrument on a concrete beam which is elastically bedded and excited by a metal bar. The resonance frequency is measured which is proportional to the square root of the dynamic elastic modulus. Table 2 shows the results.

The numbers show a steep increase of the dynamic modulus up to 49 days of storage. This increase is due to continuing hydration. After 49 days, the dynamic modulus stays almost constant except the measurement on Upper Rhine gravel at 168 days. There is a reduction of about 20% which, however, recovers again after 280 days.

3.2 Compressive and tensile strength, static modulus of elasticity

The compressive strength is determined on 150 mm cubes, whereas the tensile strength is gained on cylinders by splitting and the static modulus of elasticity is measured by compression of cylinders. All values are the mean of three specimens. Figure 1 shows the results of the concretes with greywacke aggregates. The values of the tensile strength and the static modulus of elasticity are normalized with respect to the reference value after 35 days of fog room storage at 40°C. The compressive strength is plotted in absolute numbers in order not to mix up the lines. It can be seen that the modulus of elasticity of the concrete stays constant up to 140 days and then drops to 50% after 560 days.

The tensile strength increases a little up to 140 days and then decays to 67%. The compressive strength of the concrete is reduced by 5 MPa after 560.

Figure 2 shows the results with quartz porphyry concrete. Tensile strength and modulus of elasticity of the concrete decrease by 32 and 54%, respectively after 560 days. The compressive strength is reduced by 2 MPa.

Finally, the results of the crushed gravel concrete are presented in Figure 3. The decay of the modulus of elasticity is very obvious during the first 140 days. After that time it stays constant. The same applies for the tensile strength.

The compressive strength of the crushed gravel concrete is reduced by 3 MPa.

4 DISCUSSION

4.1 Compressive strength

As Figures 1 to 3 indicate the compressive strength is the property least affected by the ASR. The slow/late rocks become cracked due to reaction of the alkalis with the rocks. Greywacke showed in the pristine state veins of pyrite and calcite which were dissolved during the exposure. Veins in quartz porphyry were originally filled with chlorite and hematite which was also dissolved during the exposure [5]. The dissolution creates open cracks in the grains which are compressed at compressive loading, however, the compressive strength does not suffer much from such a degradation process. The strength loss of the greywacke concrete amounts to about 7% after 560 days, the one of quartz porphyry concrete is 2%, and the one of crushed gravel is 4%.

4.2 Tensile strength

When the grains have got cracks due to the dissolution of cementing substances an important component of the concrete is weakened. Opposite to compressive loading tensile loading causes an opening and propagation of the crack. Figures 1 to 3 show the relation between tensile strength and exposure time. The concrete with greywacke aggregate lost 33% of tensile strength, with quartz porphyry 32%, and with crushed gravel 21%. Comparing the strength losses at compressive and tensile loading the loss at the latter loading is 3 to 5 times higher. The observation that the tensile strength is much more affected by ASR than the compressive strength has been made on structures in service several times before [8], however, the observations were not made on slow/late aggregates.

4.3 Modulus of elasticity

The modulus of elasticity has been measured dynamically and statically. Table 2 shows the dynamic modulus of elasticity as function of exposure time whereas Figures 1 to 3 contain the static modulus of elasticity in normalized form. The dynamic modulus of greywacke concrete seems not to be affected by the exposure, also quartz porphyry concrete seems unaffected. The dynamic modulus of crushed gravel concrete shows a decay of 20% in the course of exposure but recovers later again. This result means that the dynamic modulus of elasticity is not very sensitive to the alkali-silica reaction and is therefore not a good indicator for ASR. The reason for this fact is the type of loading which is, from a mechanical point of view, negligibly low and the mass and geometry of the concrete specimen plays an important role in the test. One can also assume that ettringite crystals grow into the cracks and increase the stiffness but, to a lesser amount, the strength [9].

In contrast to the measurement of the dynamic modulus of elasticity, the static modulus of elasticity is determined from the stress-strain diagram between 5 and 30% of the compressive strength, i.e. at a much higher stress level. Cracks in the aggregate grains are compressed and therefore the static modulus must decrease with the exposure time since the dissolution process is progressing. Figures 1 to 3 show how the static modulus develops during 560 days of storage in the fog room. The static modulus of greywacke concrete diminishes by 51%, of quartz porphyry concrete by 54%, and of crushed gravel concrete by 50%. The comparison between the two moduli of elasticity is made by dividing the static modulus by the dynamic modulus for the exposure time between 35 and 560 days. The results are plotted in Figure 4 for the concretes tested.

When the measurements started the ratio of the two moduli amounts to about 0.90 for the concretes. This value is in accordance with literature findings [10]. With increasing exposure time, the ratio decreases substantially. The ratios come to 0.42 for greywacke concrete, to 0.39 for quartz porphyry concrete and to

0.45 for crushed gravel from the Upper Rhine valley. The numbers reveal the sensitivity of this property with respect to the alkali reaction. It is suggested to use either the static modulus of elasticity as indicator for ASR degradation or the ratio between static and dynamic modulus.

5 SUMMARY AND CONCLUSIONS

The paper has reported on an experimental study with three concrete mixes the coarse aggregates of which were greywacke, quartz porphyry, and crushed gravel from the upper Rhine valley. All three aggregates deem to be slow/late aggregates. The main conclusions are:

i) The exposure in a fog room of 40°C up to 560 days shows the degradation of all three concretes.

ii) The dynamic modulus of elasticity cannot predict the degradation of concrete due to ASR. It stays almost constant from 49 days to 560 days.

iii) The compressive strength is affected by ASR, but less than the tensile splitting strength.

iv) The static modulus of elasticity is most affected by ASR.

v) For assessment of degraded structural concrete, it is proposed to use the static modulus of elasticity as reliable indicator.

6 ACKNOWLEDGEMENT

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7 REFERENCES

[1] Giaccio, G., Zerbino, R., Ponce, J.M., Batic, O.R. (2008): Mechanical behavior of concretes damaged by alkali-silica reaction. Cement and Concrete Research 38 (7): 993-1004

[2] Kubo, Y., Watanabe, Y., Ueda, T., Nomura, N. (2008): Influence of ASR expansion on mechanical properties of concrete deteriorated by ASR. 13th ICAAR, June 16 – 20, 2008, Trondheim, Norway, 9 pp

[3] Copuroglu, O. (2010): Effect of silica dissolution on the mechanical characteristics of alkali-reactive aggregates. Journal Advanced Concrete Technology 8 (1): 5-14

[4] Batic, O., Gaccio, G., Zerbino, R. (2004): On the effect of ASR cracking on the mechanical bahaviour of concrete in tension and compression. Proc. 12th Int. Conf. Alkali-aggregate reaction in concrete: 1136-1141

[5] Reinhardt, H.W., Mielich, O. (2011): A fracture mechanics approach to the crack formation in alkali sensitive grains. Cement and Concrete Research 41 (3): 255-262

[6] EN 197-1 (2000): "Cement – Part 1: Composition, specifications and conformity criteria for common cements, CEN

[7] DIN 1045-2 (2008): Concrete, reinforced and prestressed concrete structures – Part 2: Concrete – (in German)

[8] Siemes, T., Visser, J. (2000): Low tensile strength in older concrete structures with alkali-silica reaction. 11th ICAAR, Québec: 1029-1038

[9] Mehta, P.K. (1983): Mechanism of sulfate attack of portland cement concrete – Another look. Cement and Concrete Research 13 (3): 401-406

[10] Neville, A.M. (1995): Properties of concrete, 4th ed., Longman Group, Burnt Mill

TABLE 1: Composition of concrete mixes					
Concrete indicator	Aggregate	Storage	Cement		Aggregate proportion[1)]
		40°C fogroom	Designation	Total alkali content	
			-	M.-% $Na_2O_{equ.}$	Vol.-%
CEM I GW	crushed greywacke	x	CEM I 32.5 R	1.24	30 + 70
CEM I QP	crushed quartz porphyry	x	CEM I 32.5 R	1.24	
CEM I UR	crushed gravel from Upper Rhine	x	CEM I 32.5 R	1.24	

[1)] 30 Vol.-% non-reactive sand, 70 Vol.-% reactive aggregates

TABLE 2: Dynamic modulus of elasticity, in GPa								
Type of aggregate	Storage duration, days							
	0	49	83	168	224	280	457	560
Greywacke	36	48	49	49	50	50	51	51
Quartzporphyry	36	49	50	47	46	47	49	49
Upper Rhine gravel	31	46	45	39	40	42	46	46

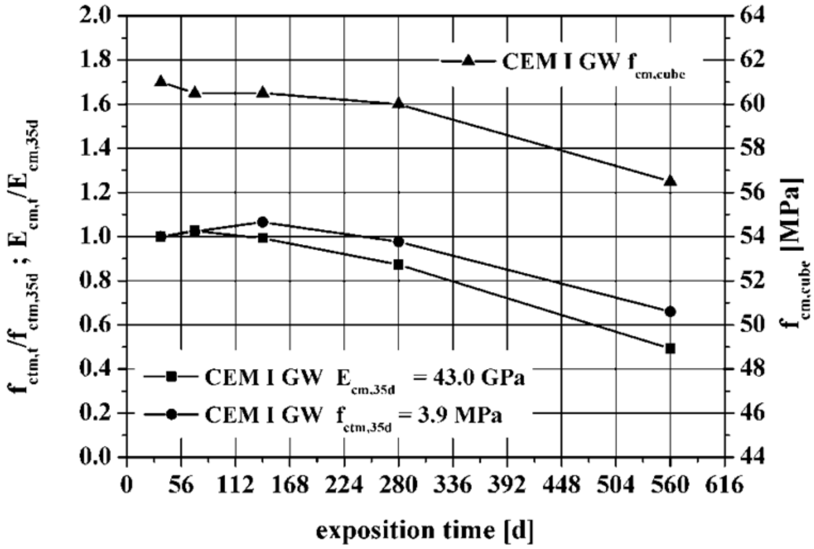

FIGURE 1: Normalized tensile strength and static modulus of elasticity of greywacke concrete (GW) on the left ordinate, compressive strength at the right ordinate

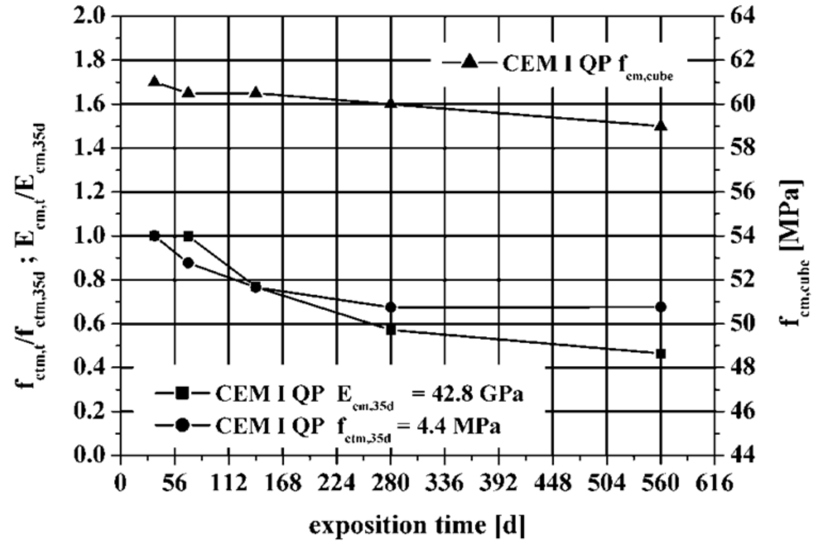

FIGURE 2: Normalized tensile strength and static modulus of elasticity of quartz porphyry concrete (QP) on the left ordinate, compressive strength at the right ordinate

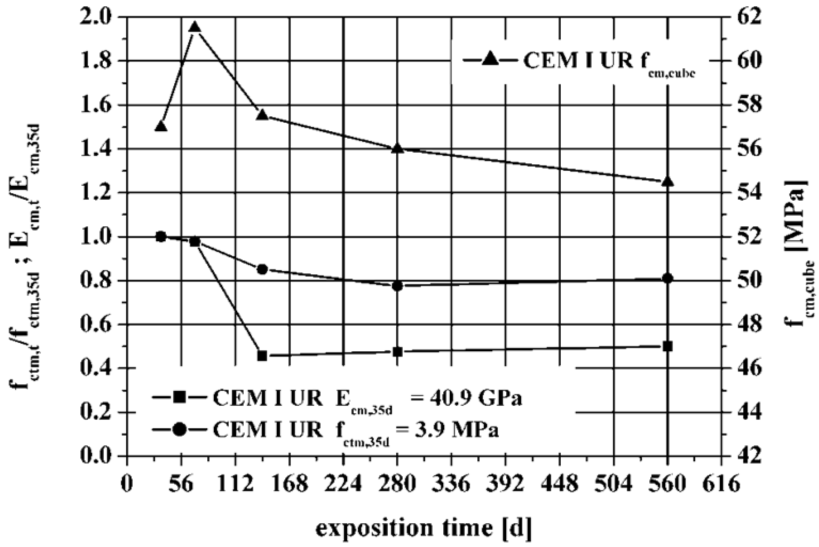

FIGURE 3: Normalized tensile strength and static modulus of elasticity of crushed gravel concrete (UR) on the left ordinate, compressive strength at the right ordinate

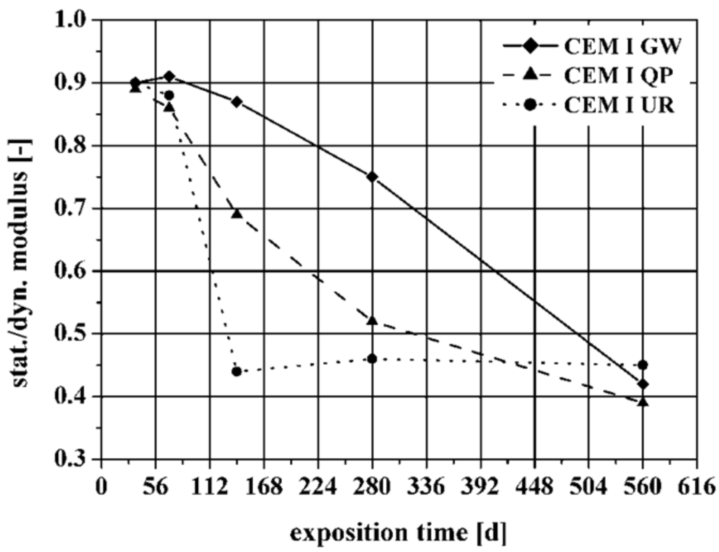

FIGURE 4: Ratio of static to dynamic modulus of elasticity for of the three concretes tested as function of exposure time