US-Poland Workshop
on Diagnostics of Concrete Materials and Structures
for Infrastructure Facilities
Warsaw, May 17 and 18, 2004

HOW TO PREVENT SCALING OF CONCRETES IN THE OUT-DOOR STRUCTURES?

Daria Jóźwiak-Niedźwiedzka[1]

Abstract

The subject of the investigations was the influence of pre-wetted lightweight aggregate on damage of the concrete surface due to cyclic freezing and thawing in the presence of de-icing salts tested according to the Swedish Standard SS 13 72 44 (the Borås method). Six series of concrete specimens were made with the same water/binder (w/b) ratio 0.32, cement volume 400 kg/m^3 and content of superplasticiser 8.8 kg/m^3. One series, S4/2, contained air-entrainer. Other two series S4/7 and S4/8 were made with water/cement ratio equal to 0.45 and lower cement content 340 kg/m^3. In a few series sand fraction 0÷2 mm and basalt fraction 2÷4 mm were partly or totally replaced by wetted lightweight aggregate. Concretes S3/1, S3/3, S4/7 and S4/8, have failed the test, the best results were obtained for concrete S3/6 (with fraction 2÷4 mm replaced by half) and S4/2 (air-entrained). Application of an air-entraining agent is rather expensive, more expensive than LWA, and at a construction site it is neither easy nor reliable. It seems that the replacement of a part of aggregate by LWA could be more effective to improve the scaling resistance.

Keywords

Concrete, scaling resistance, internal curing, expanded clay

Introduction

In Central and Eastern Europe the climatic conditions in winter season are particularly severe for concrete constructions. The successive freezing/thawing cycles cause both external and internal concrete deterioration. In a winter season, there may be over 100 cycles to be supported by out-door structures. When de-icing salts are used the situation is getting more serious. This study is concentrated on deteriorations of the external layers of high performance concretes (HPC) and ordinary concretes (OC) caused by cyclic freezing and thawing – the scaling of concrete.

Many published investigations lead to the following conclusions, (e.g. Pigeon, Lankard, Fagerlund [1-3]). The phenomenon of scaling is a progressive type of deterioration that slowly eats away consecutive thin layers of paste and mortar from the exposed surfaces of

---

[1] M. Sc., Institute of Fundamental Technological Research, Polish Academy of Sciences, 00-049 Warsaw, Swietokrzyska 21, djozwiak@ippt.gov.pl

concrete elements. This occurs usually only when concrete freezes in the presence of de-icing salts. Low value of water/cement ratio and all other parameters characteristic for high quality concretes allow to limit the scaling effects. Scaling is most likely to occur on surfaces that were over vibrated, towelled too early and subjected to extensive plastic shrinkage, or where excessive bleeding appeared.

The outdoor concrete structures are exposed to various external agents acting on outer surfaces. Therefore their resistance against scaling is not like strength a bulk property but in the first place a surface property, determined by the composition and properties of surface layers, indicated by the term "skin of concrete". Kreijger, [4], described three different surface layers. First layer is the cement skin (about 0.1 mm thick), second – the mortar skin (about 5 mm) and third – the concrete skin (about 30 mm). The structural differences in the layers are due to the wall effect, to sedimentation and segregation as a result of gravity, to compacting methods like vibration, and to permeation and evaporation of water in and out of concrete.

The microstructure of the surface layers of concrete structures is not very well recognized. It is known that these layers are mostly made of cement paste (e.g. Weber and Reinhardt [5]), and that their porosity is higher than in the other regions of concrete structures. When fresh concrete is exposed to air, then water evaporates what results in a considerable reduction of the compressive strength. Simultaneously, systems of microcraks appear if appropriate wet curing was not applied. For high performance concretes when the w/c ratio is low and the microstructure is very dense, proper early curing is necessary to achieve the designed properties of concrete. To ensure the indispensable content of water needed for the correct hydration process several investigators (e.g. Weber and Reinhardt, Schwesinger and Sickert, Zhutovsky et al. [5-8]) used the pre-soaked lightweight aggregate (LWA) as internal water reservoirs, thus acting in a somewhat "intelligent" way.

The transport of water in concrete depends on its microstructure and on existing humidity gradient. As the hardening of concrete advances, in the cement paste a system of pores develops. Silica fume concretes show a refined pore structure with smaller radii than in ordinary concrete. Theoretically the capillary forces of the cement paste are high enough to absorb water from lightweight aggregate grains and to transport it to the drier cement paste regions, where the reaction with unhydrated cement may advance. The suction forces in the capillary pores are inversely proportional to the radius; the smaller the capillary pores in the cement paste the higher are the suction forces. With advanced hydration of cement and increasing density of the structure the transport of water and vapour slows down and stops when the relative humidity in the lightweight aggregate grain and in the hardened cement paste are in equilibrium. The lower the relative humidity of the environment, the stepper is the gradient between the surface layers and more distant layers. Due to water evaporation this gradient increases and at the surface layer the moisture from the lightweight aggregate is transported to the cement paste faster than in the interior of the considered element. When water from lightweight aggregate takes part at the hydration process, the structure of concrete surface layers is denser, reducing the water evaporation and the diffusion process becomes slower. The surface layers of concrete with lightweight aggregate are denser than of traditional high performance concretes [8], and therefore more resistant to scaling.

Materials and laboratory test methods

Two commercially available Polish cements were used: CEM I 45.5 R „Chelm" and CEM I 32.5 R „Malogoszcz" (both similar to ASTM Type III). The silica fume from plant "Laziska" was used in the form of dry uncompacted powder. Normal weight aggregate (NWA) was used: fine aggregate was an ordinary river sand, fraction 0÷2 mm; coarse aggregates were basalt and granite. The basalt fraction: 2÷4 mm and 8÷16 mm, granite fraction was 4÷8 mm. As the lightweight aggregate was used expanded clay Keramzite, which was sieved and divided into two fractions: 0÷2 mm (LWA 0÷2) and 2÷4 mm (LWA 2÷4). A naphthalene sulfonate-melamine resin-based High Rate Water Reducing Admixture (HRWRA) was applied with a liquid specific gravity of 1.15 and solid content of 30 percent. A commercial neutralized vinsol resin-based air-entraining agent (AEA) was used. The composition of all concrete mixes is given in Table 1. Concretes S3/1 – S3/6 and S4/2 may be considered as High Performance Concretes (HPC) while series S4/7 and S4/8 are Ordinary Concretes (OC).

All concrete mixes marked as S3 and S4/2 were made with constant w/c ratio equal to 0.35 and w/b=0.32 (HRWRA = 2% of cement and silica fume mass). Ordinary concretes S4/7 and S4/8 were performed with w/c ratio equal to 0.45 (HRWRA = 2% of cement mass). Two references mixes S3/1 and S4/2 were made, without any lightweight aggregate. The first mix, S3/1, was performed without air-entraining admixture and the second one S4/2 contained air-entrainer 0,03% by weight of binder. The silica fume: cement ratio was approximately 10 % by mass. In concretes S3/3 and S3/4 sand fraction was replaced by volume by LWA 0÷2 mm in quantity of 1/2 and 1/3 part of sand volume. In concretes S3/5, S4/7 and S3/6, S4/8 – all or a half of volume basalt 2÷4 mm was replaced by LWA 2÷4 mm, respectively. Soaking of LWA 0÷2 and 2÷4 was reached in a water container during 24 hours before mixing. Water content added with LWA was taken into account for final mixture proportion.

Table 1. Composition of the concrete mixes in kg/m^3

Series Composition	S3/1	S3/3	S3/4	S3/5	S3/6	S4/2	S4/7	S4/8
CEM I 42,5R	400	400	400	400	400	400	-	-
CEM I 32,5 R	-	-	-	-	-	-	340	340
Sand 0÷2 mm	700	350	466.7	700	700	700	700	700
Basalt 2÷4 mm	267	267	267	-	133.5	267	-	133.5
Granite 4÷8 mm	267	267	267	267	267	267	267	267
Basalt 8÷16 mm	608	608	608	608	608	608	608	608
LWA 0÷2 mm	-	99	66	-	-	-	-	-
LWA 2÷4 mm	-	-	-	67.8	33.9	-	67.8	33.9
Silica fume	40	40	40	40	40	40	-	-
Water	140	96.8	111.2	110.4	125.2	140	123.4	138.2
HRWRA	8.8	8.8	8.8	8.8	8.8	8.8	6.8	6.8
Air-entrainer (AEA)	-	-	-	-	-	0.13	-	-
Water/binder (w/b)	0.32	0.32	0.32	0.32	0.32	0.32	0.45	0.45

The same mixing procedure was used for all concretes.

1. Dry mixing of normal weight aggregate for 3 min.,
2. Half the amount of water was added,
3. Cement and silica fume was added and mixed for 1 min.,
4. Finally the lightweight aggregate and the rest of water with admixtures was added and mixed for 3 min.

The workability, density and air-content were measured directly after mixing. All tests were performed according to Polish Standard PN-88/B-06250. The specimens were vibrated in forms and covered by plastic film. After de-moulding the specimens were stored for 24 hours in water and then in air at 20±2°C and 65±5% relative humidity until testing.

For each of the series 100x100x100 mm cubes were cast for compressive strength tests, determination of air-void characteristic and scaling tests. Three 40x40x160 mm beams were also cast for determination of the dynamic modulus.

Compressive strength test was performed after 28 days. Air-content, specific surface α, spacing factor L and content of micropores below 0.3 mm A_{300} in the hardened concrete specimens were measured with PN-EN 480-11 method on plane sections (computer program ImagePro Plus) also after 28 days. Dynamic modulus E_{dyn} was tested according to ASTM C 215-85. Salt scaling tests were performed according to Swedish Standard SS 13 72 44 (so-called Borås method [9, 10]). Freeze/thaw exposure was carried on one-dimensionally on the upper horizontal surface of the specimens – cast surface, while the remaining surfaces were isolated against humidity and heat transfer. After 21 days of curing the top exposed surface was covered with 3% saline solution. Then the cooling and heating cycles, each of 24 hours, were applied. The successive temperature cycles were recorded in the saline solution layer on the top of specimens every hour with the digital thermometer LB-711 system working with 6 surface probe.

The scaled material was collected and weighed after given numbers of freeze/thaw cycles, and the results expressed as mass per unit area were recorded. The end of testing of the ordinary concretes according to the Swedish Standard is 56 cycles and for the concretes containing silica fume – 112; the experiment was prolonged up to 143 cycles.

The conformity criteria for concretes according to Borås method are based on mass of scaling at 28 days (m_{28}), 56 days (m_{56}) and at 112 days (m_{112}) and are expressed verbally:

- Very good: m_{56} average < 0.10 kg/m^2
- Good: m_{56} average < 0.20 kg/m^2 or
  m_{56} average < 0.50 kg/m^2 and $m_{56}/m_{28} < 2$ or
  m_{112} average < 0.50 kg/m^2
- Acceptable: m_{56} average < 1.00 kg/m^2 and $m_{56}/m_{28} < 2$ or
  m_{112} average < 1.00 kg/m^2
- Unacceptable: the above not complied with.

Results and discussion

The results of the workability, density and air-content are given in Table 2. Table 3 gives the characteristic of all other concrete parameters.

Table 2. Characteristics of the fresh concrete mixes

Series / Characteristic		S3/1	S3/3	S3/4	S3/5	S3/6	S4/2	S4/7	S4/8
Slump	[mm]	35	70	80	60	40	50	170	150
Air-content	[%]	4.6	4.2	4.8	4.8	4.2	4.8	3.7	2.8
Unit mass	[kg/m3]	2475	2372	2391	2379	2453	2466	2429	2487

As expected, the addition of silica fume showed reduced the workability down to slump equal approximately to 100 mm. Regarding the HPC, the NWA replacement by pre-wetted LWA in the series slightly increased and in one series decreased the workability. The workability of HPC containing pre-wetted LWA was a bit higher than workability of concretes without LWA and as expected, lower than for OC without silica fume.

The value of air-content in HPC measured in the fresh mix remained on the same level, about 4.6%, for the OC this level was ~3.3%. Nearly all concretes that contained LWA (except S4/8) showed lower values of density than concretes made with NWA, because LWA replacement was calculated by volume not by mass.

Table 3. The obtained results of the tested concretes

Series Characteristic	S3/1	S3/3	S3/4	S3/5	S3/6	S4/2	S4/7	S4/8
f_{c28} [MPa]	84.6	79.3	74.1	88.3	76.7	73.9	71.7	71.5
E_{dyn} [GPa]	53.6	45.9	47.1	52.9	51.9	54.2	47.5	48.6
Porosity [%]	2.21	4.00	3.00	4.08	5.11	4.92	4.35	4.46
Specific surface, α [mm^{-1}]	22.96	20.63	17.24	17.17	16.47	21.77	31.99	18.2
Spacing factor, L [mm]	0.30	0.24	0.33	0.29	0.28	0.23	0.16	0.27
Pore volume below 0.3 mm, A_{300} [%]	0.58	0.74	0.63	1.05	0.8	0.98	1.01	0.42

As it was expected the compressive strength value was higher for concretes with w/b ratio equal 0.32 than for ordinary concretes, w/b=0.45. The aggregate replacement by pre-wetted LWA had no or very small influence on the compressive strength and this influence could be neglected.

The values of the E_{dyn} for all concretes with LWA were lower than for other similar concretes with LWA, but the maximum difference was only about 8 GPa (15%). In the series of concretes with LWA higher values of E_{dyn} than concretes with w/b=0.32 were observed.

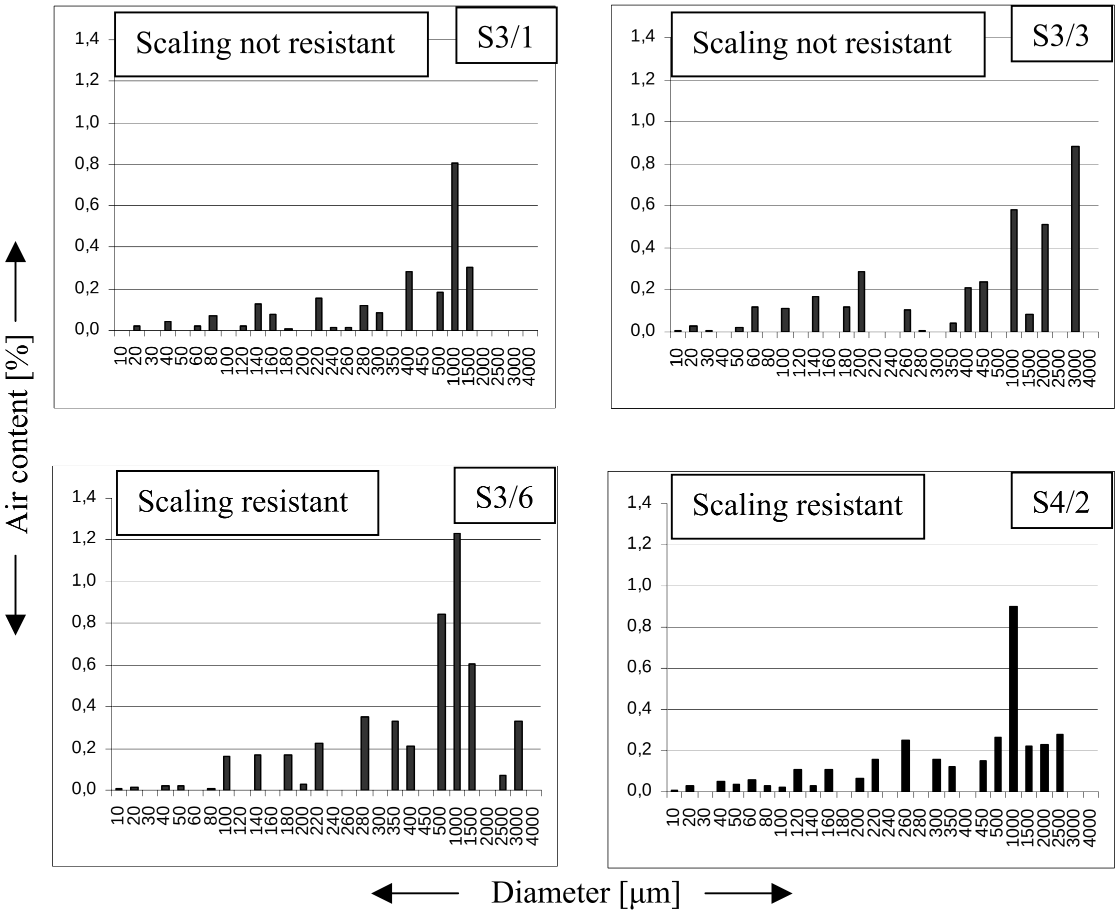

Fig.3. Distribution of air-pore diameters versus respective air content

Figure 4 shows the distribution of the air-voids. The values of porosity, and consequently that of specific surface α, spacing factor L and content of micropores A_{300} showed very large diversification. In the first place the values of air-content measured in a fresh mix vary from the values of porosity measured on concrete plane section. As is presented in Fig. 3 the percent of the air-content in the air-voids perimeter class for four chosen concretes S3/1, S3/3, S3/6 and S4/2 is not very homogenous and not unequivocal. The total porosity for those concretes varies from 2.21 to 5.11%. However, concretes with pre-wetted LWA (both HPC and OC) showed approximately two times higher porosity than non air-entrained concrete. In relation to HPC the specific surface ranged from 16.47 mm^{-1} to 22.96 mm^{-1} and showed higher values for concretes without LWA but for concrete without air-entrainer the content of micropores presented the lowest value. The lowest value of porosity showed HPC without both air-entrainer and LWA. The OC porosity results were comparable. The largest differences were observed in the HPC with LWA.

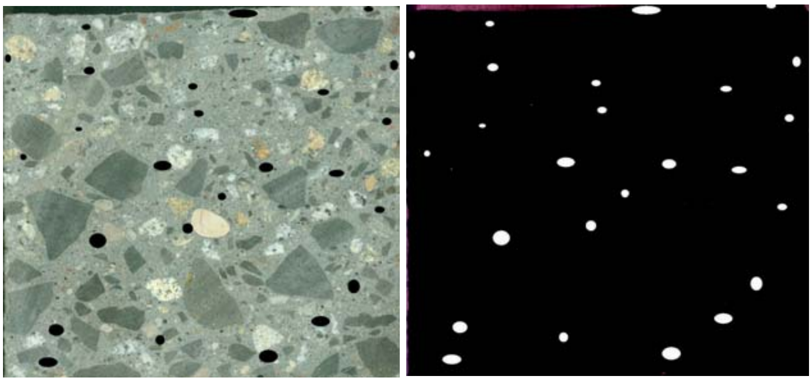

Fig.1. Concrete S3/6, bitmap (left) and binary image (right);
w/b=0.32; a half of 2÷4 mm LWA was replaced

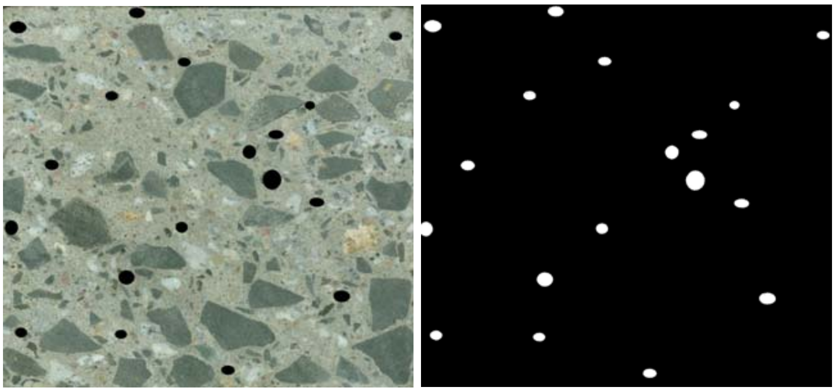

Fig.2. Concrete S4/8, bitmap (left) and binary image (right);
w/b=0.45; a half of 2÷4 mm LWA was replaced

Figures 1 and 2 show the bitmap and binary images of the S3/6 and S4/8 concretes. Visual field is 100x100mm; the top of the image is the cast surface of the specimen. The plain sections of specimens were properly prepared and after scanning the binary conversion were used. On the bitmap type image the elements of structure are grains of normal, and lightweight aggregate (black spots), and cement paste filling the space between grains. On the binary version of pictures only lightweight aggregate is shown as white spots and their distribution shows that the replacement of the part of NWA by pre-wetted LWA does not cause any segregation during mixing and vibration of the fresh mix. In all verified cross-sections the lightweight aggregate was uniformly distributed in specimens. What was particularly important for the scaling process - the lightweight aggregate was distributed also in the surface layer.

Fig. 4 shows that the concrete specimens S4/7 and S4/8 and with LWA failed the SS 13 72 44 test, probably because both series had relatively high w/c ratio equal to 0.45, and were made without air-entraining admixture, each point of the diagrams represents mean value from six specimens. Also as it was expected, the positive results were achieved for air-entrained concrete S4/2: scaling after 112 cycles lower than 0.26 kg/m^2. The concretes made with LWA showed various results after 112 cycles of cyclic freezing and thawing. The best result from all series achieved concrete S3/6, made without air-entraining admixture but with replacement of a half of 2÷4 mm fraction by pre-wetted LWA by volume. Two HPC series failed the Borås test. Concrete S3/1 without air entraining and the other concrete, S3/3 with a half of replaced fraction 0÷2 mm. This situation could be interpreted as a result of low porosity (less than 4%). SS 13 72 44 appeared to be a viable test for evaluating scaling resistance of HPC containing pre-wetted LWA.

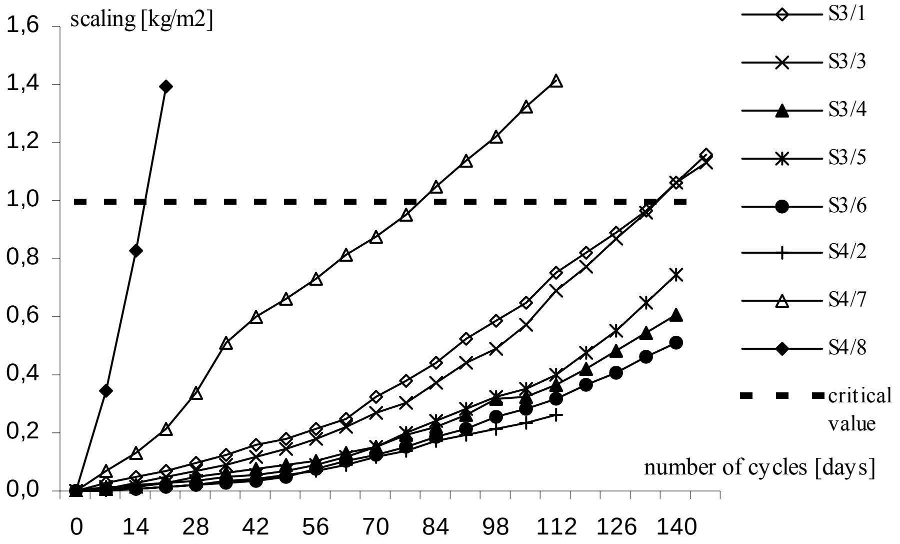

Fig. 4. Results of the frost resistance tested according to the Borås method

Conclusions

The effect of NWA replacement by pre-wetted LWA on compressive strength, E_{dyn}, porosity and scaling resistance of high performance concretes and ordinary concretes was investigated. The following conclusions can be drawn from this preliminary study:

1. The values of compressive strength and dynamic modulus in the HPC case, with and without LWA were similar.
2. Under cyclic freezing and thawing, the behaviour of HPC specimens was different from those of OC specimens. This observation suggests that replacement of LWA can be effective only for low water/binder ratio concretes.
3. The HPC specimens without both air-entrainer and LWA showed insufficient scaling resistance (not satisfying condition of m_{56}/m_{28}). It can be suggested that concretes with low w/b ratio need to be air-entrained or replacement of adequate fraction aggregate with LWA should be made.
4. The application of the air-entraining agents is rather expensive, more expensive than pre-wetted LWA, and on a construction site is neither easy nor reliable. It seems that the replacement of the part of aggregate by LWA may be considered as more effective to improve the scaling resistance.
5. Future research is needed in following directions:

- The influence of the replacement of LWA on the internal frost resistance, e.g. determined according to ASTM C 666 A or B method.
- The influence of the cement type on the frost resistance and scaling resistance of concrete containing pre-wetted LWA.
- The sensitivity of the freeze-thaw durability of concrete with saturated LWA to the curing time and conditions.

References

Pigeon M. (1994) Frost Resistance. A critical look. Concrete technology: past, present, and future. In: Proc. of V. Mohan Malhotra Symposium, ACI, Detroit, SP-144, p.141-158.

Lankard D. (2001) Scaling revisited, Concrete International, May, p.43-49.

Fagerlund G. (2001) The future structural stability of concrete structures exposed to frost, In: Banthia N., Sakai K. and. Gjørv O.E., editors. Third International Conference on Concrete Under Severe Conditions, The University of British Columbia, Vancouver, Canada, p.851-860.

Kreijger P.C. (1984) The skin of concrete composition and properties, Materials and Structures, 17(100), p.75-283.

Weber S., Reinhardt H.W. (1997) A new generation of high performance concrete: concrete with autogenous curing, Advanced Cement Based Materials, 6, p.59-68.

Weber S., Reinhardt H.W. (1999) Manipulating the water content and microstructure of HPC using autogenous curing, Modern Concrete Materials: Binders, Additions, Admixtures, Eds. R.K. Dhir. T.D. Dyer, London, p.567-577.

Schwesinger P., Sickert G. (2000) Reducing shrinkage in HPC by internal curing by using pre-soaked LWA, Proceedings of International Workshop on Control of Cracking in Early-Age Concrete, Tohoku University. Japan

Zhutovsky S., Kovler K., Bentur A. (2002) Efficiency of lightweight aggregates for internal curing of high strength concrete to eliminate autogenous shrinkage, Materials and Structures 35 March, p.97-101.

Test Methods for the Freeze-Thaw Resistance of Concrete – Test with Water or with Sodium Chloride Solution – Part 1: Scaling, CEN/TC 51, prEN xxxx, Draft: April 1999, pp. 27.

Jóźwiak-Niedźwiedzka D. (2002) Scaling resistance of different concretes tested with Borås method, International Symposium on Non-Traditional Cement&Concrete, Brno, p.463-472