INFLUENCE OF PRE-WETTED LIGHTWEIGHT AGGREGATE ON SCALING RESISTANCE OF HIGH PERFORMANCE CONCRETES

Daria Jóźwiak-Niedźwiedzka
Institute of Fundamental Technological Research, Polish Academy of Sciences
Swietokrzyska 21, 00-049 Warszawa, Poland
e-mail: djozwiak@ippt.gov.pl

Abstract
The subject of the presented investigations was 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). The groups of six series of concrete specimens were made with the same water/cement ratio 0.35, the cement content 400 kg/m^3 and superplasticiser 8.8 kg/m^3. The sand fraction 0÷2 mm and basalt 2÷4 mm were replaced by different contents of pre-wetted lightweight aggregate. Only one of series of specimens, S3/2, contained air-entrainer. The air content in the hardened concrete specimens has been measured with ASTM C 457 method on the plane sections. The concretes S3/5 and S3/6, with fraction 2÷4 mm replaced completely or by half by pre-wetted lightweight grains have proven excellent durability in the meaning of SS 13 72 44, even much better than air-entrained concrete S3/2.

Introduction
The outdoor concrete structures are exposed to various external agents acting on outside 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, [1] describes 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). These 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 is not very well recognized. It is known that these layers are mostly made of cement paste [2], and that their porosity is higher than in the other regions of concrete structures. The process of drying can modify the pore structure and increase the freezable water content. 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 correct hydration process several investigators [3-6] used the presoaked lightweight aggregate 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 normal concrete. The radii of these pores are also smaller than in the lightweight aggregate so that for water is transported a humidity gradient is created. 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, 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 get the higher are the suction forces. With increasing density of the structure the transport of water and later vapor 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 is, 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 enters to hydration process, the structure of concrete surface layers is more dense, reducing the water evaporation and the diffusion process becomes slower. The surface of concrete with lightweight aggregate will be denser than of traditional high performance concretes [6], and therefore more resistant to scaling.

Laboratory tests

The objective of realized investigations was to compare the scaling resistance of non air-entrained concretes made with pre-wetted lightweight aggregate fraction 0÷2 mm and 2÷4 mm with ordinary and air-entrained high performance concretes. Six series of concrete cubes 100 mm were made in the laboratory conditions.

The lightweight aggregate used was expanded clay called "Keramzyt", which was sieved and divided into two fractions: 0÷2 mm (LWA 0÷2) and 2÷4 mm (LWA 2÷4). Soaking of LWA 0÷2 and 2÷4 was reached in water container during 24 hours before mixing. Rapid hardening Portland cement type CEM I 42,5R was used and silica fume was added as a 10% (mass) addition. The superplasticiser and air-entrainer were used correspondingly in amount of 2% and 0.03% of the binder mass (cement and silica fume). Compositions of all concretes are shown in table 1.

Table 1 Mixture compositions of concretes

Series / Composition	S3/1	S3/2	S3/3	S3/4	S3/5	S3/6
Cement 42,5R	400	400	400	400	400	400
Sand 0÷2	700	700	350	466.7	700	700
Basalt 2÷4	267	267	267	267	-	133.5
Granit 4÷8	267	267	267	267	267	267
Basalt 8÷16	608	608	608	608	608	608
LWA 0÷2	-	-	99	66	-	-
LWA 2÷4	-	-	-	-	67.8	33.9
Silica fume	40	40	40	40	40	40
Water	140	140	96.8	111.2	110.4	125.2
Superplasticizer	8.8	8.8	8.8	8.8	8.8	8.8
Air-entrainer	-	0.13	-	-	-	-

All concrete mixes were made with constant w/c=0.35 and w/b=0.32. As the reference mixes were considered: S3/1 – without air-entrainer and S3/2 with air-entraining admixture. The sand fraction 0÷2 mm and basalt fraction 2÷4 mm was replaced by volume by LWA, with corresponding fraction. In concretes S3/3 and S3/4 sand fraction was replaced by LWA 0÷2 mm in quantity of 1/2 and 1/3 part of sand volume. In concretes S3/5 and S3/6 – all and a half of volume basalt 2÷4 mm was replaced by LWA 2÷4 mm, respectively. Water content added with LWA was taken into account for final mixture proportion.

The mixing procedure of all concretes was:

1. dry mixing of normal weight aggregate for 3 min.,
2. half the amount of added 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.

Air content, specific surface α and the spacing factor L in the hardened concrete specimens were measured with ASTM C 457 method on the plane sections (computer program ImagePro Plus).

Frost/salt scaling tests were performed according to Swedish Standard SS 13 72 44 (so-called Borås method [7, 8]) on cubic specimens 100 mm. Freeze/thaw exposure was carried on one-dimensionally on the upper horizontal surface of the specimens, while the remaining surfaces were isolated against humidity and heat transfer. After 21 days of curing (24 hours in water and then in air at 23°C and 65% relative humidity) the top exposed surface was covered with 3% saline solution. Then the cooling and heating cycles, each of 24 hours, were applied according to figure 1. 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 result was expressed as mass per unit area was recorded.

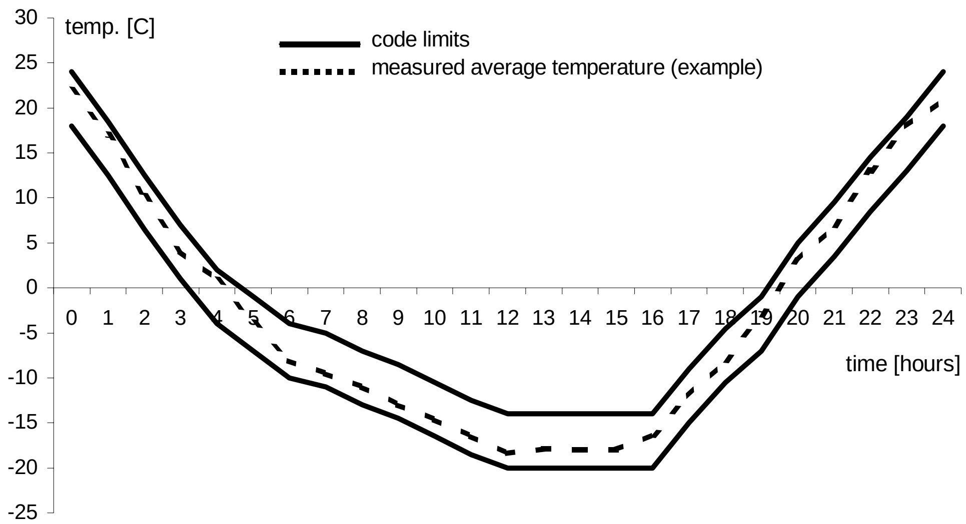

Fig.1 Freeze/thaw cycle according to SS 13 72 44

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

The compressive strength f_{c28}, dynamic Young modulus E_{dyn}, porosity, specific surface α and spacing factor L were determined on all series of specimens at an age of 28 days. The results are given in tab.2.

The images of cross-sections of concretes S3/5 and S3/3 are shown in fig.3 and fig.4. 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, and cement paste filling the space grains. On the binary version of pictures only lightweight aggregate is shown, in the fig.3 LWA 2÷4 mm and in the fig.4 – LWA 0÷2 mm.

Table 2 Characteristics of tested concretes

Characteristic \ Series	S3/1	S3/2	S3/3	S3/4	S3/5	S3/6
Density [kg/m^3]	2475	2498	2372	2391	2379	2453
Slump [mm]	35	50	70	150	60	40
Absorbability [%]	2.81	3.24	4.13	3.90	4.00	2.97
Porosity [%]	2.21	4.05	4.00	3.00	4.08	5.11
Spacing factor L [mm]	0.30	0.37	0.24	0.33	0.29	0.28
Specific surface α [mm^{-1}]	22.96	13.01	20.63	17.24	17.17	16.47
$f_{cm.28}$ [MPa]	84.6	91.7	79.3	74.1	88.3	76.7
E_{dyn} [GPa]	53.6	53.2	45.9	47.1	52.9	51.9
$f_{bend.28}$ [MPa]	10	9.2	9.8	11.2	10	10.9

It has been observed that the replacement of the part of aggregate does not cause any problems with mixing or vibrating the fresh concrete mix. In both cases the lightweight aggregate is uniformly distributed in hole specimens and what is particulary important for the scaling tests - the lightweight aggregate is distributed also in the surface layer.

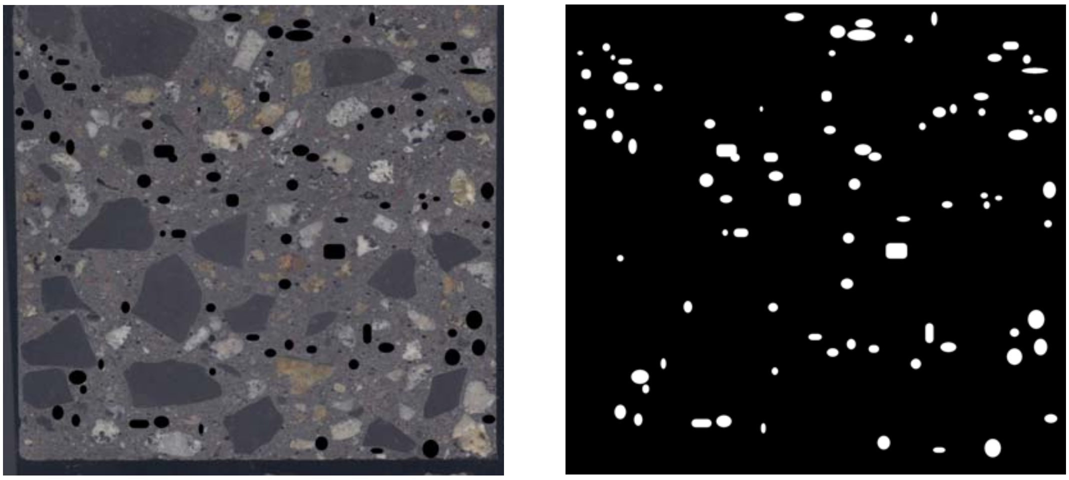

Fig. 3. Concrete S3/5, bitmap (left) and binary image (right)

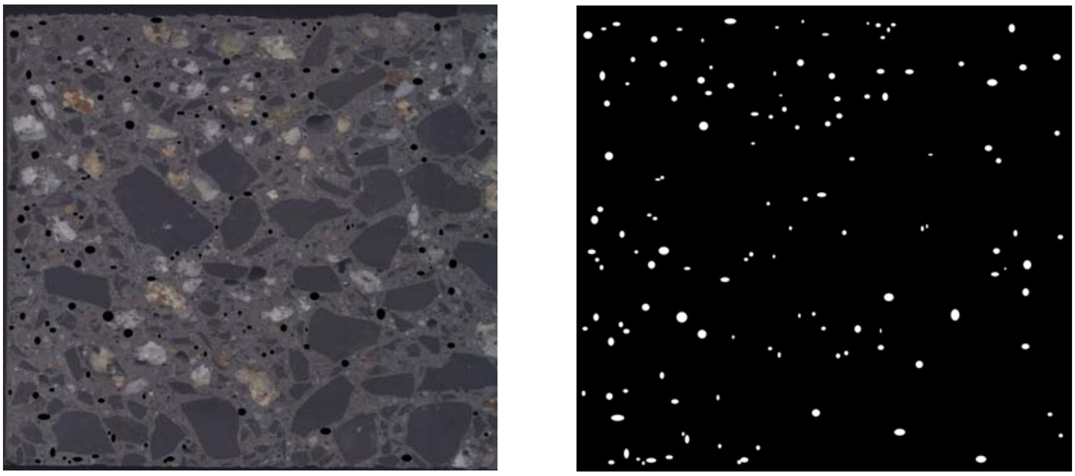

Fig. 4. Concrete S3/3, bitmap (left) and binary image (right)

After 112 cycles all tested concretes showed required scaling resistance in the presence of deicing salts. After closer analysis it may be noted, however, that series S3/2 had not been well aerated, and their specific surface α and spacing factors L showed incorrect distribution of the entrained air bubbles. Lightweight aggregate concretes have shown better scaling resistance in the presence of deicing agents showed, and especially concrete S3/5 and S3/6. According to SS 13 72 44 those concretes are very good in the meaning of scaling resistance, because m_{56} average < 0.10 kg/m^2. The curves number of cycles –scaling mass is shown in Fig. 5.

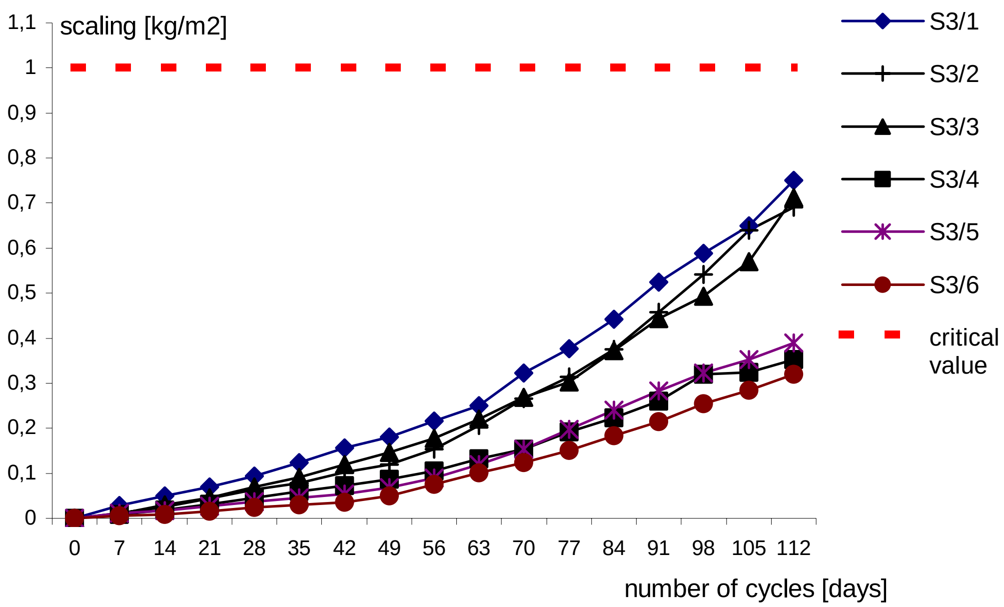

Fig. 5. Results of the frost resistance tested according to the Borås method

Conclusions

The lightweight aggregate was distributed in the all-concrete volume and also in the surface layer. In laboratory conditions and probably also in a ready-mix plant it may be easier to use pre-wetted lightweight aggregate than to perform correctly air-entrainment.

The concretes with LWA 2÷ 4 mm in the comparison of reference concrete S3/1 and aerated concrete S3/2 have shown similar bending strength (S3/5) or even its increase (S3/6). The compressive strength was higher for S3/5 than for the reference concrete S3/1 about 4.3%, but was lower for concrete S3/6 – 9.3%.

Application of the Borås test method for determination of the scaling resistance of concrete has shown that the best results were obtained for the concretes made with pre-wetted lightweight aggregate fraction 2÷ 4 mm, S3/5 and S3/6.

The air-entraining agents are quite expensive, more expensive than LWA, and their applying in the construction site is not easy. It seems that the replacement of the part of aggregate by LWA could be effective in the meaning of the scaling resistance.

The future research will be focused on the optimization of the composition of high performance concretes with lightweight aggregate with regard to the resistance against scaling.

Acknowledgements

The results are part of a research program carried on in the framework of NATO Project SfP 97.1888 „Concrete Diagnosis”

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