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Scaling resistance of high performance concretes containing a small portion of pre-wetted lightweight fine aggregate

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Abstract

The subject of the investigation 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, S3/2, contained an air-entraining agent. Series S4/7 and S4/8 were made with water/cement ratio equal to 0.45 and a lower cement content 340 kg/m^3. In a few series the 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, failed the test. The best results were obtained for concrete S3/6 (with the 2–4 mm fraction replaced by half) and S3/2 (air-entrained). The application of an air-entraining agent is more expensive than LWA, and at a construction site it is not always easy to control. It seems that the replacement of a part of aggregate by LWA could be a more effective way to improve the scaling resistance.

Keywords: Concrete; Scaling resistance; Internal curing; Expanded clay

1. Introduction

In Central and Eastern Europe the climatic conditions in the winter season are particularly severe for concrete construction. 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 more serious. This study concentrates on deterioration of the external layers of high performance concretes (HPC) and ordinary concretes (OC) caused by cyclic freezing and thawing which takes the form of the scaling of concrete.

Many published investigations lead to the following conclusions, (e.g. [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 concrete elements. This occurs usually only when concrete freezes in the presence of de-icing salts. Low values of water/cement ratio and all other parameters characteristic of high quality concrete limit the scaling effect. Also, scaling is most likely to occur on surfaces that were over-vibrated, trowelled too early and subjected to extensive plastic shrinkage, or where excessive bleeding occurs.

The outdoor concrete structures are exposed to various external agents acting on their outer surfaces. Their resistance against scaling is not a bulk property (strength). It is a surface property, determined mainly by the composition and properties of the surface layer, usually referred to the term “skin of concrete”. Kreijger [4], described three different surface layers. The first layer is the cement skin (about 0.1 mm thick), second is the mortar skin (about 5 mm) and the third is the concrete skin (about 30 mm). The structural differences in

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the layers are due to the wall effect, to sedimentation and segregation as a result of gravity, to improper compacting methods, 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. [5]), and that their porosity is higher than in the other regions of concrete structures. When fresh concrete is exposed to air, the water evaporates. This results in a considerable reduction of the compressive strength. Simultaneously, systems of microcraks appear if appropriate wet curing is 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. Several investigators (e.g. [5–8]) used the pre-soaked lightweight aggregate (LWA) as internal water reservoirs, to ensure the correct content of water needed for the hydration process. The transport of water in concrete depends on its microstructure and on the ambient humidity gradient. As 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 particle and in the hardened cement paste are in equilibrium. The lower the relative humidity of the environment, the steeper 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 to the interior. When water from lightweight aggregate takes part in the hydration process, the structure of the concrete surface layers is denser, reducing the effect of water evaporation and the diffusion process becomes slower. The surface layers of concrete with lightweight aggregate should be denser than traditional high performance concretes [8], and therefore more resistant to scaling.

2. Materials and laboratory test methods

2.1. Materials, mixing and curing

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 the 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. Expanded clay Keramzite was used as the lightweight aggregate. It 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%. 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 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 were made with constant *w*/*c* ratio equal to 0.35 and $w/b = 0.32$

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

Composition	Series							
	S3/1	S3/2	S3/3	S3/4	S3/5	S3/6	S4/7	S4/8
CEM I 42,5R	400	400	400	400	400	400	–	–
CEM I 32,5R	–	–	–	–	–	–	340	340
Sand 0–2 mm	700	700	350	466.7	700	700	700	700
Basalt 2–4 mm	267	267	267	267	–	133.5	–	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[a]	–	–	99	66	–	–	–	–
LWA 2–4 mm[a]	–	–	–	–	67.8	33.9	67.8	33.9
Silica fume	40	40	40	40	40	40	–	–
Water	140	140	96.8	111.2	110.4	125.2	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

[a] LWA soaked for 24 h before mixing and then drained to saturated surface dry conditions (pre-wetted).

(HRWRA = 2% of cement and silica fume mass). Ordinary concretes S4/7 and S4/8 were made with w/c ratio equal to 0.45 (HRWRA = 2% of cement mass). Two reference mixes, S3/1 and S3/2, were made, without any lightweight aggregate. The first mix, S3/1, was made without air-entraining admixture and the second one S3/2 contained air-entrainer 0.03% by mass of binder. The silica fume: cement ratio was approximately 10% by mass. In concretes S3/3 and S3/4 the sand fraction was replaced by LWA 0–2 mm, in a quantity of 1/2 and 1/3 parts of the sand volume. In concretes S3/5, S4/7 and S3/6, S4/8—all or half of the volume of 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 h before mixing. The water content of the LWA was taken into account for final mixture proportioning.

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 the forms and covered by a plastic film. After de-moulding the specimens were stored for 24 h in water and then in air at 20 ± 2 °C and 65 ± 5% relative humidity until testing.

For each of the series 100 × 100 × 100 mm cubes were cast for compressive strength tests, determination of air-void characteristic and scaling tests. Three 40 × 40 × 160 mm beams were also cast for determination of the dynamic modulus.

2.2. Test methods

Compressive strength test was performed after 28 days. Dynamic modulus E_{dyn} was tested according to ASTM C 215–85, after 28 days.

Air-content A, specific surface α, spacing factor $\bar{L}$ and the content of micropores below 0.3 mm A_{300} in the hardened concrete specimens were measured with the PN-EN 480-11 method on plane sections (computer program ImagePro Plus) after 28 days. A special program for automated air void analysis has been prepared; a linear traverse method was used. Each specimen was tested using 45-traverse lines.

Salt scaling tests were performed according to Swedish Standard SS 13 72 44 (so-called Borås method [9,10]). Freeze/thaw exposure was carried out 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 h, were applied according to Fig. 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 six surface probes.

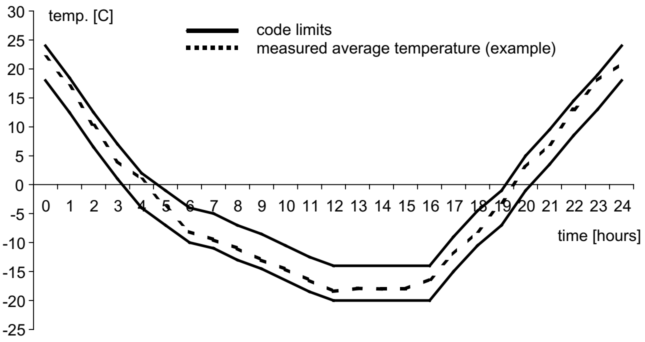

Fig. 1. Freeze/thaw cycle according to SS 13 72 44.

The scaled material was collected and weighed after a given number 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 the recommended number of cycles is 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 rated as follows:

- 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.

3. Results and discussion

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

Figs. 2 and 3 show the bitmap and binary images of the S3/6 and S4/8 concretes. Visual field is

Table 2
Characteristics of the fresh concrete mixes

Characteristic	Series							
	S3/1	S3/2	S3/3	S3/4	S3/5	S3/6	S4/7	S4/8
Slump (mm) (ASTM C143)	35	50	70	80	60	40	170	150
Porosity (%) (ASTM C173)	4.6	4.8	4.2	4.8	4.8	4.2	3.7	2.8
Unit mass (kg/m^3) (ASTM C138)	2475	2466	2372	2391	2379	2453	2429	2487

Table 3
The results of the tested on hardened concretes

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

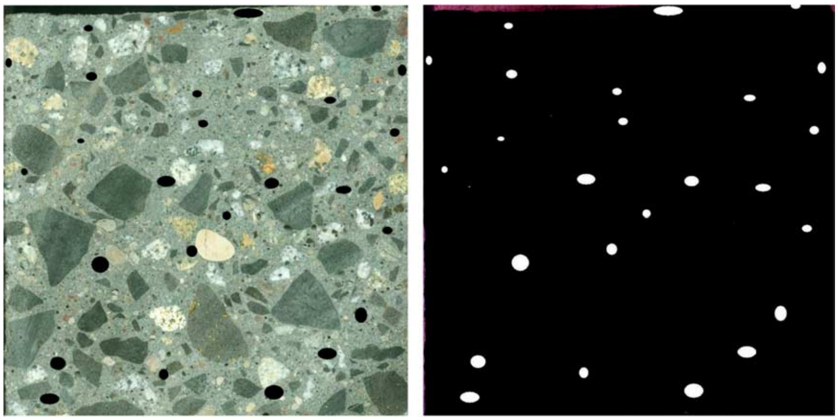

Fig. 2. Concrete S3/6, bitmap (left) and binary image (right); $w/b = 0.32$; a half of 2–4 mm LWA was replaced.

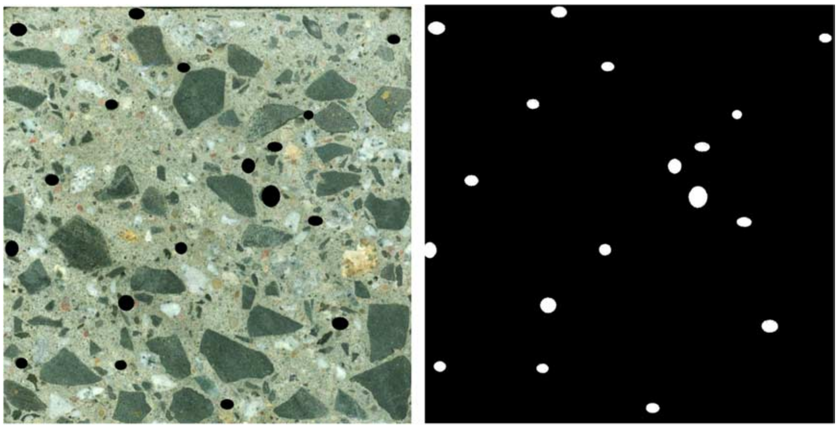

Fig. 3. Concrete S4/8, bitmap (left) and binary image (right); $w/b = 0.45$; a half of 2–4 mm LWA was replaced.

100 × 100 mm; 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 was 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 be-

tween 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 uniformly distributed also in the surface layer.

As expected, the addition of silica fume reduced the workability slump equal to approximately 100 mm, Table 2. 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 porosity 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) had lower values of density than concretes made with NWA, because LWA replacement was calculated by volume not by mass.

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 none or a very small influence on the compressive strength.

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%).

Fig. 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 variation. In the first place the values of air-content measured in a fresh mix vary from the values of porosity measured on concrete plane sections. As is presented in Fig. 4 the percent of the air-content in the air-voids perimeter class for four chosen concretes S3/1, S3/2, S3/3, and S3/6 is not very homogeneous 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

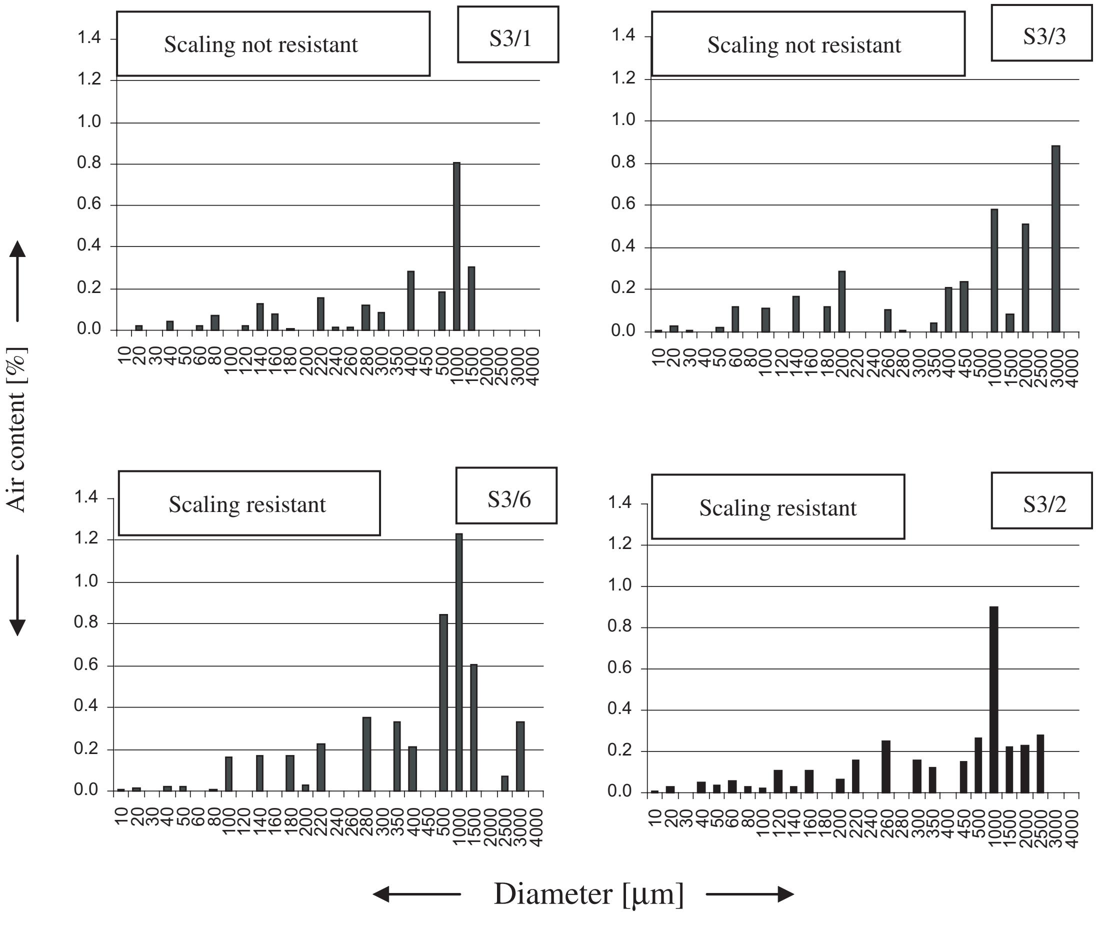

Fig. 4. Distribution of air-pore diameters versus respective air content.

values for concretes without LWA but for concrete without air-entrainer the content of micropores presented the lowest value. The lowest value of porosity occurred in HPC without both air-entrainer and LWA. The OC porosity results were comparable. The largest differences were observed in the HPC with LWA.

Fig. 5 shows the results of the scaling resistance of concretes with the same *w*/*b* ratio, equal 0.32, tested according to the Borås method. Fig. 6 shows the comparison of the scaling resistance of concretes with the same LWA replacement but with different *w*/*b* ratio. It is showed that the concrete specimens S4/7 and S4/8 both 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 on the curves represents a mean value from six specimens. Also as was expected, the positive results were achieved for air-entrained concrete S3/2: 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 was achieved for 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%). The SS 13 72 44 appeared to be a viable test for evaluating scaling resistance of HPC containing pre-wetted LWA.

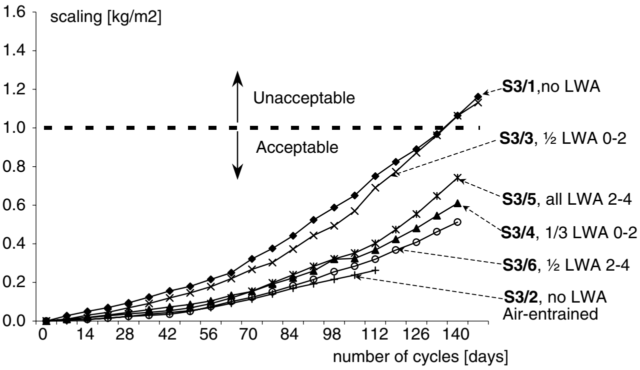

Fig. 5. Results of the frost resistance tested according to the Borås method, the same *w*/*b* = 0.32.

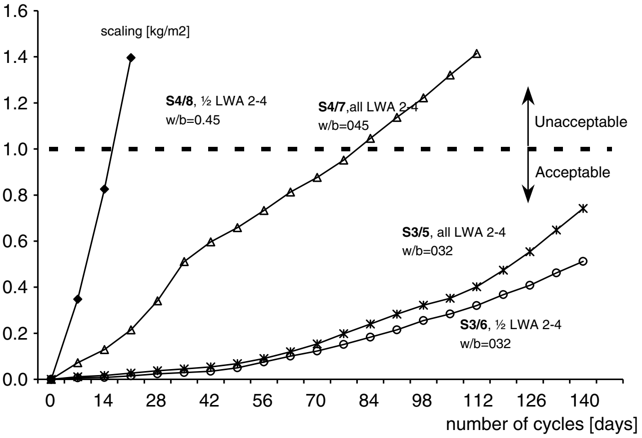

Fig. 6. Results of the frost resistance tested according to the Borås method, the same LWA replacement, and different *w*/*b* ratio.

4. 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 of HPC 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 be made with a replacement of an adequate fraction of aggregate by LWA.
4. The application of the air-entraining agents is relatively expensive. It is more expensive than pre-wetted LWA, and on a construction site is neither easy to use 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.

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