Sea Dredged Gravel versus Crushed Granite as Coarse Aggregate for Self Compacting Concrete in Aggressive Environment

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ABSTRACT
Properties of self compacting concrete (SCC) with two types of coarse aggregate - sea dredged gravel with smooth and rounded particles and crushed granite with rough and angular particles – have been studied. Sea gravel allowed a higher aggregate proportion in the concrete leading to a higher modulus of elasticity. Tensile and compressive strength were found to depend both on aggregate type and on the properties of the interfacial zone close to the aggregate surface. Freeze-thaw scaling resistance was good with crushed granite, whereas sea gravel led to more severe scaling caused by porphyry and iron-bearing sandstone particles – but not by porous flint particles.

Key words: Self compacting concrete, coarse aggregate, sea dredged gravel, crushed granite, mechanical properties, modulus of elasticity, compressive strength, splitting tensile strength, flexural strength, durability, freeze-thaw scaling resistance, porous flint.

1. INTRODUCTION

In Denmark, sea dredged gravel is the material most frequently used as coarse aggregate in concrete, including in self compacting concrete (SCC). However, when the concrete is to be exposed to severely aggressive environments the current standards exclusively allow crushed granite to be used [1]. The main reason for this is that even a small proportion of lighter and porous gravel particles can be suspected to adversely affect the durability of the concrete in terms of frost damage or alkali silica reaction. Also, the mechanical properties of the concrete may be affected by the characteristics of the coarse aggregate.

The two types of aggregate differ widely as regards the shape of the particles. The sea gravel consists predominantly of rounded and smooth particles, whereas the crushed granite particles are angular and have a rough surface. The rounded aggregate facilitates interparticle movement and thereby increases the flowability of SCC as compared to the angular crushed granite aggregate. As a consequence the volume fraction of aggregate in the concrete can be increased.

This will lead to a higher modulus of elasticity, lower shrinkage, lower heat of hydration and lower cost due to a reduced cement content. On the other hand, the smooth surface of rounded sea gravel may result in lower adhesion between cement paste and aggregate as compared to the rough surface of crushed granite. This would tend to reduce the strength - especially the tensile strength [2].

Due to the high number of freeze-thaw cycles during Danish winters, concrete exposed to water and deicing agents needs to possess a high freeze-thaw scaling resistance. Although the properties of the cement paste play the dominant role in the freeze-thaw scaling resistance of the concrete, the aggregate may also have a significant influence.

In the present paper the above issues are further investigated and discussed, based on a recent study [3].

2. EXPERIMENTAL

2.1 Materials

The two types of coarse aggregate used in the project are shown in Figures 1 and 2. The sea gravel was dredged from the Jutland Reef off the west coast of Denmark and subsequently processed and classified (4 – 16 mm). It consisted of approximately 70 % granite, 25 % flint and 5 % other types of rock - primarily sandstone, porphyry, quartzite and limestone. Approximately half of its flint content was dense and harmless to concrete; the remainder was porous and could be suspected to adversely affect the durability in terms of alkali silica reaction and deterioration due to freezing and thawing. The crushed granite (4 – 16 mm), from Sløvåg/Halsvig in Norway, has been used for concrete in severe environments for many years without causing any durability problems.

The other constituent materials of the concrete were a classified (0 – 4 mm) and washed sand material from a Danish inland deposit, approved for use in aggressive environment, a Danish sulphate resistant and low alkali portland cement (CEM I 42,5 N (HS/EA/$\leq$2)), a fly ash from a Danish power plant, a microsilica (condensed silica fume) of Norwegian origin, a vinsol and tenside based air entraining admixture, a lignosulphonate based water reducing admixture, and a polycarboxylic ether based superplasticizing admixture.

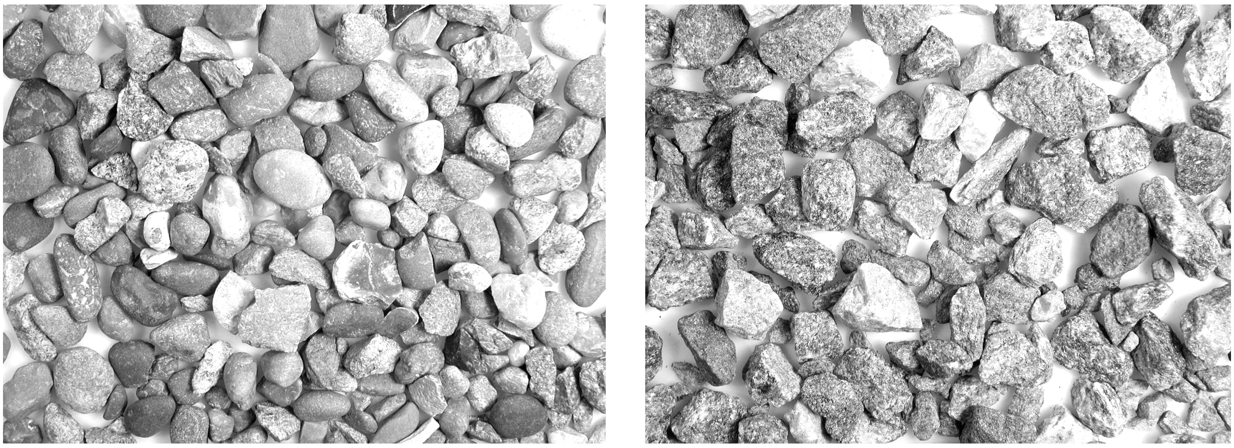

Figure 1 - Sea gravel (left) and crushed granite (right)

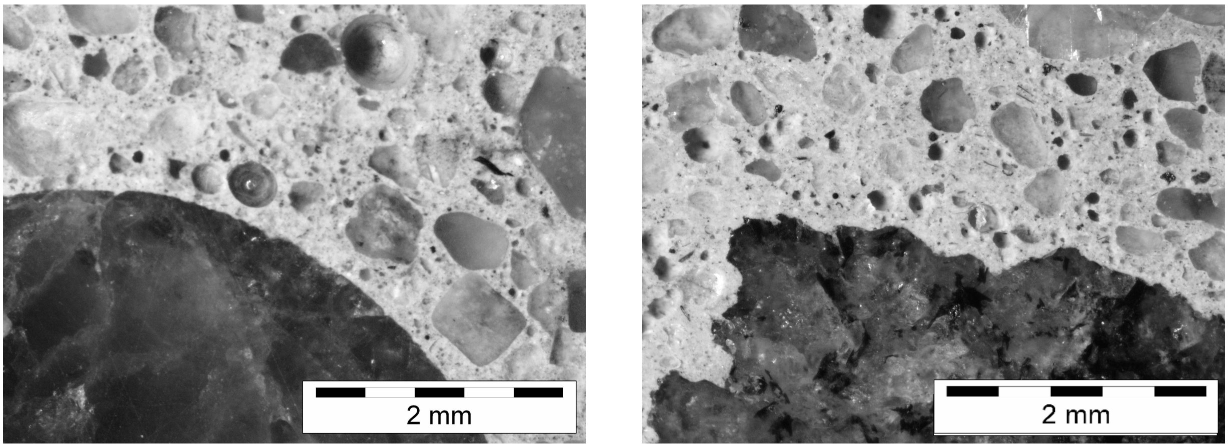

Figure 2 - Microscope image of sea gravel (left) and crushed granite (right) particles embedded in the concrete (the particles are the large dark parts in the lower part of the pictures)

2.2 Mix design

The basis of the mix designs chosen in the project was to fulfil the code requirements [1] of a concrete to serve in “aggressive” (Class A) and in “extra aggressive” (Class E) environment, and in addition it was chosen to include a high performance concrete (HPC) having a still higher strength and durability level.

Thus, three pairs of concrete mixes were prepared, each pair constituting one concrete with sea gravel and one with crushed granite coarse aggregate. All mixes where designed to have a slump flow of about 600 mm and an air content of about 5 %. The binder composition was the same in all mixes: 80 % cement, 15 % fly ash and 5 % microsilica.

The water to binder ratios (W/B) used for Class A, Class E and HPC were 0.40, 0.36, and 0.28, respectively. Via a number of trial mixes carried out to meet the above requirements it was found that the necessary paste content was 330 l/m^3 in mixes with sea gravel and 359 l/m^3 in mixes with crushed granite. The final mix designs are shown in Table 1 together with the properties of the fresh concrete. The deviations from the targeted values of slump flow and air content are considered to be random.

Table 1 - Mix design and fresh concrete properties

Mix designation	AS	AG	ES	EG	HS	HG	Density
Cement [kg/m^3]	285	311	300	333	338	375	3200
Flyash [kg/m^3]	53	58	56	63	63	70	2300
Microsilica [kg/m^3]	18	20	19	21	21	23	2290
Water [kg/m^3]	142	155	134	149	117	131	1000
Additives [kg/m^3]	4.0	4.3	4.9	5.2	5.8	5.9	1100
Sand [kg/m^3]	636	626	636	626	636	626	2640
Sea gravel [kg/m^3]	1131	-	1131	-	1131	-	2640
Crushed granite [kg/m^3]	-	1088	-	1088	-	1088	2695
W/B [-]	0.40	0.40	0.36	0.36	0.28	0.28	-
Slump flow [mm]	630	570	630	550	590	640	-
Air content [%]	4.0	4.4	5.0	6.5	4.2	6.5	-
Aggregate content [vol%]	66.9	64.1	66.9	64.1	66.9	64.1	-

2.3 Mechanical properties

The following mechanical properties were measured in accordance with the procedures in the indicated standards: Compressive strength [4], flexural strength [5], tensile splitting strength [6], and modulus of elasticity.

The specimens used for measuring the compressive strength, modulus of elasticity and tensile splitting strength were cylinders (100 mm diameter, 200 mm high), while prismatic specimens (100 mm x 100 mm x 420 mm) were used for measurement of the flexural strength. All specimens were cured in mold at 20^{o}C for 1 day, then demoulded and cured in water at 20^{o}C until the time of testing. Compressive strength, tensile splitting strength and modulus of elasticity were measured at 28 days age, while flexural strength was measured at 60 days age.

2.4 Freeze-thaw resistance

The specimens used for determination of the freeze-thaw scaling resistance were 55 mm thick slices saw cut from 100 mm diameter test cylinders. At the start of the test the specimens had been cured in water for 90 days, followed by drying for 7 days at 65 % RH and finally resaturated for 3 days.

During testing the specimen surface was covered by a 3 mm deep 3 % NaCl solution and subjected to temperature cycles between -20 °C and +20 °C at the rate of one cycle per day. After 7, 14, 28, 42, and 56 cycles the amount of material which had scaled off the surface was determined [7].

In addition to the concrete tests, the freeze-thaw resistance of the coarse aggregate itself has been determined. In this test, following the relevant standard procedure [8], the aggregate was submerged in demineralised water and subjected to 10 temperature cycles between -18 °C and +20 °C at the rate of one cycle per day, after which the weight loss of the aggregate was determined. A further test series was carried out where the aggregate was submerged in a 3 % NaCl solution in order to create exposure conditions similar to those of the concrete test.

4. RESULTS AND DISCUSSION

4.1 Mechanical properties

The mechanical properties test results are shown in Figure 3. Each data point represents three specimens. In order to minimize scatter in the results due to variation of the air content between batches the directly measured results have been adjusted so as to correspond to an air content of 5 %, by changing the compressive strength by 5 %, and the modulus of elasticity by 2 % per percent-point change of the air content [9].

The modulus of elasticity is seen to increase somewhat with deceasing values of W/B. However, as should be expected, the amount and the type of aggregate play the major role for the magnitude of the modulus of elasticity. This is reflected in the results which show that the modulus with sea gravel aggregate is significantly higher than that with crushed granite, the aggregate volume fraction of sea gravel being higher due to the rounded particle shape as mentioned previously.

The compressive strength, the flexural strength and the tensile splitting strength all increase significantly when W/B is decreased, as expected. At higher W/B (and lower strength level) crushed granite aggregate leads to a higher strength than sea gravel, whereas the opposite is seen to be the case at lower W/B (and higher strength level). This is assumed to originate in the properties of the interfacial zone between the hardened paste and the aggregate particle surface. At high W/B the paste phase is more porous and the undulations of the rough granite surface acts as shear keys resisting propagation of cracks along the aggregate surface, much more so than is the case for the smoother sea gravel particles. At low W/B, however, the interfacial zone is much denser, and the presence of microsilica gets a more pronounced effect in refining the microstructure [10] and securing a strong connection between the paste and the surface of the smooth sea gravel particles which inherently are stronger than the crushed granite particles. The latter is based on the observation that significantly more crushed granite particles were torn apart during the tests than sea gravel particles.

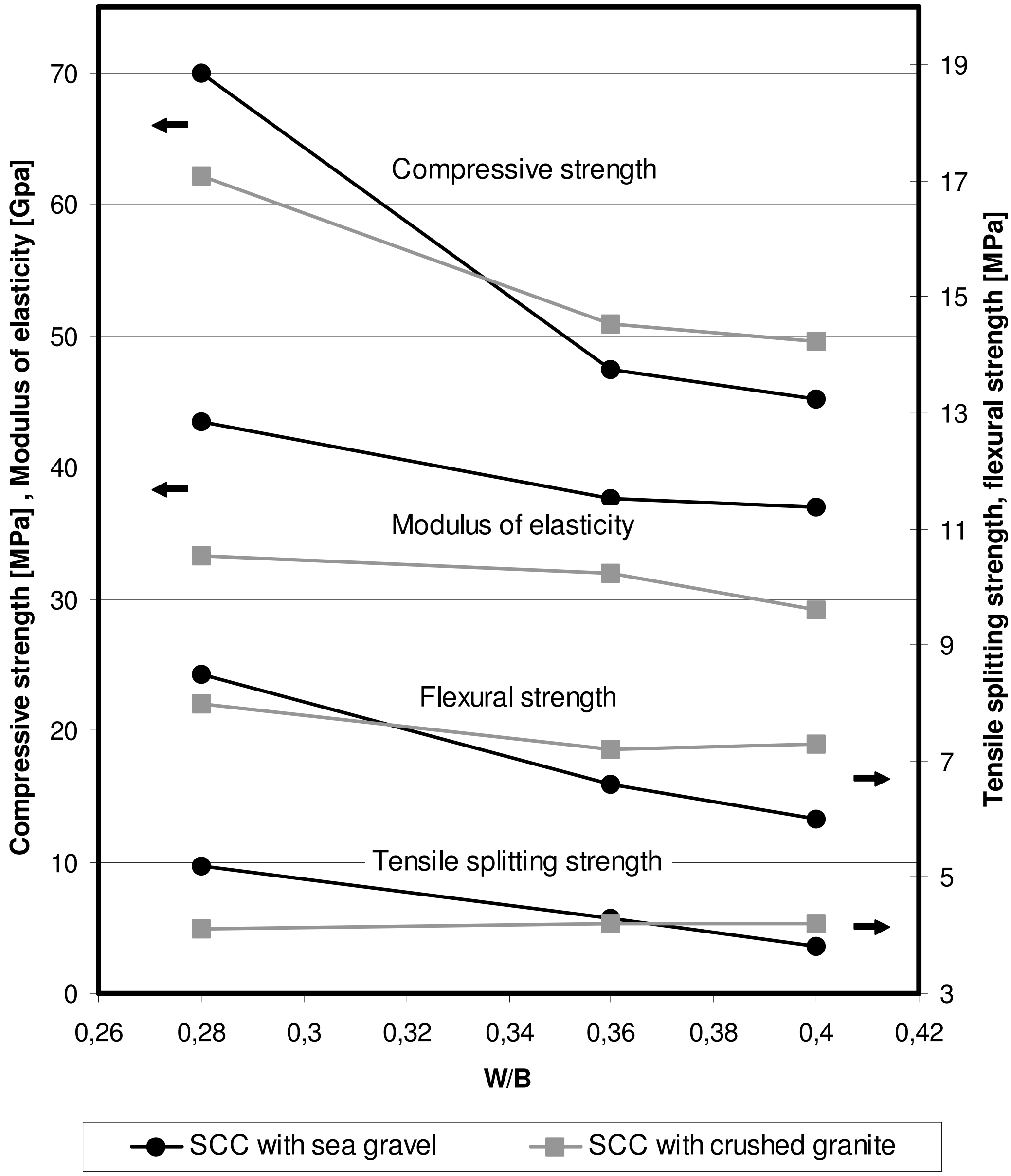

Figure 3 - Mechanical properties. Arrows indicate the axis to be used.

4.2 Freeze-thaw scaling resistance

Figure 4 shows the amount of surface scaling as a function of the number of freeze-thaw cycles. Each data point represents six specimens.

To meet the freeze-thaw scaling resistance requirement of the standard [1] for the aggressive and extra aggressive environment classes the scaling after 56 cycles must not exceed 0.5 kg/m^2 and it must not be greater than twice the 28 cycle value. The latter condition is met by all of the concrete mixes, but mixes AS and ES both exceed the maximum scaling amount after 56 cycles, while all of the concrete mixes with crushed granite meet both conditions.

The air content measured in the fresh SCC's varies between 4.0 and 6.5 % (cf. Table 1). Within that range it is well established [11] that higher air content will lead to lower freeze-thaw scaling. However, the air content difference alone is not able to explain the large differences in scaling between the various types of concrete in Figure 4. For example, Mix AS with sea gravel has an air content of 4.0 %, and Mix AG with granite has an only slightly higher air content of 4.4 %, but the extent of scaling of AS is more than twice that of AG despite the fact that the two mixes have equal W/Bs.

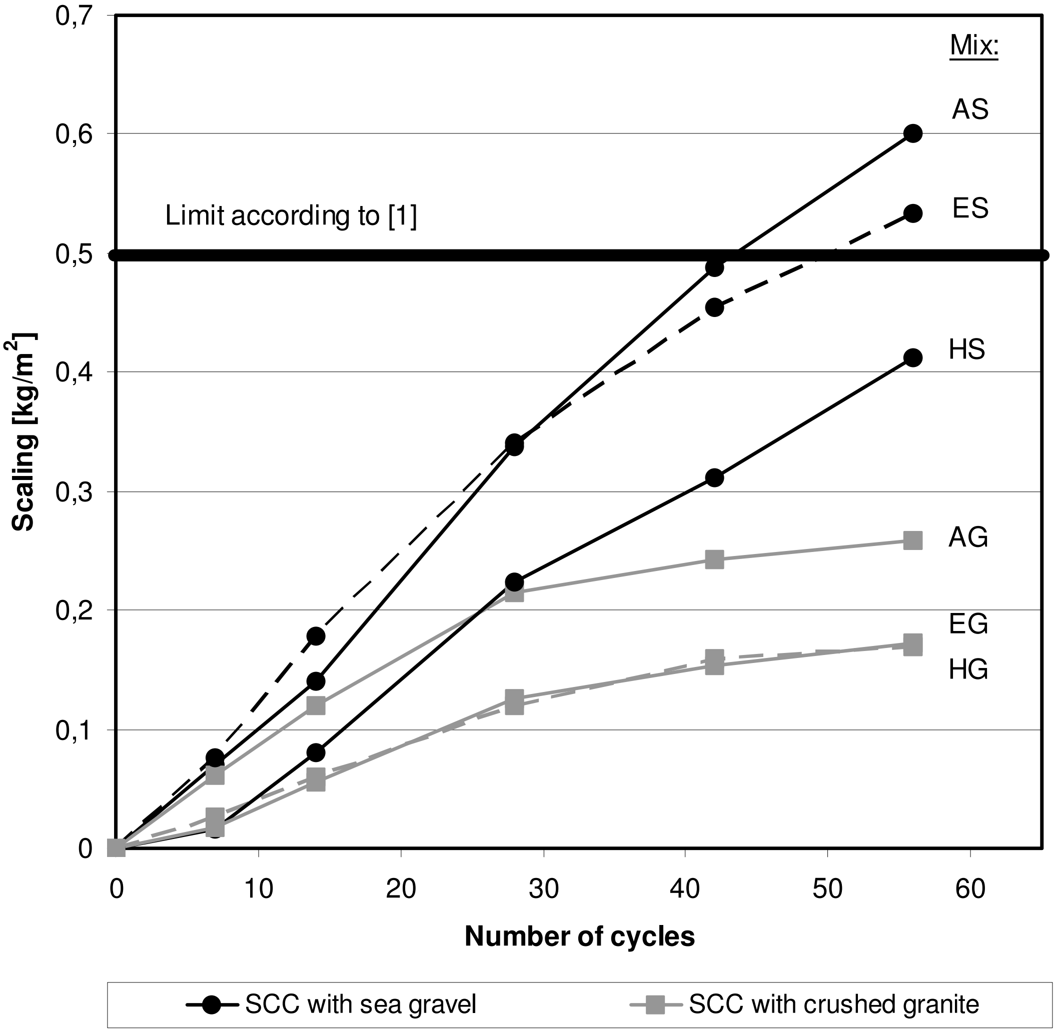

Figure 4 - Cumulative amount of scaled material as a function of the number of freeze-thaw cycles.

Inspection of the scaled-off material from the specimens with crushed granite showed that it consisted almost solely of hardened cement paste. However, from the sea gravel concretes a large quantity of ruptured stone material was observed in addition to the cement paste. This was particularly pronounced for two (out of six) test specimens from series ES which exhibited an amount of scaling about twice that of the other four specimens, the excess scaling having clearly been caused by pop-outs from coarse aggregate particles in the surface. A closer inspection revealed that the ruptured stone particles were slightly magnetic, and it was subsequently determined that the stones were porphyry and iron-bearing sandstone. Examples of such scaled-off stone fragments are shown in Figure 5.

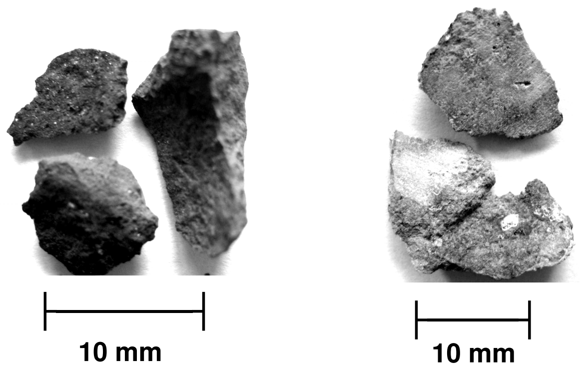

Figure 5 - Stone fragments from the scaled-off material.

Originally it was expected that porous flint particles would contribute significantly to the scaling of SCC with sea gravel, but no ruptured stones of porous flint have been observed in any of the tests carried out. Porous flint may however affect the freeze-thaw resistance indirectly, because the absorption is high, and water may be squeezed out during freezing and thereby deteriorate the surrounding cement paste [12]. On the other hand, no pop-outs from porous flint particles have been observed in the experiments.

The results of testing the freeze-thaw resistance of the aggregate material itself are shown in Figure 6.

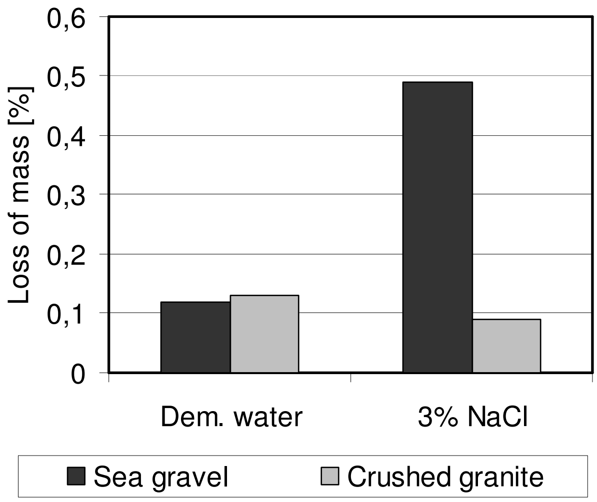

Figure 6 - Freeze-thaw test on coarse aggregate

It is seen that the sea gravel and the crushed granite underwent approximately equal and low mass losses in demineralised water, whereas in NaCl solution the sea gravel had a mass loss that was about four times greater. Inspection of the scaled material showed that porphyry and iron-bearing sandstone were the main contributors to the mass loss during freezing in NaCl solution. The reason for this is believed to be a combination of expansion caused by corrosion of the iron in the stones and a decomposition of bonds in the stones caused by the presence of chlorides.

Normally there is a connection between density of a coarse aggregate and its freeze-thaw resistance properties, e.g. higher density will lead to better freeze-thaw resistance. The porphyry and iron-bearing sandstone have densities above 2500 kg/m^3 which normally would be considered high. Contrary to expectation it is therefore not the light particles that are ruptured. This is the case both when testing concrete and when testing the coarse aggregate itself.

5. CONCLUSIONS

At equal flow properties SCC with sea gravel had an aggregate content of 67 % by volume as compared to 64 % with crushed granite. This contributed to the modulus of elasticity of the concretes being systematically 20-30 % higher with the higher content of sea gravel aggregate.

Tensile splitting strength, flexural strength, and compressive strength all showed the same pattern: At the highest W/B (0.40) the SCC with sea gravel exhibited significantly lower values than the SCC with crushed granite, whereas the opposite was the case at the lowest W/B (0.28). This is believed to be due to the characteristics of the interfacial zone between the hardened paste and the aggregate particle surfaces: At high W/B the paste phase is more porous and the undulations of the rough granite surface acts as shear keys resisting propagation of cracks along the aggregate surface, much more so than is the case for the smoother sea gravel particles. At low W/B, however, the interfacial zone is denser and has a finer microstructure which is able to provide a strong connection to the surface of the smooth sea gravel particles which in turn are stronger and than the crushed granite particles.

The resistance against freeze-thaw scaling in the presence of deicing agents was best with crushed granite coarse aggregate. It was found that porphyry and iron-bearing sandstone particles in the sea gravel caused pop-outs in the surface and were prone to disintegrate during freezing and thawing. This occurred to such an extent that the sea gravel concretes for aggressive and extra aggressive environments failed to meet the requirements of the standard. Porous flint present in the sea gravel, however, which was initially suspected to be problematic, did not seem to adversely affect the freeze-thaw scaling resistance of the concrete.

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REFERENCES

1. DS 2426:2004, “Concrete – Materials – Rules for application of EN 206-1 in Denmark”, Danish Standards, 2004, 1. edition
2. Neville, A.M., “Properties of Concrete”, Longman Group Limited, England, 1995, 4. edition
3. Kristensen, L.F., Skúlason, M., “Søsten versus knust granit i selvkompakterende betoner i aggressive miljøer”, Master Thesis, Aalborg University, 2006
4. DS/EN 12390-3:2001, ”Testing hardened concrete - Part 3: Compressive strength of test specimens”, Danish Standards, 2001, 1. edition
5. DS/EN 12390-5:2002, ”Testing hardened concrete - Part 5: Flexural strength of test specimens”, Danish Standards, 2002, 2. edition
6. DS/EN 12390-6:2002, ”Testing hardened concrete - Part 6: Tensile splitting strength of test specimens”, Danish Standards, 2002, 2. edition
7. prCEN/TS 12390-9:2005, ”Testing hardened concrete - Part 9: Freeze-thaw resistance - Scaling”, Danish Standards, 2005
8. DS/EN 1367-1,2001, “Tests for thermal and weathering properties of aggregates – Part 1:Determination of resistance to freeze-thaw”, Danish Standards, 2001
9. Herholdt, A. D., Justesen, C. F. P., Nepper-Christensen, P., Nielsen, A.: “Beton-Bogen” (The concrete book), 2. ed., 1985. Aalborg Portland CtO, Aalborg, Denmark
10. Penttala, V., Komonen, J., “Effect of aggregates and microfillers on the flexural properties of concrete”, *Magazine of Concrete Research*, No. 179, p. 81-97, 1997
11. Pinto, Roberto C. A., Hover, C. Kenneth, “Frost and scaling resistance of High-Strength Concrete”, Portland Cement Association, Bulletin RD122, 2001
12. Pigeon, M., Pleau, R., “Durability of concrete in cold climates”, E & FN SPON, 1995