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A survey study on durability of high-performance concrete

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Abstract

The new developments in the field of high-performance concrete represent a giant step toward making concrete a high-tech material with enhanced characteristics and durability. Concrete can be damaged by many processes, such as the freezing of trapped water. The most severe damaging factor to concrete in raining position today is the freeze-thaw scaling. Concrete, intended for outdoor structures must in general not exceed the $1\ kg/m^2$ scaling limit in a frost resistance test carried out in accord with the Swedish standard SS 137244 on frost resistance. In this research, the mixes were mostly designed as a conventional vibrated concrete although one series was designed as self-compacting concrete. The results showed the w/b ratio one needs to achieve for a durable mix design varies with different types of aggregates.

Keywords: Durability of Concrete, Freeze-Thaw Resistance, Chloride Penetration, Rheology, Compressive Strength

Introduction

Concrete is a composite construction material composed primarily of aggregate, cement and water. There are many formulations that have varied properties. The aggregate is generally coarse gravel or crushed rocks such as limestone, or granite, along with a fine aggregate such as sand. The cement, commonly Portland cement, and other cementitious materials such as fly ash and slag cement, serve as a binder for the aggregate. Concrete can be damaged by many processes, such as the freezing of trapped water. The most severe damaging factor to concrete in raining position today is the freeze-thaw scaling. The recent developments in the field of high-performance concrete (HPC) represent a giant step toward making concrete a high-tech material with enhanced characteristics and durability. These developments have even led to it being a more ecological material in the sense that the components—admixtures, aggregates, and water—are used to their full potential to produce a material with a longer life cycle. Be that as it may, we know that concrete will never be an eternal material when measured against a geological time frame. Any concrete, if we look far enough into the future, will end its life cycle as limestone, clay, and silica sand, which are the most stable mineral forms of calcium, silica, iron, and aluminum in the earth's environment. Therefore, all we can do as engineers or scientists is to extend the life cycle of this artificial rock as much as possible. When evaluating the durability of a concrete mix with regard to freezing and thawing a lot of fundamental variables should be considered, for instance type of aggregates, w/b ratio, minimum cement or binder content and so on. The concept of repeated cycles of freezing and thawing represents a severe environmental condition that may cause scaling and or deterioration of the concrete. With the use of de-icing chemicals this problem becomes more severe (Sabir, 1997; Pigeon et al., 1996).

When water freezes, it expands about 9%. As the water in moist concrete freezes, it produces pressure in the pores of the concrete. If the pressure developed exceeds the tensile strength of the concrete, the cavity will dilate and rupture. The accumulative effect of successive freeze-thaw cycles and disruption of paste and aggregate can eventually cause expansion and cracking, scaling, and crumbling of the concrete.

The concrete that was known as high-strength concrete in the late 1970s is now referred to as HPC because it has been found to be much more than just stronger: it displays enhanced performances in such areas as durability and abrasion resistance. Although widely used, the expression "HPC" is very often criticized as being too vague, even as having no meaning at all. Since there is no single best definition for the material known as HPC, it is preferable to define it as a low water/binder concrete which receives an adequate water curing.

Deicing chemicals for pavements include sodium chloride, calcium chloride, magnesium chloride, and potassium chloride. These chemicals reduce the freezing point of the precipitation as it falls on pavements. A recent trend has seen a wide variety of blends of these materials to improve performance while reducing costs, and best practice indicates that a liberal dosage greater than 4% in solution tends to decrease the potential for scaling of pavement surfaces. The high concentration of deicers reduces the number of freezing and thawing cycle exposures to the pavement by significantly lowering the freezing point.

For concrete to suffer damage or for reinforcement to corrode, three conditions are vital. First, a concrete mix of a high w/c ratio and poor curing leads to high capillary porosity. Comparable effects may even be encountered for concrete with low w/c ratio in case of poor curing or insufficient compaction which leads to micro voids. Loading in service, repeated heating and cooling cycles or alternative wetting and drying, may lead to micro cracks. All these mishaps may lead to unwanted porosity in the concrete. Secondly, an exposure to an aggressive environment such as sulphate attack, corrosion promoted by chlorides or carbonation as well as alkali silica reaction, all depending on the surroundings of the concrete. Third, the presence of water. These factors have all to be present in one form or other for the concrete structure to be damaged (Hale et al., 2009; Aitcin, 2003)

HPC can be made with cement alone or any combination of cement and mineral components, such as, blast furnace slag, fly ash, silica fume, metakaolin, rice husk ash, and fillers, such as limestone powder. Ternary systems are increasingly used to take advantage of the synergy of some mineral components to improve concrete properties in the fresh and hardened states, and to make high performance concrete more economical and ecological (Gjorv, 2009)

The w/b ratio can be controlled indirectly by the water content of a concrete mix, and can be reduced by increasing the binder content or by decreasing the water content. Water in excess of the amount necessary for hydration of the paste leaves capillary cavities within the hardened paste. Therefore it is highly desirable to limit the use of water in fresh concrete to the minimum needed, thus increasing the compressive strength and decreasing drying shrinkage (Cordon, 1996; Arnfelt, 1946)

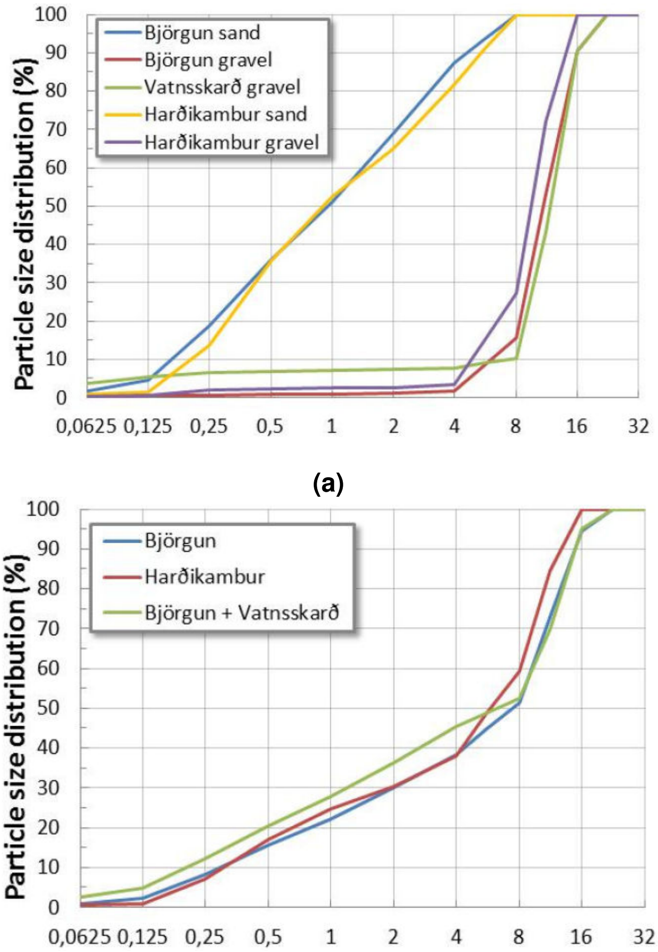
Material and method

Three materials are essential to design a concrete mix; aggregates, cement and water. One could say that it is as simple as this, and it is true that one can make a concrete mix with these ingredients, but the quality of the final product may be far from being the durable concrete construction member one is looking for. There are a couple of points that one has to bear in mind when designing high strength (HSC) or high performance concrete (HPC). First, one needs to lower the water/cement ratio at least down to 0,32; by doing so one reduces the capillary porosity. That may be achieved by introducing a good quality superplasticizer, and/or by use of supplementary cementitious materials either by addition or on a replacement basis. Silica fume is a supplementary material which plays a big role in making the concrete mix not only stronger but also more durable. What the silica fume particles do is to act as ball bearings between the cement particles and also attack the calcium hydroxide to form a secondary calcium silicate hydrate gel which improves the interface transition zone, which is the weak zone between the cement paste and the aggregates (Verbeck, and Klieger, 1957) Another essential point is the coarse aggregate. The coarse aggregate can become the weakest link in concrete when the strength of the hydrated cement paste is drastically increased by lowering the water/cement ratio. In such cases concrete failure can start to develop within the coarse aggregate. Furthermore it is not always practical to decrease the water/cement ratio below a certain level from a mechanical point of view, because the strength of the HPC will not significantly exceed the compressive strength of the aggregate. But although the compressive strength is not increased by decreasing the water/cement ratio, the durability and the compactness of the HPC is improved (Petersson,1984)

Data for this research was acquired from Danish rapid hardening Portland cement type CEM I 52.5 N. In the following we describe this project in details. In this project, two deliveries of 1500 kg big bags were delivered to

The Innovation Center Iceland. The first big bag was delivered in the beginning of 2009 and the second one in the beginning of 2010. Silica fume consists of micro-spheres which are able to fill the voids between the cement particles as the average size of these micro-spheres is smaller than 0.1. It is not recommended to use a high dosage of silica fume (>10% of binder) because of the resulting increase in water requirement of the concrete mix as well as the increase of brittleness. This increase in brittleness is not relevant for low grade concretes (25 MPa) but with increased strength the brittleness increases (Fagerlund, 1994). In this project, however, a dosage of 6% and 12% silica fume (on binder basis) were used to see the effect of a normal dosage andthat of an over dosage. In all of the mix designs, the use of a superplasticizerwas essential to compensate for the excessive water requirement caused by the high specific surface area of the silica fume (Fagerlund, 1994).

It is essential that the quality of the aggregate is good to achieve a high performance and durable concrete. Unfortunately Icelandic aggregates are very porous and therefore it was decided to use three types of aggregates ranging in saturated surface dry water content from as high as 6,3% down to 1,4%. The Porosity of the aggregates affects their water absorption and thereby the workability of the fresh concretes mix, as well as the properties of the hardened concrete, such as frost resistance and strength (Fagerlund, 1977). With regards to the particle size distribution when high performance or high strength concrete is designed, it is preferred that the sand ranging from sieve size 0,5 - 4 mm be as little as possible or have the distribution around 35 - 40% on sieve size 4, without the possibility of segregation (Collins, 1944).



(b)

Figure 1. Particle size distribution of each of the aggregates (a), as well as their combined particle size distribution (b).

The freeze-thaw measurements were done according to the CEN/TR 15177 [13-14] standard, which is based on the Swedish standard SS 137244. For freeze-thaw resistance testing, two slices from each of the 150 mm cube specimens were sawn perpendicular to the top surface of the cube and three specimens out of these four were subjected to freeze-thaw attack in presence of a 3 mm deep layer of 3% sodium chloride (NaCl) solution. At (24 ± 2) hours after casting the specimen were removed from the moulds and placed in a bath of tap water having the temperature of (20 ± 2)℃ until the specimen were 7 days old. Then they were removed from the water bath and placed in a climate chamber of (20 ± 2)℃ and a relative humidity of (65 ± 5)% where they were stored until the freeze-thaw test started. This phase of drying is crucial, therefore the climate must be controlled to a high precision, as it has a big influence on the test results.

If the samples are not dried, or if the samples are exposed to severe drying, the salt scaling seems to be enhanced; therefore, a moderate drying is used, which might represent real conditions in a reasonably good manner. Specimens that are not dried contain water in interfaces and in other defects, and this water might cause trouble during the freeze-thaw test. By applying mild drying this water is got rid of and not regained when dried specimen is put in water again. (Powers, 1945; Powers, and Helmuth, 1953 Fagerlund, 2004; Petersson,1976)

Twenty-one days after the specimens were cast; two 50 mm thick slices were sawn from each cube, a total of 4 slices. The cube was sawn perpendicular to the top surface and the saw cut in the middle is the cut that is subjected to testing. Directly after sawing, the specimens were washed in tap water and excess water wiped of the surface subjected to testing. The test specimens were then returned to the climate chamber.Twenty-five days after casting each test specimen was placed in a plastic box, after sealing all the sides and the bottom of the specimen with silicon putty, leaving the test surface free to be tested against freeze-thaw attack. Again as soon as the specimens were ready they are placed in the climate chamber.

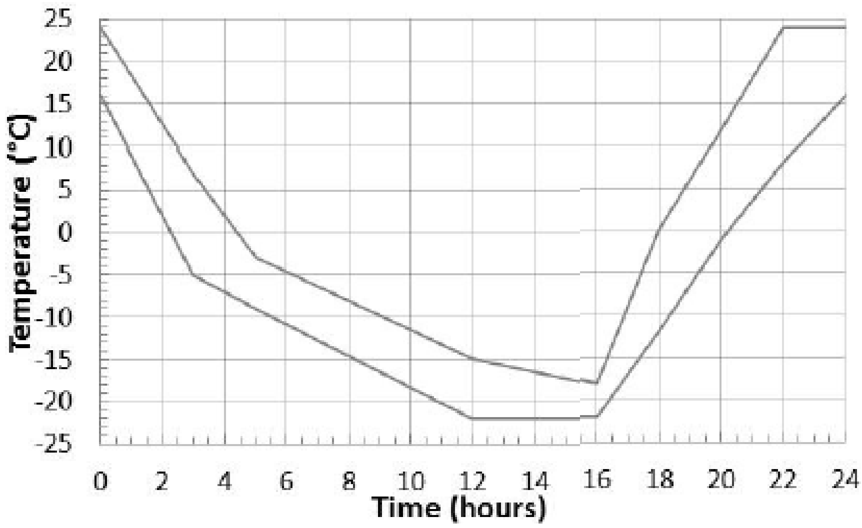


Figure 2. Allowed temperature fluctuation at the center of the test specimen through one cycle, temperature in ℃ as a function of time in hours.

Table 1. Mix designs on phase I with aggregate

No.	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)			(%) of binder
CVC mix designs							
SM01	407	0	407	162	0,409	0,409	0,0
SM02	417	0	417	149	0,389	0,389	0,0
SM03	382	24	406	162	0,408	0,434	5,9
SM04	357	49	406	161	0,406	0,462	12,1
SM05	391	25	416	148	0,368	0,392	6,0
SM06	367	50	417	149	0,367	0,417	12,0
SM07	440	28	468	149	0,334	0,355	6,0
SM08	407	56	463	148	0,333	0,379	12,1
SM12	544	0	544	159	0,297	0,297	0,0
SM13	513	33	546	163	0,306	0,324	6,0
SM14	471	64	535	159	0,307	0,349	12,0
"Semi SCC" mix designs							
SM09	553	0	553	151	0,300	0,300	0,0
SM10	509	33	542	149	0,292	0,311	6,1
SM11	476	65	541	149	0,290	0,330	12,0
SM15	456	0	456	147	0,344	0,344	0,0
SM16	431	28	459	142	0,339	0,361	6,1
SM17	404	55	459	142	0,332	0,378	12,0
SM18	412	0	412	143	0,388	0,388	0,0
SM19	412	0	412	164	0,419	0,419	0,0
SM20	391	25	416	166	0,420	0,446	6,0
SM21	361	49	410	163	0,417	0,473	12,0
SM22	426	0	426	152	0,385	0,385	0,0
SM23	400	26	426	152	0,383	0,408	6,1
SM24	373	51	424	151	0,380	0,432	12,0

Twenty-eight days after casting the specimen, the freeze-thaw test started with re-saturation of the specimen. A 3 mm deep layer of de-ionized water was poured onto the test surface of each specimen and left for (72 ± 2) hours at a temperature of (20 ± 2)℃. Not earlier than 15 minutes before the specimen was placed in the freezing chamber, the de-ionized water was removed and a 3 mm thick layer of a freezing medium, in this case a water solution of sodium chloride (NaCl) was placed onto the test surface. The specimens were then placed in a thermally insulated box and the top is covered with a polyethylene sheet to prevent evaporation.

Then the specimens were placed in the freezing chamber and the freeze-thaw cycles started. The temperature of the freezing chamber was controlled so that the temperature of the freezing medium at the centre of the test surface fell between the two lines in Figure 2. The air temperature in the freezer was never to fall below -27℃.

Table 2. Measurement results on samples in fresh and hardened state from the above mix designs

No.	(mm)	(mm)	(Pa)	(Pa s)	(MPa)	(kg/m^3)	(kg/m^2)	
CVC mix designs								
SM01	180		113	130	73,5	2490	2,34	1,4
SM02	190		214	196	78,0	2506	1,39	1,2
SM03	180		173	127	74,7	2476	20,65	7,4
SM04	200		144	119	71,6	2472	5,35	3,5
SM05	180		267	174	83,0	2497	5,43	4,2
SM06	180		249	166	86,0	2497	2,57	2,9
SM07	200		550	220	89,8	2504	0,57	1,8
SM08	245	580	123	97	89,3	2496	0,96	2,0
SM12	210		663	183	82,1	2509	0,19	1,4
SM13	60		1113	119	82,3	2510	0,20	2,0
SM14	220	360	171	85	83,3	2455	0,55	2,3
"Semi SCC" mix designs								
SM09	255	680	189	192	84,2	2519	0,30	1,6
SM10	265	695	136	143	92,0	2525	0,39	1,9
SM11	265	660	52	108	91,9	2501	0,51	2,2
SM15	270	565	59	92	73,3	2496	1,96	1,7
SM16	270	570	109	122	73,9	2450	0,96	2,0
SM17	270	480	93	92	79,3	2479	2,06	2,4
SM18	270	600	74	118	63,4	2505	1,31	1,4
SM19	270	560	60	89	60,9	2480	8,74	2,1
SM20	270	575	64	72	71,4	2504	8,91	3,1
SM21	270	570	60	72	70,6	2460	11,52	4,6
SM22	270	625	87	127	67,4	2502	2,39	1,6
SM23	270	590	98	99	74,5	2486	6,22	3,0
SM24	270	620	55	77	76,4	2469	5,98	3,5

The freeze-thaw curve should resemble the natural temperature variations in situ. Accordingly the cycle duration should be 24 hours, since this resembles the daily temperature cycle in situ. The minimum temperature is -20℃. This can be assumed to be representative for most parts of Europe. Other temperature cycles may suit better in some regions. Furthermore the rate of cooling is of interest and should resemble the actual conditions as closely as possible. The cooling rate should be about 1,5- 3℃/h, which is the maximum cooling rate found in most parts of the northern and central Europe. By applying 56 cycles of freeze-thaw resistance one simulates the winter season in many parts of the northern and central Europe because during those 56 cycles the total time under zero degrees is about one month (Fagerlund, 1995)

After 7, 14, 28, 42 and 56 cycles, the following procedure was followed for each specimen during the thawed phase of the solution.

- The excess freezing medium was poured off and the scaled material washed away and collected from the test surface with tap water.
- A fresh freezing medium was applied to the test surface.

The test specimen was returned to the freezing chamber at the point of cycle phase time (0 –30) min.

Since the design called for water content around 160 kg/m3, SM18 was used for results. Table 1 and Table 2 display the layout of the mix designs and measurements results.

In phase I, the only emphasis was on freeze-thaw resistance. Later, when these mixes were finished it was decided to include chloride penetration as an additional durability factor in this project.Accordingly, this series was redone under phase II and chloride penetration test conducted.

In Iceland the recommended limits for scaling after 56 freeze-thaw cycles test is set to be less than 1kg/m2. A secondary recommendation is that the ratio between scaling after 56 freeze-thaw cycles and 28 freeze-thaw cycles should not exceed 2.

Result and discussion

A total of 38 mix designs were produced with aggregates, and in two phases, phase I and phase II.In phase I, 24 mix designs were carried out in two stages; mixes designed as conventional vibrated concrete (CVC) and mixes designed as semi self compacting concrete ("Semi SCC").In regard to the CVC mix designs, 11 mix designs were cast where the slump was to be in the range (200 ± 20) mm, although two of these (SM08 and SM13) did not satisfy this condition, SM08 having a slump of 245 mm and SM13 having a slump of 60 mm. Nonetheless they were tested and regarded as CVC mixes. The mix designs ranged from w/b ratio 0,41 down to 0,30 in four steps and the silica fume content was 0% (a blank mix), 6% and 12% of binder. Table 1 and table 2 display the layout of the mix designs and the measurement results.

In regard to the "Semi SCC" mix designs, 13 mix designs were cast where the slump was intended to be (270 ± 20) mm. All these mixes passed the required conditions. The mix designs ranged from w/b ratio from 0,42 down to 0,29 in four steps with silica fume dosages of 0% (a blank mix) 6% and 12% of binder. One mix design was reproduced (SM18), a mix designed for w/b ratio of 0,39 and no silica fume. The reproduction (SM22) had w/b ratio of 0,385 and water content of 164 kg/m3 and the cement content was 426 kg/m3, while the original had a water content of 160 kg/m3 and cement content 412 kg/m3.

Figure 3 concerns samples with no silica fume and displays the scaling as a function of the number of freeze-thaw cycles and different w/b ratios. The left part of the figure refers to CVC and the right one to SCC. The figure shows clearly that a frost resistant mix design can be achieved by lowering the w/b ratio to 0,30, irrespective of concrete type. The other mixes (with w/b ratio 0,34 or higher) do not pass the 1kg/m2 limit.

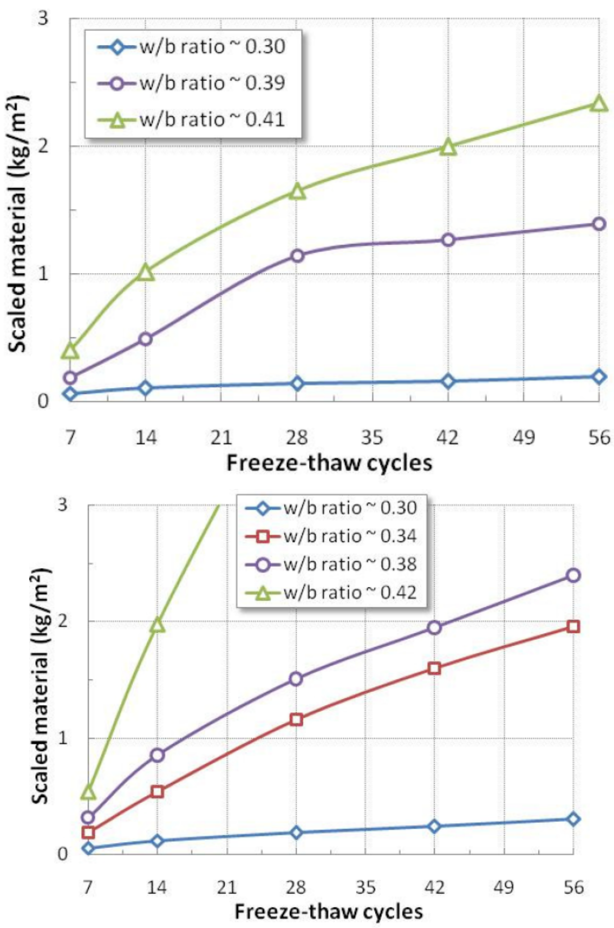


Figure 3: Scaling as a function of freeze-thaw cycles for different w/b ratios and no addition of silica fume, CVC and SCC

Conclusion

The new developments in the field of high-performance concrete represent a giant step toward making concrete a high-tech material with enhanced characteristics and durability. Concrete can be damaged by many processes, such as the freezing of trapped water. The most severe damaging factor to concrete in raining position today is the freeze-thaw scaling. Concrete, intended for outdoor structures must in general not exceed the $1\ kg/m^2$ scaling limit in a frost resistance test carried out in accord with the Swedish standard SS 137244 on frost resistance. In this research, the mixes were mostly designed as a conventional vibrated concrete although one series was designed as self-compacting concrete. Samples from 75 mix designs were tested with emphasis on frost resistance, chloride penetration,rheological properties and compressive strength. Moreover, some additional measurements such asslump, slump flow, air content and density were carried out. The variables were the silica fume contentin two steps 6% (normal dosage) and 12% (overdosage) of binder as well as a no silica fume addition(blank), different aggregates ranging from a very porous (6,3% saturate surface dry water content) toless porous (in the range 1,5-2,0%) and varying w/b ratio, ranging from 0,42 – 0,26. The water contentwas kept constant at 150 ± 5 kg/m3, except for part of the mixes where the water content was 160 ± 10 kg/m3. In addition 5 mix designswere cast with air entrainment, in order to assess frost resistance, chloride penetration, rheologicalproperties and compressive strength. Besides these, some supporting measurements such as slump,slump flow, air content and density were carried out. Those five mixes ranged in w/b ratio from 0,54 to0,41 with a constant water content of 165 ± 5 kg/m3, they had 6% silica fume incorporated andcontained Haroikambur aggregates. The air content was intended to be in the 5-6% range.

Within the limitation of the work carried out one can draw the following conclusions:

- By lowering the w/b ratio the freeze-thaw resistance improved significantly, as expected.
- By adding silica fume on a replacement basis (6% silica fume of binder) the freeze-thawresistance improved significantly and Vatnsskaro gravel wasapplied. The same tendency was observed in case of Haroikambur aggregates.
- Generally, twelve percent silica fume addition (of binder) did not contribute significantly to thefrost resistance (beyond the effect achieved by 6% silica fume added). Possibly there is notenough water in the system to activate the additional 6% silica fume. One exception wasencountered; a case of Haroikambur aggregates, but the outcome is partly based onassumptions.
- The w/b ratio for mix designs not containing any silica fume at which scaling does not exceedthe recommended maximum of 1 kg/m2, is in the range of 0,30 to 0,36 depending on the type ofaggregate. To be on the safe side it is recommended to apply a w/b ratio of 0,30 or lower whenno silica fume is present in the mix. Such a mix will, on the other hand, be very stiff and viscous.
- The w/b ratio for mix designs containing 6% silica fume of binder, at which the scaling does notexceed the recommended maximum of 1 kg/m2 is in the range of 0,33 to 0,35 depending on thetype of aggregate. To be on the safe side it is recommended to apply a w/b ratio of 0,33 orlower when silica fume content of binder is 6%. Such a mix is more workable than mix withoutsilica fume.
- The w/b ratio for mix designs containing 12% silica fume of binder, at which the scaling does notexceed the recommended maximum of 1 kg/m2 is in the range of 0,31 to 0,35 depending on thetype of aggregate. To be on the safe side it is recommended to apply a w/b ratio of 0,31 orlower when silica fume content of binder is 12%. At this silica fume content a substantialincrease in the workability of the mix is achieved, in comparison to mix designs not containingany silica fume.
- Adding silica fume on a replacement basis (6% silica fume of binder) improves significantly the chloride penetration resistance compared to mix designs not containing any silica fume. On the average the reduction in chloride penetration is in the range of 38-57% or 6,4-9,5% for each added percent of silica fume of binder, depending on what aggregate is used.
- By adding silica fume on a replacement basis (12% silica fume of binder), a significant improvement in the chloride penetration resistance was obtained. On the average the reduction in chloride penetration, attained by increasing the silica fume content from 6% to 12% of binder, was in the range of 23-34% or 3,9-5,8% for each added percent of silica fume, depending on the aggregate used. This result is in some contradiction to the freeze-thaw resistance results where it was assumed that there was not enough water in the system to activate the silica fume in full.

If further work should be carried out in this field, then here are some suggestions for extensions.

First, and of main interest is to reveal the effect of changing to an aggregate with lower water absorption (saturated surface dry) than those used here. Norwegian aggregates might be proposed; these have saturated surface dry water content of about 0,3%, which is significantly lower than encountered for most Icelandic aggregates.

Secondly, the tendency of mix designs containing no air entrainment to escalate in scaling throughout the 56 freeze-thaw cycles should be looked at. Compared to mix designs containing air entrainment or in some cases mix designs with no air entrainment as well as with no silica fume present, these mix designs seem to escalate in scaling for the first 14 or 28 freeze-thaw cycles but subside after that. This is a concern that should be looked at and studied further, along with measurements on inner structural damage.

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