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Freeze/Thaw Durability of Concrete with Fly Ash

Master of Science Thesis in the Master's Programme Structural engineering and Building Performance Design

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Department of Civil and Environmental Engineering
Division of Building Technology
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CHALMERS UNIVERSITY OF TECHNOLOGY
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Examensarbete / Institutionen för bygg- och miljöteknik,
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ABSTRACT

Fly ash, which is a by-product from combustion of pulverized coal, can partly replace the cement in concrete. In AMA Anläggning 07 (2008), which is a guideline for construction of civil engineering structures in Sweden, the content is limited to 6% of the cement content in exposure class XF4 and 11% in the other exposure classes. The performance of concrete with fly ash is in many situations improved compared to Portland cement concretes, but there are fears regarding freeze/thaw durability. The project aims at investigate the properties of concrete with fly ash, with special focus on freeze/thaw durability. The work has mainly been done as a laboratory study. Concretes with different amounts of fly ash (0%, 6% and 20% of cement weight) and different efficiency factors ($k=0.4$ and $k=1.0$) has been investigated. Furthermore, the effects of different curing periods and temperature during curing of the concrete with 20% fly ash have been studied. The fly ash was introduced separately to the concrete mixture. The tests have been limited to air entrained concretes with additions of fly ash according to the specifications in SS 13 70 03 (2008). The test performed were foam index test, slump, air content, scaling under freeze/thaw, compressive strength, rapid chloride migration and air void analysis.

The results showed that the freeze/thaw durability of properly air entrained concretes with fly ash is similar to corresponding Portland cement concretes. The air entraining agents worked effectively in the concrete with fly ash, even though the dosage was higher than for concrete without fly ash. Prolonged curing and higher temperature gave less resistant concrete (20% fly ash) regarding freeze/thaw, possibly due to increase of the hydraulic pressure. Addition of 20% fly ash, prolonged curing and higher temperature reduced the chloride migration coefficient, which is in consistence with findings in the literature. Addition of only 6% fly ash affected neither the freeze/thaw durability, nor the chloride migration.

Key words: concrete, fly ash, durability, freeze/thaw, scaling, chloride migration

Frostbeständighet hos flygaskabetong

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SAMMANFATTNING

Flygaska, som är en biprodukt från förbränning av kol, kan delvis ersätta cement i betong. I AMA Anläggning 07 (2008) är innehållet begränsat till 6 % av cementet i exponeringsklass XF4 och 11 % i övriga exponeringsklasser. Betong med flygaska har många positiva egenskaper, men det finns farhågor gällande frostbeständigheten. Projektet syftar till att undersöka egenskaper hos betong med flygaska, med speciellt fokus på frostbeständighet. Huvuddelen av arbetet har gjorts med försök i laboratorium, där betong som överensstämmer med krav enligt SS 13 70 03 (2008) har studerats. Luftinträdd betong med olika mängder flygaska (0 %, 6 % och 20 %) samt olika effektivitetsfaktorer ($k=0,4$ och $k=1,0$) har undersökts. Även undersökningar av hur förlängd härdningstid och högre temperatur vid härdning påverkar egenskaperna hos betong med 20 % flygaska har gjorts. Flygaskan introducerades separat i betongblandningen. De tester som utförts är: skumindex, sättmått, lufthalt, avflagning vid frysning, hållfasthet, kloridmigrationskoefficient och karakterisering av luftporstruktur.

Resultaten visade att frostbeständigheten hos korrekt luftinträdd betong med flygaska är liknande eller bättre, än hos den utan. Luftporbildaren fungerade effektivt i betongen med flygaska, även om mängden var högre än hos betongen utan flygaska. Förlängd härdningstemperatur och ökad temperatur påverkade frostbeständigheten negativt, möjligtvis p.g.a. ökning av det hydrauliska trycket. Betong med 20 % flygaska, längre härdningsperiod och högre härdningstemperatur minskade värdet på kloridmigrationskoefficienten, vilket är förenligt med resultat från litteraturen. Ingen skillnad mellan betongen med 6 % flygaska och den utan kunde upptäckas gällande frostbeständigheten och kloridmigrationskoefficienten.

Nyckelord: betong, flygaska, frostbeständighet, avflagning, kloridmigration

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Preface

This master thesis aims at investigating the freeze/thaw durability of concrete with fly ash. The project was made in co-operation between Thomas Concrete Group AB and Chalmers University of Technology, division of Building Technology, as part of SBUF project 12382 *Beständighetsegenskaper hos anläggningsbetong med stenkolsflygaska*.

I would like to thank my supervisors, Professor Tang Luping (Chalmers) and Dr. Anders Lindvall (TCG) for their help during this project work. Also, I would like to thank Ingemar Löfgren (TCG). Furthermore, I would like to thank for all the help I got with the laboratory work, by Stina Ericsson (TCG), Pernilla Kamperin (TCG), Andreas Karlsson (TCG) and Marek Machowski (Chalmers). For printing my thesis and finding references, I would like to thank Ingela Gustafson (Chalmers).

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Anna Knutsson

Notations

d	days of curing
D_{RCM}	chloride migration coefficient from non-steady-state migration experiments (NT BUILD 492)
k (<i>k-factor</i>)	fly ash cementing efficiency factor
M	maturity
m_n	scaled material after n cycles (SS 13 72 44)
t	time
T	temperature
$t_{x,n}$	curing period in 55 °C, tested for scaling at freezing
(w/c)	water/cement ratio
$(w/c)_{eq}$	equivalent water/cement ratio

1 Introduction

1.1 Background

Fly ash, which is a by-product from combustion of pulverized coal, can partly replace the cement in concrete. With the new concrete standard SS-EN 206-1 (2001), additions of fly ash in concrete have been allowed in Sweden. In SS 13 70 03 (2008), the content of fly ash has been limited to 25% of CEM I clinker content by weight in exposure classes XF4, XD3 and XS3. In the other exposure classes the fly ash content is limited to 50%. However, AMA Anläggning 07 (2008) limits the content to 6% of cement weight in exposure class XF4 and 11% in the other exposure classes.

The performance of concrete with additions of fly ash is in many situations improved compared to that of concrete mixed with Portland cement only. There are some situations where the performance of fly ash concretes may not be improved. One situation is when the concrete is subjected to freeze/thaw actions, where concerns have been raised regarding the durability.

In the literature there are some investigations regarding the freeze/thaw durability of concretes with additions of fly ash. The results from these investigations show generally that the freeze/thaw durability of fly ash concrete is similar or slightly worse compared Portland cement concretes. This is explained by that there are problems with the compatibility between the fly ash and the air entraining agents used to create air pores in the concrete. The fly ash contains unburned carbon, which may adsorb the air entraining agents, reducing the active agents, and in this way influence its effect negatively.

1.2 Purpose

The project aims at investigating properties of concretes containing fly ash, with special focus on the freeze/thaw durability. The results from the project are expected to improve the knowledge regarding freeze/thaw durability of concretes with additions of fly ash and air entraining agents.

1.3 Method and limitations

The work has mainly been done as a laboratory study, complemented with a literature study. In the laboratory study, concretes with different amounts of fly ash (20%, 0% and 6% of cement weight) and different efficiency factors ($k=0.4$ and $k=1.0$) have been studied with focus on the freeze/thaw durability. Furthermore, the effects of different curing conditions of the concrete with 20% fly ash have been studied. The specimens were tested after being exposed to prolonged curing duration as well as to increased temperature. In the fresh concrete air content and slump were measured. In the hardened concrete tests regarding strength, chloride migration and scaling under freeze/thaw were performed. Furthermore, a foam index test was performed to investigate the compatibility between the fly ash and air entraining agents.

The laboratory study has been limited to concretes containing air entraining agents and with additions of fly ash according to the specifications in SS 13 70 03. The air content in the fresh concrete was designed to $(4.5\pm 0.5)\%$ by volume and $(w/c)_{eq}$ was specified to 0.45.

2 Concrete with Fly Ash

Fly ash can partly replace cement in concrete. Replacing the content of cement, the production cost as well as the environmental impact, e.g. from CO₂, is reduced. Use of fly ash improves the workability, reduces the demand of water, and reduces the temperature rise in the fresh concrete. Furthermore, addition of fly ash gives higher long time strength of concrete and reduces the permeability. The fly ash can either be blended in the cement or added separately in the concrete at mixing.

Fly ash is a by-product from combustion of pulverized coal. As the coal is heated to high temperatures, it liquefies. It is thereafter cooled rapidly, which forms spherical particles. The fly ash consists mainly of silica (SiO₂), aluminium oxide (Al₂O₃), iron oxide (Fe₂O₃) and calcium oxide (CaO). Due to incomplete combustion and organic additives used in the collecting process, the fly ash also contains some unburned carbon. The carbon content of the fly ash is approximately determined by loss-on-ignition (LOI) test, which means that the fly ash is heated to high temperatures, leading to combustion of the unburned carbon. [ACI Committee 232 (1996)]

2.1 Pozzolanic activity of fly ash

Fly ash is not cementitious by itself, but will together with cement, produce cementitious compounds. However, fly ashes with higher contents of CaO can to some extent be cementitious. The primary contributor to the pozzolanic reaction in fly ash is the silica, which combines with calcium hydroxide and water to form the binder in concrete, calcium silicate hydrate (C–S–H).

At hydration, the cement reacts with water, forming durable binder. Most properties of the hardened cement paste are given when tricalcium silicates (C₃S) and dicalcium silicates (C₂S) reacts with water (H), forming C–S–H (C₃S₂H₃) and calcium hydroxide (CH). [Illston (2001)]

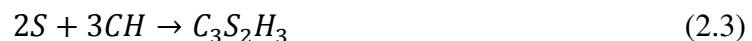
The C₃S reacts faster than the C₂S:



The reaction with C₂S makes an important contribution to the long term strength:



The silica (S) in the fly ash will in a finely divided form and in the presence of moisture, at ordinary temperatures, react chemically with calcium hydroxide from the hydration of cement, forming cementitious compounds. The reaction is secondary, but it is not possible to differentiate the C–S–H produced from pozzolanic reactions, from that from the cement hydration: [Illston (2001)]



Since this pozzolanic reaction is secondary, it will occur somewhat later than the hydration of the cement, for some ashes even up to one week after the hydration of the cement has started. First when enough cement has been hydrated to increase the pH of the pore water to at least 13.2, the glassy particles in the fly ash can be broken down. In the beginning, after the particles have been broken down, the products from the reactions are formed on and close to the fly ash particles. However, by time, further products will diffuse into the pore system. This will give finer capillary pores, thus reducing the overall porosity of the concrete. The rate of pozzolanic activity is

depending upon the fineness of the fly ash particles; finer particles give faster hydration. [Neville (2003)]

2.2 Usage of fly ash in concrete

With the new concrete standard SS-EN 206-1 (2001) it has been allowed to use additions of fly ash in concretes used in Sweden. The highest permitted amount of fly ash and $(w/c)_{eq}$ is given in SS 13 70 03 (2008), which is a Swedish adaption of EN 206-1. In SS 13 70 03 (2008), the content of fly ash has been limited to 25% of cement content in exposure classes XS3, XD3 and XF4, and 50% in the other exposure classes. AMA Anläggning 07 (2008), which is a guideline for construction of civil engineering structures, defines more restrictive amounts of fly ash. In AMA Anläggning 07 (2008), the content has been limited to 6% in exposure class XF4 (high water saturation, with de-icing agents or sea water) and 11% in the other exposure classes. The highest permitted fly ash content according SS 13 70 03 (2008) and AMA Anläggning 07 (2008) is presented in Table 2.1. A short description of the exposure classes is attached in Appendix D.

Even though the long time strength is higher for concrete with fly ash than without, the strength at earlier ages is lower. If the cement is replaced by fly ash on a one-for-one basis, strength would be lower during the first months. The strength of concrete is highly dependent on the water/cement (w/c) ratio, so one way to achieve higher strength at early ages is to decrease the water content in relation to the binder content. This means that to achieve equivalent strength at early ages, the mass of fly ash has to be larger than the cement it is replacing. Due to this a concept with fly ash cementing efficiency factor (k) has been developed. In this approach, the mass of fly ash (F) replaces kF of the cement to achieve the same 28-days strength for the concrete with fly ash as for the one without. A k -factor which equals to 1.0 means that the fly ash does replace the cement on a one-to-one basis and a k -factor less than 1.0 means that the amount fly ash is larger than the cement it is replacing. Instead of using w/c ratio or water/binder ratio, the equivalent water/cement ratio $((w/c)_{eq})$ is used, which is defined in Equation 2.4. [SS-EN 206-1 (2001)]

$$(w/c)_{eq} = \frac{W}{C+k \cdot F} \quad (2.4)$$

where

- W : water content (by mass)
- C : content of Portland cement (by mass)
- k : efficiency factor
- F : content of fly ash (by mass)

The highest permitted value of $(w/c)_{eq}$ required, according to 13 70 03 (2008), differs between the exposure classes, see Table 2.1.

The value of the k -factor in SS-EN 206-1 (2001), does not depend upon the fly ash, but only on the type of cement. The k -factor is defined to 0.2 and 0.4 for CEM I 32,5 and CEM I 42,5, respectively. But in some national application documents other, higher, factors exists.

The k -factor is in reality not only dependent upon the cement type, but also the fineness of the fly ash. Furthermore, the properties of the concrete do affect the k -

factor. Higher design strength gives lower k -factor. [Dhir (1997)] Also, lower w/c ratio gives higher k -factor [BVK (2007)].

Table 2.1 Highest permitted $(w/c)_{eq}$ and highest permitted additions of fly ash according to SS 13 70 03 (2008) and AMA Anläggning 07 (2008).

Exposure class	Highest permitted $(w/c)_{eq}$	Highest permitted amount of fly ash [%]	
		SS 13 70 03 ^a	AMA Anläggning 07 ^b
X0	-	50	11
XC1	0.90	50	11
XC2	0.60	50	11
XC3	0.55	50	11
XC4	0.55	50	11
XD1	0.45	50	11
XD2	0.45	50	11
XD3	0.40	25	11
XS1	0.45	50	11
XS2	0.45	50	11
XS3	0.40	25	11
XF1	0.60	50	11
XF2	0.45	50	11
XF3	0.55	50	11
XF4	0.45	25	6
XA1	0.50	50	11
XA2	0.45	50	11
XA3	0.40	- ^c	11

^a wt-% of CEM I clinker content

^b wt-% of cement content

^c decision of each individual case

The requirements for the chemical and physical properties for fly ash are specified in EN 450-1. In Table 2.2, requirements are presented.

Table 2.2 Requirements for the chemical and physical properties for fly ash, specified in SS-EN 450-1 (2007).

Property	Allowable values
LOI	< 5 wt%
Fineness $\geq 45 \mu\text{m}$	< 40 wt%
Chlorides (Cl)	< 0.10 wt%
Equivalent Na ₂ O	< 5.0 wt%
Particle density	Declared values $\pm 0.20 \text{ t/m}^3$
Activity index	> 75 % (28 d) > 85 % (90 d)

2.3 Strength development and maturity of concrete

The rate of strength development for concrete with fly ash is lower at the beginning than for concrete with plain Portland cement. However, as illustrated in Figure 2.1, concrete with fly ash does continue to gain strength, which means that after some weeks or months, the strength of this concrete will be higher than for the concrete containing ordinary Portland cement. The pozzolanic activity does improve the strength of the transition zone, i.e. the interface between the paste and aggregate, in the concrete by secondary effects. Furthermore, better packing of particles in the fresh state when fly ash is included will reduce the porosity, hence also leading to higher strength. [Illston (2001)]

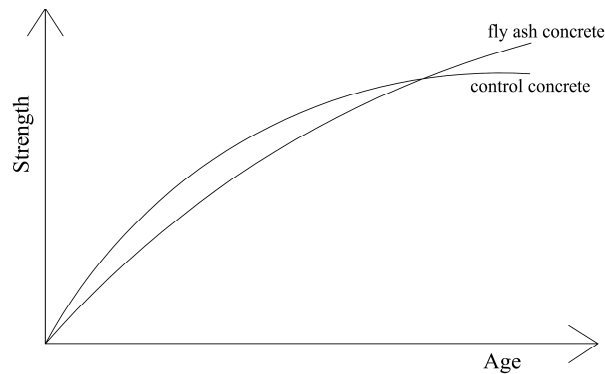


Figure 2.1 Schematic of strength development of fly ash concrete compared to concrete without fly ash

The strength development for concrete containing fly ash is, as for concrete with plain Portland cement, dependent upon the temperature. Higher temperature will increase the rate of strength development. However, the strength of the mature concrete without fly ash will be lower when cured at higher temperatures, which will not be the case for the concrete with fly ash. Furthermore, when concrete with fly ash has been exposed to heat during curing, the pozzolanic reaction continues at higher rate even though the temperature is decreased. [Malhotra (1994)]

Besides the curing regime, other variables that affect the strength development of concrete with fly ash are the chemical composition, particle size and reactivity of the fly ash. [Malhotra (1994)]

Since the strength of concrete increases with curing duration and temperature, the maturity (M) is defined as the product of curing time (t) and temperature (T):

$$M = \sum t \times (T + 10) \quad (2.5)$$

It is assumed that when the temperature falls below $-10\text{ }^{\circ}\text{C}$, the hydration reaction will stop, which does explain the addition of 10 at the temperature in the equation above. [Illston (2001)]

The results from Equation 2.5 may be some doubtful, especially for lower temperatures. The maturity function could be expressed more precise by applying the Arrhenius relation:

$$M = const \cdot \int_{t_0}^{t_i} e^{-\frac{Q}{RT}} dt \quad (2.6)$$

where:

T : temperature of the concrete at age t [K]

Q : activation energy for cement hydration [kJ/mol]

R : universal gas constant

The activation energy does depend on the type of cement used, the w/c ratio, additions and admixtures. It does range between 30 and 65 kJ/mol for cement hydration. [Burström (2001)]

2.4 Resistance of chloride ingress for concrete with fly ash

Chloride ions from de-icing salts can penetrate into concrete by transport of chlorides in water, diffusion of the ions in water and by absorption. If the chloride ions reach the reinforcement, corrosion may occur. Not all of the chlorides in the concrete do affect the corrosion of steel; some ions are chemically bound to the hydration products from the cement, whereas others are physically bound being adsorbed on the surface of the gel pores. It is only the free chloride ions that can damage the reinforcement. The penetration of chloride ions is also dependent on the permeability of the concrete; a more permeable concrete will lead to less resistance against penetration. [Neville (2003)]. Concrete with fly ash has shown better resistance against chloride penetration than concrete with ordinary Portland cement. This is partly due to that fly ash creates a denser structure, which reduces the permeation; but also due to that concrete with fly ash binds the chloride ions better, thus leaving fewer ions free. [Dhir (1999)].

An experimental study of durability of concrete regarding chloride ingress where done by Leng (2000). The resistance to chloride ions was shown to be affected by the w/c ratio and the amount of fly ash in the concrete. Higher w/c ratio gave a concrete with more pores and more paths for the chloride solution to be transported through, leading to a concrete which is less resistant against penetration of chloride ions. Diffusion coefficients were tested for concrete with 11%, 43% and 67% fly ash of the cement content. The results showed that more fly ash gave a more durable concrete.

The active alumina (Al_2O_3), which exists in larger amounts in fly ash than in Portland cement, is able to bind the chloride ions. In Dhir (1999), the binding capacity was found to be at maximum at a replacement of fly ash of 50% of the cement, but optimum at about 30%. Concrete with fly ash replacing 33% of the cement, the binding capacity was four times larger than for ordinary Portland cement. Furthermore, the binding capacity increased with the concentrations of chloride ions. Replacement of the cement by 30% fly ash was found to improve the resistance against chloride ions with two to four times.

A more mature concrete will be less permeable, thus more resistance regarding chloride ingress. Higher curing temperature will accelerate the pozzolanic reactions leading to a less porous concrete with fly ash. [Ramezaniapour (1995)] Prolonged curing will as well lead to a less permeable concrete [Neville (2003)].

2.5 Freeze/thaw durability of concrete with fly ash

The concrete will always contain some water in the pores and as this water freezes, it will expand with about 9%. If there is not enough space to accommodate this extra volume, a disruptive pressure will be created, which may lead to pressure cracking

and scaling. Due to the hydraulic and osmotic pressure, the disruption will be further increased. [Ramachandran (1995)]

When the water starts to freeze in the completely water filled pores, there is not enough space to accommodate the extra volume, thus the unfrozen water has to be transported to empty spaces. This flow of the unfrozen water through the capillary pores and gel pores of the cement paste will create a hydraulic pressure. The hydraulic pressure is affected by the distance between the pores and the fineness of the capillary pores; longer distance and finer pores increases the pressure. The disruptive pressure will be further enhanced by osmotic pressure. Concrete subjected to freezing and thawing can be damaged externally or internally. For concrete subjected to a salt solution, external damage is normally the case, which means removal of small chips or/and flakes on the surface of the concrete. Concrete subjected to pure water is more likely to be damaged by internal cracking. [Fagerlund (1994)]

The structure of the air void system is of great importance to create a freeze/thaw durable concrete. There has to be sufficient space in the concrete to accommodate the increase of volume as the water freezes to ice. Therefore, a minimum content of air has been set to about 3% of volume. Furthermore, due to the hydraulic pressure, the distance the water has to be transported, the so called spacing factor, should be around less than 0.20-0.25 mm. [Fagerlund (1994)]

2.5.1 Air entraining agents in concrete with fly ash

To achieve a freeze/thaw durable concrete, air entraining agents (AEAs) are used. The AEAs do incorporate air in the fresh concrete by stabilizing the air, thus creating a system of air bubbles in the hardened concrete that fulfils the requirements with regard to freeze/thaw resistance. That is, increasing the amount of air and decreasing the distance between the air pores. The entrained air in the concrete does not, however, affect the durability if poor, coarse aggregates, regarding freeze/thaw resistance, are used. [Ramachandran (1995)]

The AEAs are surfactants, i.e. their molecules are strongly adsorbed at air-water or solid-water interfaces. The molecules consist of a negative, hydrophilic head, and a hydrophobic tail, see Figure 2.2. The hydrophilic head becomes oriented towards the aqueous phase or adsorbed on the surface of the cement particle, whereas the hydrophobic tail becomes oriented towards the air; thus creating a stable air bubble. Since the hydrophilic heads are negatively charged, the bubbles will also be negatively charged. Repulsion forces will therefore be created between the bubbles. Another stabilizing action, is the orientation of a layer of water around the bubbles, which will separate the bubbles and stabilize and deflocculate the system. [Fagerlund (1994)]

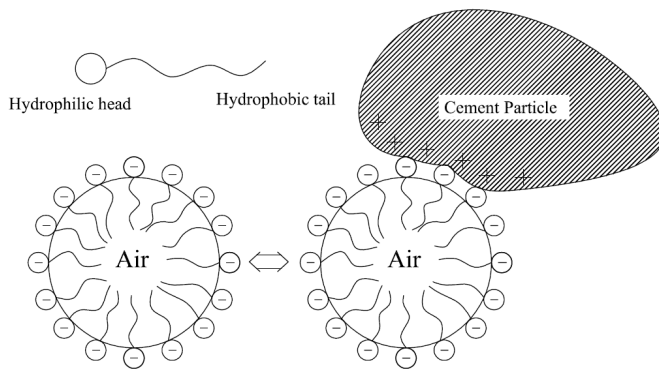


Figure 2.2 Schematic of air entrainment in the fresh concrete.

In the fresh concrete with fly ash, the AEAs are strongly adsorbed on particles in the fly ash. The unburned carbon in the fly ash seems responsible for the adsorbed surfactants. The surface of the carbon particles are non-polar, thus the hydrophobic parts of the surfactants, which also are non-polar, will be adsorbed onto the carbon surface, see Figure 2.3. Consequently, surfactants adsorbed on the carbon cannot assist to stabilize the entrained air. [Pedersen (2008)]

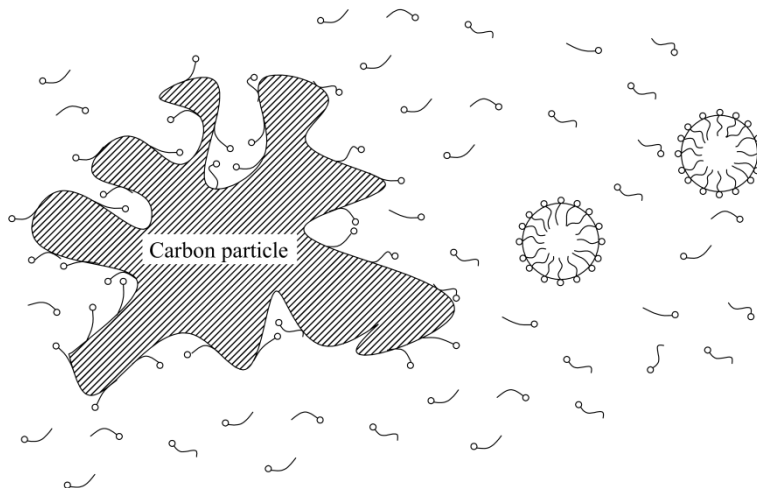


Figure 2.3 Adsorption of the air entraining agents on the carbon surface, which leaves less AEAs free to form stable air bubbles in the cement paste. (Not in scale, the carbon particles are estimated to be 10^7 times larger than the agents.)

The loss of air can be compensated, to some extent, by more AEAs. However, due to normal variations in the fly ash, too high dose of AEAs may lead to large air content and too big variations in the air structure [Pedersen (2008)]. Zhang (1996) showed that for constant air content, the dosages of AEA increased by addition of fly ash. The dosage was dependent, not only on the source of fly ash, but also on the sort of AEA used.

All of the weight loss in the LOI test is not due to loss of carbon content. About 99% of the LOI is estimated to originate from the carbon content; even though this value has been questioned to be too high. The remaining part of the loss comes from decomposition of carbonates and removal of water combined in clay minerals. Another drawback with this test is that the only parameter measured is the amount of unburned carbon. The adsorption of surfactants is also dependent on the specific surface area, the accessibility of the surface area and the chemical nature of surface of the carbon; which all is parameters not considered in the LOI test. [Pedersen (2008)]

Another method to determine the compatibility of the AEAs with the fly ash is the foam index test. This method is not standardized and is carried out in different manners, but it indicates how well the AEAs are compatible with the fly ash. Fly ash, cement and de-ionized water are mixed together in a dispenser. The cement is included in the mix to create a solution that resembles that of the actual concrete mixture. The consistency of the mix will be thinner than that of the concrete mixture, to make sure that all particles will be wet. The AEAs are added in small aliquots and the dispenser is then shaken again. This is repeated until a stable foam can be detected on the surface. The foam will become stable when the unburned carbon is saturated and the surfactants are able to form stable air bubbles. The amount of AEA needed to create the foam is taken as the foam index. Normally this value is subtracted with a blank value, i.e. the foam index for a mix without fly ash; this to eliminate variations in the value caused by the cement. In Külaots (2003), a foam index test was carried out with fly ash which had been subjected to a LOI test. The fly ash was therefore considered having 0% carbon. The foam index was then the same as for a blank sample, which is confirming the theory that it is the carbon that adsorbs the surfactants from the AEAs. [Külaots (2003)]

Results from foam index test, performed at different laboratories, can be difficult to compare. The endpoint of the test, i.e. when a stable foam has been formed, is visual determined and therefore subjective. Furthermore, it can be difficult to exactly measure the amount of AEAs added, since the size of the drops differs. The chemical nature as well as the aqueous solutions also contributes to the uncertainties in the method. The duration of the foam index test is of minutes, whereas the adsorption of the surfactants can contain in hours. This depends on the fly ash which is used. [Külaots (2003)]

2.5.2 Freeze/thaw durability of concrete with fly ash

The literature shows that the durability is similar or slightly less for air entrained concrete with fly ash as without. A summary of the freeze/thaw durability of air entrained concrete with fly ash, using results from different sources is shown in Table 2.3. As can be seen, the concrete with about 40% fly ash of cement weight, or less, is durable regarding de-icing salt scaling, whereas the concrete with higher amounts of fly ash is non-durable. Concrete with fly ash perform well when subjected to freezing and thawing, irrespectively of the amount of fly ash in the concrete, considering internal damage.

Table 2.3 Summary of the results coming from different sources regarding freeze/thaw durability of air entrained concrete with fly ash.

Reference	FA/C ^c [%]	FA/(C+FA) ^d [%]	k-factor	Surface scaling	Internal damage
Rønning (2001) ^a	25	20	-	Durable	Not tested
Fagerlund (1988) ^a	5	5	-	Durable	Not tested
	30	23	-	Durable	Not tested
Gebler (1986) ^b	33	25	1.0 and 0.67	Durable	Durable
Schießl (2001) ^b	43	30	1.0	Durable	Not tested
Müller (2007) ^a	25	20	-	Durable	Durable
	43	30	-	Durable	Durable
	54	35	-	Durable	Durable
Jepsen (2001) ^b	11	10	0.4	Durable	Durable
	73	42	0.4	Durable	Durable
Bouzoubaâ (2001)	120 ^b	55	0.64	Non-durable	Durable
	120 ^a	55	-	Non-durable	Durable
Bortz (2010) ^b	67	40	1.0	Non-durable	Not tested
Li (2009) ^b	25	20	1.0	Durable	Not tested

^a fly ash blended in the cement

^b fly ash separately added

^c Percent b.w. of fly ash of cement content

^d Percent b.w. of fly ash of total binder content

Rønning (2001) tested air entrained concrete containing blended cement with 20% fly ash considering freeze/thaw durability. The level of scaling was acceptable; however, the concrete with fly ash showed to have less resistance regarding scaling under freezing and thawing, than the control concrete without fly ash. The scaling rate, however, decreased more with time for the concrete with fly ash, which was attributed to the slower strength gain at early ages for concrete with fly ash. Both concrete with 20% fly ash and concrete without fly ash, without AEAs was non-durable regarding scaling under freezing and thawing, but the concrete with fly ash behaved worst, probably due to lower air content.

Fagerlund (1988) made an investigation of freeze/thaw durability of concrete containing blended cement with 5% fly ash. The results show that concrete containing 5% fly ash without entrained air showed bad resistance, but with entrained air the concrete was durable. He also found that concrete containing blended cement with 23% fly ash with AEAs was durable.

In a study done by Gebler (1986), the resistance against de-icing scaling for air entrained concretes with 33% fly ash of the cement content was found to be slightly less than for the control concretes without fly ash, but the resistance was still at a level of good. The *k*-factor was chosen to 1.0 or 0.67. Specimens were cured at lower temperature (4.4 °C), which influenced the resistance more negatively for concrete with fly ash than that without. This was attributed to that concrete containing fly ash is more sensitive to the temperature, which affects the strength development, than concrete without. Tests showed that the concrete with 25% fly ash was also durable regarding internal damage when exposed to freezing and thawing.

In Schießl (2001), air entrained concrete with 30% of the cement replaced with fly ash on a one-to-one basis, showed less good resistance regarding freeze/thaw on the surface than concrete without fly ash. However, the level of scaling was at an acceptable level. The resistance was further improved by prolonged curing.

Müller (2007) tested air entrained concrete with different amount of fly ash in blended cement. The different amounts of fly ash tested were 0%, 20%, 30% and 35%. All mixtures had significantly less scaling at the surface than what is acceptable. The concretes with 0%, 20% and 30% showed similar behaviour, whereas the concrete with 35% showed slightly worse.

Jepsen (2001) investigated two different air entrained concretes; one with 11% fly ash of cement weight as well as a concrete with 73% fly ash (40% of the cement was replaced with fly ash) for scaling under freeze/thaw. Both concretes mixtures also contained 6% silica fume. The concretes with only 11% fly ash performed very well. The concrete with higher volume of fly ash (73%) performed considerably worse, but still at acceptable level. The bad resistance was attributed to the large spacing factor (0.30 mm). The resistance of the concrete regarding scaling under freezing and thawing for concrete with 73% fly ash did improve when subjected to prolonged curing, whereas the resistance of the concrete with only 11% fly ash were unaffected. Both of the concretes tested, showed no signs of internal damage.

In Bouzoubaâ (2001), air entrained concretes from two different mixtures were tested; one with the fly ash separately added to the mixture and one where the fly ash was blended with the cement. The cement was by 55% replaced by fly ash in both mixtures, which means that the amount of fly ash is 120% of cement by weight. Both concretes did perform bad considering scaling under freezing and thawing, even though the air content (7.2% and 5.7%) were at acceptable level. The *w/c* ratio of the control concrete was chosen to obtain similar 28-days compressive strength, as for the concretes with fly ash. In this case, it corresponds to a *k*-factor of 0.64 for the concrete with fly ash. The control concrete, showed good durability, regarding scaling under freezing and thawing. Even though the resistance regarding de-icing scaling was shown to be bad for the concrete with fly ash, the resistance regarding internal damage was good.

Bortz (2010) studied how the source of fly ash influences the durability regarding scaling under freeze/thaw. The source of the fly ash, which affects the properties of the fly ash, had high impact on the resistance of freeze/thaw scaling. The amount of fly ash was 67% of cement content and it replaced the cement on a one-to-one basis. However, none of the tested concretes were durable.

Li (2009) tested air entrained concrete with 25% fly ash of cement content and $k=1.0$, regarding freeze/thaw durability for concrete with prolonged curing. The results showed that the resistance for concrete with fly ash was good, but the resistance of the concrete without fly ash is better.

3 Testing Program

Concretes with different amounts of fly ash (0%, 6% and 20%) and different k -factors ($k=0.4$ and $k=1.0$) have been studied with special focus on the freeze/thaw durability. Furthermore, the effects of different curing conditions of the concrete with 20% fly ash have been investigated. The specimens were tested after being exposed to prolonged curing duration as well as to increased temperature.

The concretes have been tested regarding scaling at freezing, chloride migration and compressive strength. Slump tests were performed to measure the workability of the concrete mixtures and the air contents were measured on the freshly mixed concretes. Also, a foam index test has been performed to investigate the compatibility between fly ashes and AEAs. Furthermore, air void analysis was performed on the hardened concrete.

3.1 Materials and specimens

In total, specimens from eight different concrete mixtures have been tested with regard to freeze/thaw durability:

- Four mixtures with 20% fly ash, efficiency factor $k=0.4$
- One mixture with 20% fly ash, efficiency factor $k=1.0$
- Two different reference mixtures, without fly ash
- One mixture with 6% fly ash, efficiency factor $k=0.4$

Ten cubes and four cylinders were casted from each mixture.

As a main binder Cementa Degerhamn Anl ggningscement (CEM I 42.5 N MH/SR/LA) was used in all mixtures. The fly ash used was Warnow F ller (Rostock), which complies with SS-EN 450-1 (2007), see Table 3.1 for properties. Two types of fine aggregate were used; Sj sand (0-4 mm) and Hol (0-8 mm). As coarse aggregate crushed stone, Tagene (5-8 mm and 8-16 mm), were used. The AEA used was SikaAer-S (1:10), synthetic tenside, and the superplasticizer used was Sikament 56/50, PCE. The proportions of all mixtures are shown in Table 3.2.

Mixtures 1-4 and 8 have a k -factor equal to 0.4, which is according to SS-EN 206-1 (2001). The k -factor for mixture 5 was chosen to 1.0, which means that the cement was replaced by fly ash on a one-to-one basis. Two mixtures without fly ash were tested as reference as well as a mixture with 6% fly ash, which is the recommended maximum amount in exposure class XF4, according to AMA Anl ggning 07 (2008).

Since the freeze/thaw resistance of the concrete is highly dependent on the air content, the air content has been targeted to $(4.5\pm 0.5)\%$, measured in the fresh concrete. The amount of AEAs needed to achieve the target air content was added to each mixture; therefore, the amount of AEAs varies between the different mixtures. Furthermore, the superplasticizer was necessary to achieve the targeted air content in the concretes with 20% fly ash. The $(w/c)_{eq}$ was chosen to 0.45 for all mixtures, which is the highest permitted value of $(w/c)_{eq}$ in exposure class XF4 according to SS 13 70 03 (2008).

Table 3.1 Properties of the used fly ash and allowable values according to SS-EN 450-1 (2007) [TCG (2009)]

Property	Characteristic values	Allowable values (according to SS-EN 450-1)
LOI	2.60 wt%*	< 5 wt%
Fineness $\geq 45 \mu\text{m}$	16 wt%*	< 40 wt%
Chlorides (Cl ⁻)	< 0.01 wt%	< 0.10 wt%
Equivalent Na ₂ O	2.4 wt%*	< 5.0 wt%
Particle density	2.10 \pm 0.20 t/m ³ *	Declared values \pm 0.20 t/m ³
Activity index	78.8 % (28 d)*	> 75 % (28 d)
	89.6 % (90d)*	> 85 % (90 d)

*Mean value

Table 3.2 Proportions of each concrete mixture.

Mixture No.	1-4	5	6	7	8
% fly ash	20	20	0	0	6
<i>k</i> -factor	0.4	1.0	-	-	0.4
(<i>w/c</i>)-ratio	0.49	0.54	0.45	0.45	0.46
(<i>w/c</i>) _{eq} -ratio	0.45	0.45	0.45	0.45	0.45
Cement ^a [kg/m ³]	355.0	335.0	375.0	400.0	380.0
Fly ash ^b [kg/m ³]	71.0	67.0	0.0	0.0	22.8
<i>Aggregate:</i>					
Fine (0-4 mm) ^c [kg/m ³]	424	424.1	443.7	431	431.8
Fine (0-8 mm) ^d [kg/m ³]	341.8	341.9	357.6	347.4	348.1
Coarse (5-8 mm) ^e [kg/m ³]	170.3	170.3	178.1	173.1	173.4
Coarse (8-16 mm) ^e [kg/m ³]	766.2	766.3	801.7	778.8	780.2
Water [kg/m ³]	172.5	180.9	168.8	180	175.1
AEA ^f [kg/m ³]	1.42	1.34	0.38	0.4	0.38
AEA [% of cement b.w.]	0.4	0.4	0.1	0.1	0.1
Plasticizer ^g [kg/m ³]	1.42	1.34	1.5	1.6	1.52

^a CEM I 42.5 N MH/SR/LA

^b Warnow Füller

^c Sjösand

^d Hol

^e Tagene

^f SikaAer-S (1:10) (synthetic tenside)

^g Sikament 56/50 (PCE)

As mentioned in Section 2.3, concretes containing fly ash have a lower degree of strength gain at early ages, than concretes containing Portland cement only. Due to

this, some of the concrete specimens containing 20% fly ash were either cured at higher temperature or during a longer curing time than the standard recommends. The extended curing time was chosen to be 56 days and 90 days and the higher temperature were chosen to 55 °C. To reduce the risk of micro cracks in the concrete, all specimens were cured at 20 °C during the first week. However, the specimens from mixtures 1-4 (20% fly ash, $k=0.4$) were accidentally cured at 75 °C during one day of the first week. The temperature at which each mixture was cured is shown in Table 3.3.

Table 3.3 Temperature of curing for each mixture

Mixture	% fly ash	k	20 °C	55 °C
1 ^a	20	0.4		x
2 ^a	20	0.4		x
3 ^a	20	0.4	x	
4 ^a	20	0.4	x	
5	20	1	x	x ^b
6	0	-	x	
7	0	-	x	
8	6	0.4	x	

^a During one day of the first week, all specimens from these mixtures, were accidentally cured at 75 °C.

^b Specimen tested only for scaling under freeze/thaw and chloride migration test.

3.2 Tests

The following tests have been performed to measure the properties of concrete with fly ash:

- Foam index test: The compatibility between fly ash and AEAs were tested according to the method described in Kūlaots (2003).
- Fresh concrete: Slump and air content were measured according to SS-EN 12350-2 (2009) and EN 12350-7 (2009), respectively.
- Strength: The compressive strength was tested according to SS-EN 12390-3 (2009) at ages of 7, 28, 56 and 90 days for specimens cured at 20 °C and 55 °C.
- Rapid chloride migration (RCM), D_{RCM} : D_{RCM} were tested according to NT Build 492 at ages of 28 and 56 days, for specimen cured at 20 °C and 55 °C.
- Freeze/thaw resistance: The surface scaling was tested according to SS 13 72 44 (2005). Tests were performed after the specimen had been cured according to the standard, prolonged curing and cured at 55 °C.
- Air void analysis: The structure of the air void system was determined by petrographic analysis according to SS-EN 480-11 (2005).

3.2.1 Foam index test

To investigate the compatibility between the fly ash and the air entraining agents, a foam index test was performed. Even though the test is not a standardized method, its purpose is to indicate how effectively the AEAs will work in the mixture of concrete with fly ash. The procedure followed, was to a great extent the same as suggested by Kūlaots (2003), see Section 2.5.1. But, instead of a 70 ml jar a 100 ml bottle was used, which will probably not affect the results.

In a bottle with a volume of 100 ml, 2 g fly ash and 8 g cement was mixed with 25 ml de-ionized water. The bottle was shaken until all of the fly ash and cement particles were wet. The AEAs was added one by one drop, where one drop was estimated to a volume of 0.02 ml. After each drop had been added, the bottle was shaken during approximately 15 seconds. This procedure was repeated until a stable foam was visually detected in 45 seconds. The foam index value of the fly ash and cement is the amount of AEA required to form stable foam. A reference test with 10 g cement and no fly ash was also done.

3.2.2 Properties of the fresh concrete

The properties of fresh concrete were tested according to SS-EN 12350 (2009). The air content by volume of concrete was measured with the pressure method, described in SS-EN 12350-7 (2009). The principle of the method is based on the relation between the volume of air and applied pressure. The method measures the total air in the concrete, meaning both the entrained air as well as the entrapped. To measure the consistency of the concrete, slump tests were performed according to SS-EN 12350-2 (2009).

3.2.3 Compressive strength

The compressive strength has been measured according to SS-EN 12390-3 (2009). Cubes with the size 150 mm × 150 mm × 150 mm were tested for strength as well as the density at ages of 7, 28 and 56 days for all different mixtures. For two mixtures, strength was also tested at 90 days age. The strength classes were evaluated according to SS-EN 206-1 (2001). At least three specimens should be tested according to the standard at each occasion, but due to space limitations, not enough cubes had been cast. Therefore, deviation from the standard was done. The number of cubes tested at each age is shown in Table 3.4.

Table 3.4 Number of cubes tested for strength at each age of all mixtures.

Mixture	% fly ash	k	7 d	28 d	56 d	90 d
1	20	0.4	1	2	2	0
2	20	0.4	1	2	2	0
3	20	0.4	1	1	2	1
4	20	0.4	1	3	2	0
5	20	1	1	1	1	1
6	0	-	1	4	1	0
7	0	-	1	3	3	0
8	6	0.4	1	2	2	0

3.2.4 Rapid chloride migration

The chloride migration test was performed according to NT Build 492 (1999), with some minor changes. This test determines the chloride migration coefficient from non-steady-state migration experiments. A description of the testing procedure is attached in Appendix B.

The test was performed after 28 and 56 days curing for all different mixtures, after being cured at either 20 °C or 55 °C. Three specimens, which were sawn from two cylinders, were normally tested at each occasion. This is not exactly according the standard, which is prescribing that the specimens should be sawn from different cylinders. However, in this way it was possible to measure after two different curing periods. The number of specimens and cylinders tested at each age are shown in Table 3.5.

Table 3.5 Number of specimens tested for chloride migration from each mixture at different age. The first value refers to numbers of cylinders tested and the second to number of specimens tested.

Mixture	% fly ash	<i>k</i>	28 d	56 d
1	20	0.4	2 (3)	2 (3)
2	20	0.4	2 (3)	2 (3)
3	20	0.4	2 (3)	2 (3)
4	20	0.4	2 (3)	2 (3)
5	20	1	2 (3)+1 (2)*	1 (2)
6	0	-	2 (3)	2 (3)
7	0	-	2 (3)	2 (3)
8	6	0.4	2 (3)	2 (3)

* 2 cylinders cured at 20 °C and 1 cylinder cured at 55 °C

3.2.5 Scaling under freeze/thaw

The freeze/thaw tests were carried out according to SS 13 72 44 (2005), procedure IA. However, some modifications were done considering the curing regime and the number of specimen tested as well as at which cycles the measured material at the surface was collected.

A 50 mm thick slab was sawn off each cube at right angles from the top surface, so that the freeze surface comes in the middle of the cube. The specimens were thereafter kept in a climate chamber at a temperature of (20 ± 2) °C and a relative humidity of $(65\pm 5)\%$ for seven days. During this period, rubber cloth was glued to all surfaces except the freeze surface. Water was then applied on the specimens, which were kept in the chamber for further (72 ± 2) hours. The freeze medium, i.e. 3% NaCl solution, was then applied on the freeze surface. The specimens were insulated on all surfaces except the freeze surface, which was protected from evaporation.

The specimens were placed in a freezing chamber, where they were subjected to repeated freezing and thawing. The temperature of a cycle varied between (-20 ± 2) °C and (20 ± 4) °C during a period of 24 hours. According to the standard, scaled material should be collected and weighted after 7, 14, 28, 42 and 56 cycles and for extended testing also 70, 84, 98 and 112 cycles. Instead the material was collected each seven cycles, so as to follow the result more precisely.

For concrete manufactured from Portland cement, with a *w/c* ratio of 0.4-0.5 and an air content less or equal to 7.0%, the results reported as in Table 3.6 have been shown to be in good agreement with the real frost resistance. Other types of concrete may require using a different assessment procedure, for example scaling after a larger number of freeze/thaw cycles. [SS 13 72 44 (2005)]

Table 3.6 Evaluation of the results according to SS 13 72 44 (2005).

Frost resistance as tested	Requirements
Very good	The mean value of the scaled material after 56 cycles (m_{56}) is less than 0.10 kg/m^2 .
Good	The mean value of the scaled material after 56 cycles (m_{56}) is less than 0.20 kg/m^2 . or The mean value of the scaled material after 56 cycles (m_{56}) is less than 0.5 kg/m^2 at the same time as m_{56}/m_{28} is less than 2 or The mean value of the scaled material after 112 cycles (m_{112}) is less than 0.5 kg/m^2 .
Acceptable	The mean value of the scaled material after 56 cycles (m_{56}) is less than 1.00 kg/m^2 at the same time as m_{56}/m_{28} is less than 2 or The mean value of the scaled material after 112 cycles (m_{112}) is less than 1.00 kg/m^2 .
Unacceptable	The requirements for acceptable frost resistance are not met.

To achieve the same maturity for the specimen cured at $55 \text{ }^\circ\text{C}$ as for the ones cured for 56 and 90 days at $20 \text{ }^\circ\text{C}$, maturity equation 2.5 was used. The Arrhenius equation 2.6 was not suitable for this purpose, since the activation energy is not known. The calculations to decide the curing time for specimen cured at $55 \text{ }^\circ\text{C}$ are shown in equations 3.1 and 3.2, respectively.

$$(56 \text{ d})(20 + 10) = (7 \text{ d})(20 + 10) + t_{x,56}(55 + 10) \Leftrightarrow t_{x,56} = 22.6 \text{ d} \quad (3.1)$$

$$(90 \text{ d})(20 + 10) = (7 \text{ d})(20 + 10) + t_{x,90}(55 + 10) \Leftrightarrow t_{x,90} = 38.3 \text{ d} \quad (3.2)$$

where

$t_{x,56}$: curing period in $55 \text{ }^\circ\text{C}$ with maturity equivalent to 56 days

$t_{x,90}$: curing period in $55 \text{ }^\circ\text{C}$ with maturity equivalent to 90 days

Because of practical reason, the curing period for the specimen cured at $55 \text{ }^\circ\text{C}$ were chosen to 21 and 35 days, respectively. In Table 3.7 the curing regime for each mixture and number of cubes tested is shown. Schematic of the curing regime is shown in Figure 3.1. In Table 3.8 the exact number of days of the curing regime for each mixture is presented.

Table 3.7 Mixtures and No. of cubes tested for scaling at freezing

Mixture	% fly ash	k	Standard curing	56 days curing	90 days curing	55°C, corresponding to 56 days	55°C, corresponding to 90 days
1	20	0.4				4	
2	20	0.4					4
3	20	0.4		2	3		
4	20	0.4	4				
5	20	1		2	2	2	
6	0	-	4				
7	0	-	4				
8	6	0.4	4				

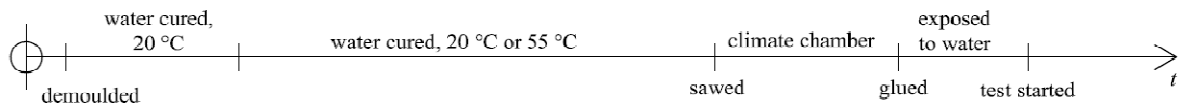


Figure 3.1 Schematic of the curing regime before tested for scaling under freeze/thaw.

Table 3.8 Curing regime for each mixture tested for scaling at freezing, no. of days

Mix	% fly ash	k	Curing regime	In mould	Water cured, 20 °C	Water cured, 55 °C	Climate chamber	Exposed to water	Total
1	20	0.4	55 °C, 28 d	1	6	21	7	3	38
2	20	0.4	55 °C, 42 d	1	6	35	7	3	52
3	20	0.4	20 °C, 56 d	1	54	-	6.5	2.5	64
			20 °C, 90 d	1	89	-	7	3	100
4	20	0.4	Standard	1	19	-	7	3	30
5	20	1.0	20 °C, 56 d	1	62	-	7	3	73
			20 °C, 90 d	1	90	-	7	3	101
			55 °C, 28 d	1	6	21	7	3	38
6	0	-	Standard	1	20	-	7	3	31
7	0	-	Standard	1	19	-	7	3	30
8	6	0.4	Standard	1	19	-	7	3	30

3.2.6 Air void analysis

The air void analysis was performed by petrographic analysis according to SS-EN 480-11 (2005). Four specimens from different concrete mixtures were tested. One specimen of each of the following mixtures was chosen:

- Mixture 3: 20% fly ash, $k=0.4$, cured 56 days at 20 °C.
- Mixture 4: 20% fly ash, $k=0.4$, standard cured.
- Mixture 5: 20% fly ash, $k=1.0$, cured 63 days at 20 °C.
- Mixture 7: 0% fly ash, standard cured.

4 Results and Analysis

4.1 Foam index test

The results from the foam index test are shown in Table 4.1. As can be seen, the amount of AEAs to achieve stable foam is similar for the solution without fly ash and the solution with fly ash. According to these results, there should be no problems with the compatibility between the fly ash and AEAs.

Table 4.1 Results from foam index test for solution with and without fly ash.

Solution	Foam index [ml/2 g-ash]
Including fly ash	0.05
Reference (without fly ash)	0.04

4.2 Properties of the fresh concrete

As shown in Table 4.2, the measured air content of all of the mixtures was within the specified range, $(4.5\pm 0.5)\%$. The slump showed some variation, however, all mixtures except two are considered to be in class S2 or S3.

Table 4.2 Air content and slump measured for the fresh concrete tested according to SS-EN 12350-2 (2009) and SS-EN 12350-7 (2009), respectively.

Mixture	Air content [%]	Slump [mm]	Slump class
1	4.5	-	S2
2	4.8	85	S2
3	4.8	110	S3
4	4.6	120	S3
5	4.2	160	S4
6	4.6	30	S1
7	4.8	110	S3
8	4.3	65	S2

As mentioned in Section 3.1, it was not possible to achieve the desired air content, $(4.5\pm 0.5)\%$, in the concrete mixture without adding superplasticizer. One explanation of this behavior may be that the superplasticizer is, in similarity to the AEAs, surfactants. The molecules of the plasticizer may be adsorbed on the surface of the unburned carbon particles from the fly ash, thus blocking the surface from the AEAs. This will lead to more AEA molecules free to form stable air bubbles.

The amount of AEAs in proportion to the content of cementitious material needed to achieve the target content of air $(4.5\pm 0.5)\%$ for each mixture is shown in Table 4.3.

As can be seen, the mixtures with 20% fly ash (mixtures 1-5) needed around four times the amount of AEAs than the mixtures without, or with only 6%, fly ash (mixtures 6-8). This would mean that the superplasticizers do not block the whole surface of the carbon particles, leaving some area free for the AEAs to be adsorbed on. The higher amount of AEAs needed to create stable air bubbles for the concrete with fly ash is consistent with what has been reported by Zhang (1996). However, it should be noted that the amount of AEAs in the concrete mixtures with 20% fly ash was within in the dosage recommended by the producer of the AEAs.

Table 4.3 Percent AEA of content cementitious material needed to achieve the target air content, $(4.5 \pm 0.5)\%$

	Mixture 1-4	Mixture 5	Mixture 6	Mixture 7	Mixture 8
AEA/C [%]	0.40	0.40	0.10	0.10	0.10
AEA/(C+FA) [%]	0.33	0.33	0.10	0.10	0.09
AEA/(C+0.4FA) [%]	0.37	0.37	0.10	0.10	0.10

The result from the foam index test, presented in Section 4.1, showed that the efficiency of the AEAs is similar in concrete with fly ash as without. However, this is in contradiction with the need of superplasticizer and the increase of amount of AEAs, in the concrete mixtures with 20% fly ash.

4.3 Compressive strength

The compression strength at 28 days age for the concrete containing 20% fly ash were slightly lower than for the other mixtures, see Figure 4.1. The strength tested after seven days were higher for the mixture with large amount of fly ash, than for the others, which is explained by that the temperature was accidentally elevated to 75 °C for about 24 hours during the first week.

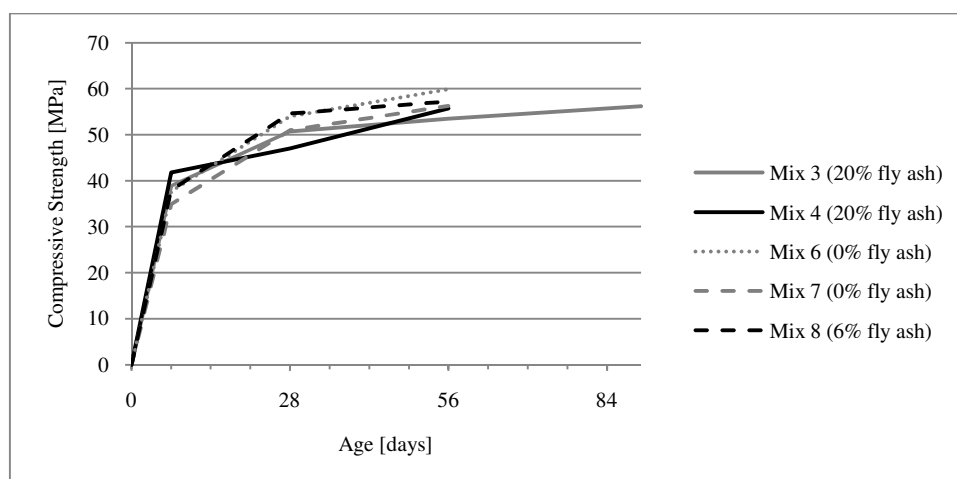


Figure 4.1 Compressive strength development for concretes with different amount of fly ash, $k=0.4$, and cured at 20 °C. Test performed at 7, 28, 56 and 90 days age. Tested according to SS-EN 12390-3 (2009).

As can be seen in Figure 4.2, the strength development for the specimen cured at 55 °C ceased somewhere around 28 days age. This means that the strength of the

specimen tested after 28 days and 42 days cured at 55 °C, were the same at the start of the test for scaling under freeze/thaw. Figure 4.3 shows the relationship between the compressive strength and the theoretical maturity, calculated with Equation 2.5. As can be seen, the strength is higher for the same maturity for the concrete cured at 55 °C than for the concrete cured at 20 °C. The strength for the concrete cured at 55 °C is, for all ages above 21 days, higher than for the specimens cured at 20 °C. This means that the maturity equation underestimated the effect of temperature and/or overestimated the effect of extended curing period for concrete with fly ash. Using the maturity equation 2.5, to achieve the duration of curing for the specimen cured at 55 °C, equivalent to those cured at 20 °C for 56 and 90 days, respectively, did not seem to fall out well.

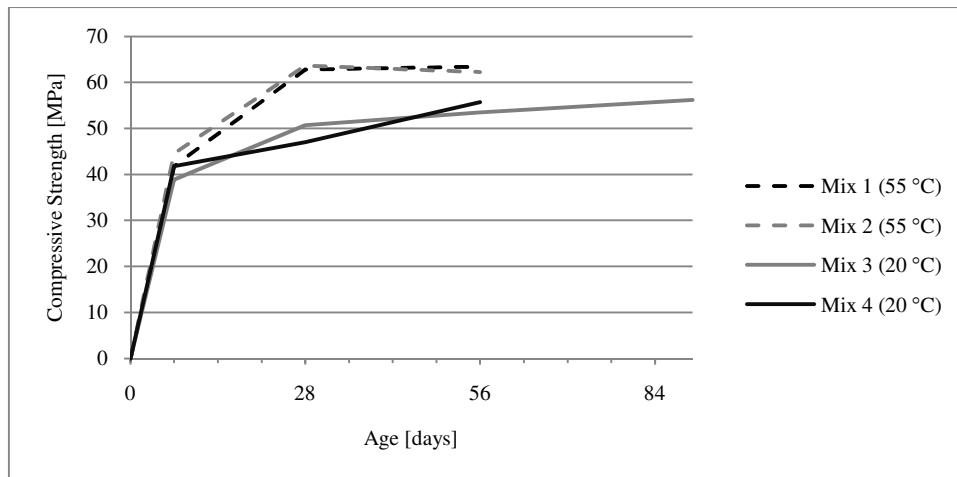


Figure 4.2 Strength development for concretes with 20% fly ash and $k=0.4$ cured at 20 °C and 55 °C. Test performed at 7, 28, 56 and 90 days age. Tested according to SS-EN 12390-3 (2009).

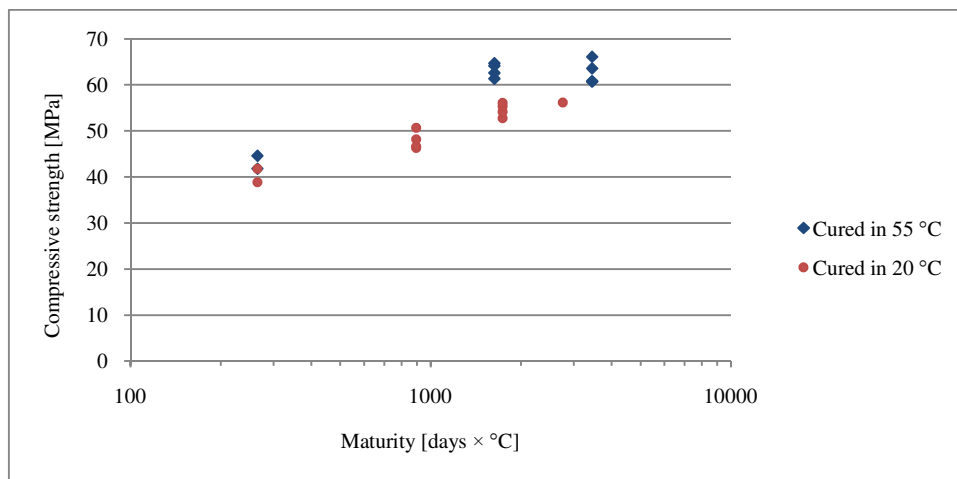


Figure 4.3 Relationship between compressive strength and maturity calculated from eq. 2.5 for mixtures with 20% fly ash and $k=0.4$ cured at 20 °C and 55 °C.

The strength development for the concrete with 20% fly ash with different k -factors ($k=0.4$ and $k=1.0$) cured at 20 °C is shown in Figure 4.4. Since higher value of the k -factor gives higher w/c ratio, larger k -factor gives lower strength.

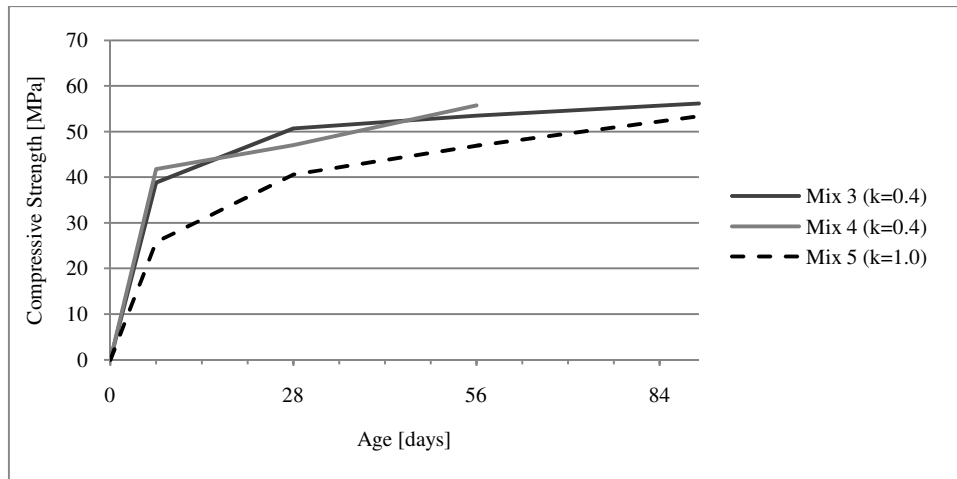


Figure 4.4 Strength development of concretes with 20 % fly ash and different k -factors ($k=0.4$ and $k=1.0$) cured at 20 °C. Test performed at 7, 28, 56 and 90 days age. Tested according to SS-EN 12390-3 (2009).

All raw data from the compressive strength and density tests are attached in Appendix A. In this Appendix, also an evaluation of the strength classes is presented.

4.4 Rapid chloride migration

The results from rapid chloride migration are shown in Figures 4.5-4.7. In Figure 4.5, the results of the values of chloride migration coefficient for mixtures with different amount of fly ash ($k=0.4$) cured at 20 °C is presented. The coefficient of the concrete with 20% fly ash ($k=0.4$) cured at 20 °C and 55 °C, is shown in Figure 4.6. In Figure 4.7, the concretes with different k -factors ($k=0.4$ and $k=1.0$) are compared. All raw data is attached in Appendix B.

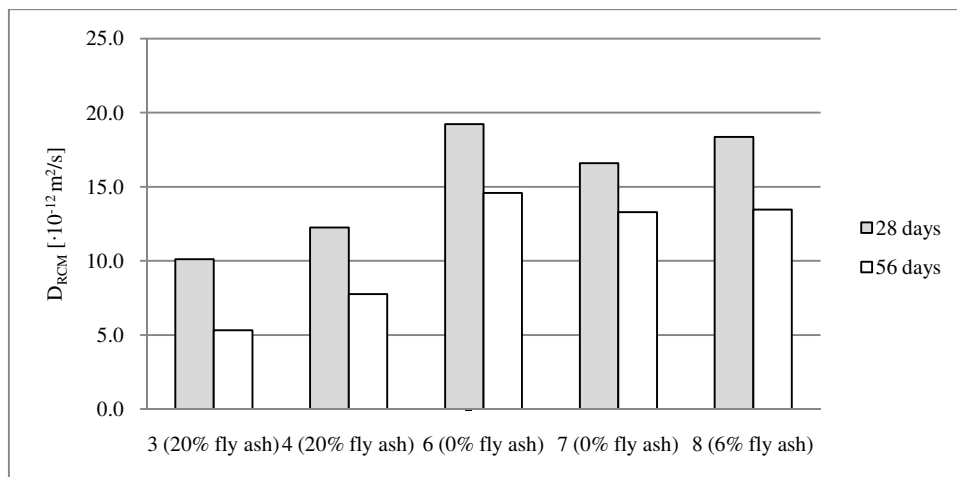


Figure 4.5 Rapid chloride migration coefficient, D_{RCM} , for mixtures cured at 20 °C with different amount of fly ash. Coefficient measured at age of 28 and 56 days. Tested according to NT Build 492 (1999).

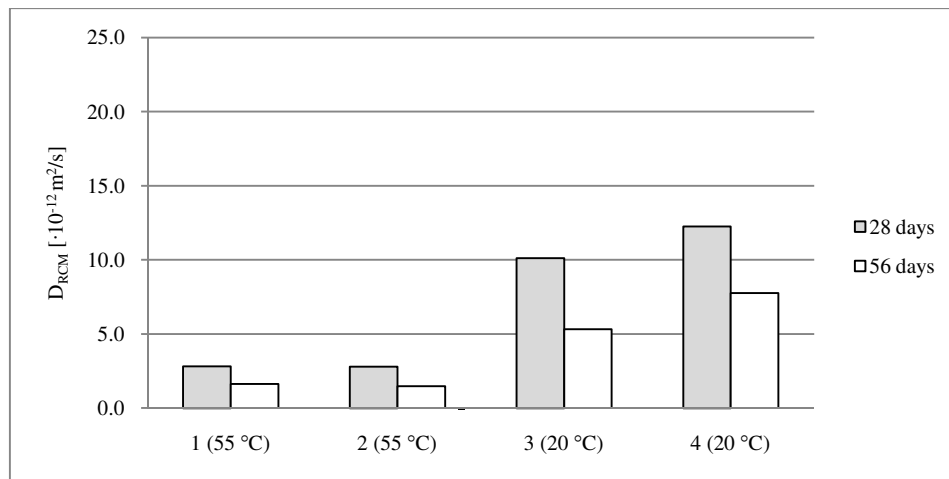


Figure 4.6 Rapid chloride migration coefficient, D_{RCM} , for mixtures with 20% fly ash and $k=0.4$ cured at different temperatures. Coefficient measured at age of 28 and 56 days. Tested according to NT Build 492 (1999).

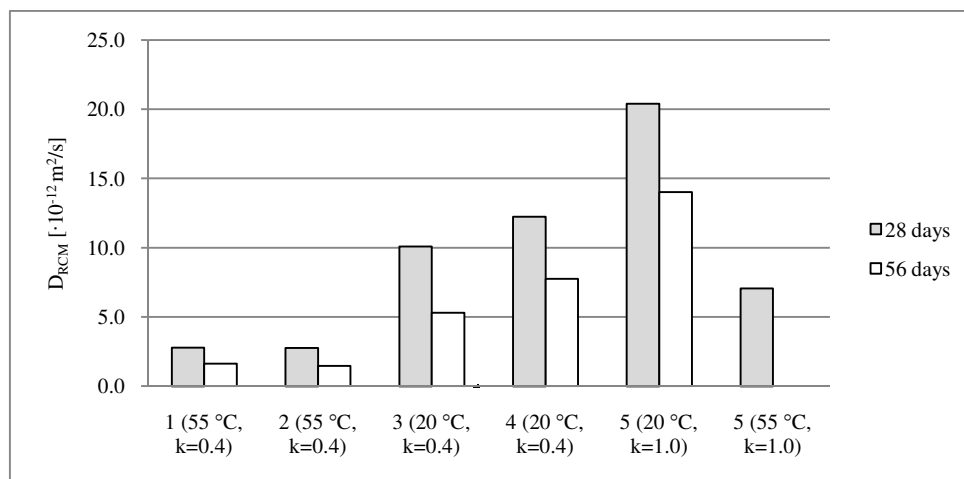


Figure 4.7 Rapid chloride migration coefficient, D_{RCM} , for mixtures with different k -factors ($k=0.4$ and 1.0). Coefficient measured at age of 28 and 56 days. Tested according to NT Build 492 (1999).

As illustrated in Figure 4.5, the coefficient was less for the concrete with 20% fly ash, $k=0.4$, than the reference concrete. The addition of fly ash for the specimen with only 6% fly ash seems not to have affected the resistance against chloride migration. Furthermore, the chloride migration coefficient decreased over time and mixtures cured at elevated temperatures also showed improved resistance against chloride penetration, see Figure 4.6. The mixture with a k -factor equal to 1.0 was shown to have higher value of chloride migration coefficient than the mixtures with k -factor equal to 0.4 independently of the temperature at curing, see Figure 4.7. This can be explained by the fact that the w/c ratio increases with the k -factor, which leads to higher permeability. As can be seen in Figure 4.5 and Figure 4.7, the values of chloride migration coefficients for the concretes without fly ash (mixtures 6 and 7) are similar to the coefficient of the concrete with 20% fly ash and $k=1.0$ (mixture 5) cured at 20 °C. This is due to that the binder content in relation to the water content is the same for these concretes.

4.5 Scaling under freezing and thawing

The scaled material after 28, 56 and 112 cycles for all concrete mixtures are shown in Figure 4.8. As can be seen, the amount of scaled material after 56 cycles was less than 0.1 kg/m^2 for all mixtures, which means that the performance is considered as very good according to the requirements in Table 3.6. The scaled material after 112 cycles was less than 0.5 kg/m^2 , so the resistance against freezing and thawing is considered as good. Raw data and photos of the specimens are presented in Appendix C.

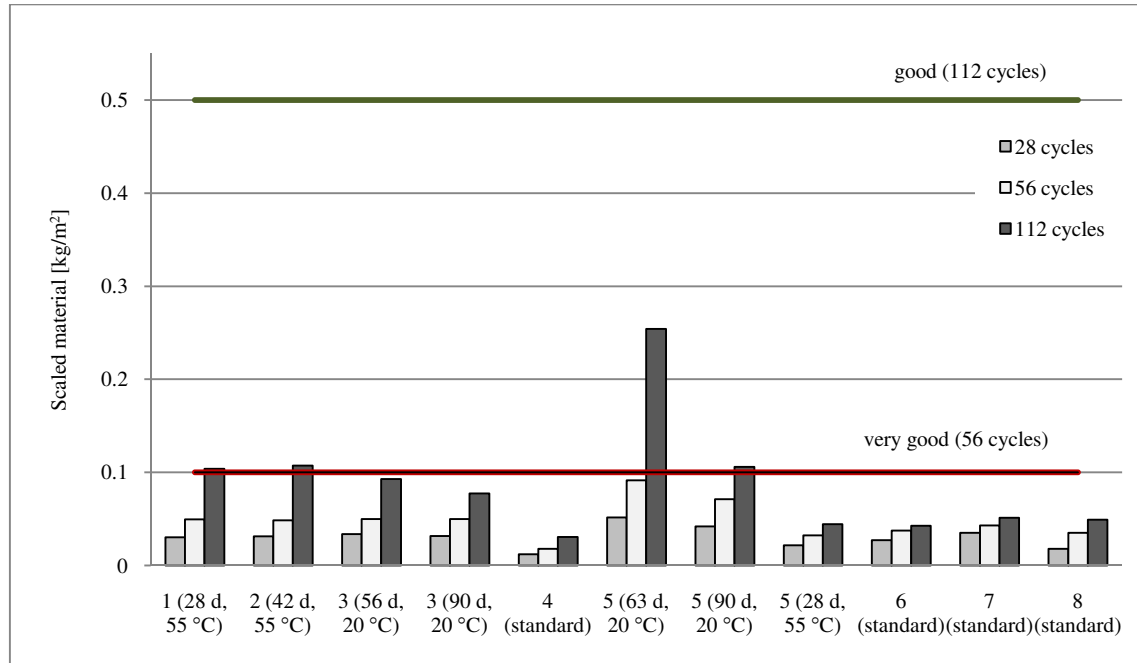


Figure 4.8 Mean values from scaling under freeze/thaw after 28, 56 and 112 cycles for concrete from all mixtures. Tested according to SS 13 72 44 (2005).

4.5.1 Variations of the results

The mixtures without fly ash (mixtures 6 and 7) had each one specimen out of four with considerably more scaled material under freezing and thawing, than the other three. The scaled material after 112 cycles for each specimen, from these concrete mixtures, is shown in Figure 4.9. The outliers are not included in the mean values. However, even if these two outliers are included, the mean value of scaled material will be less than 0.1 kg/m^2 , meaning that the resistance against freezing and thawing is considered as very good. The concrete from the mixtures with fly ash had no outliers.

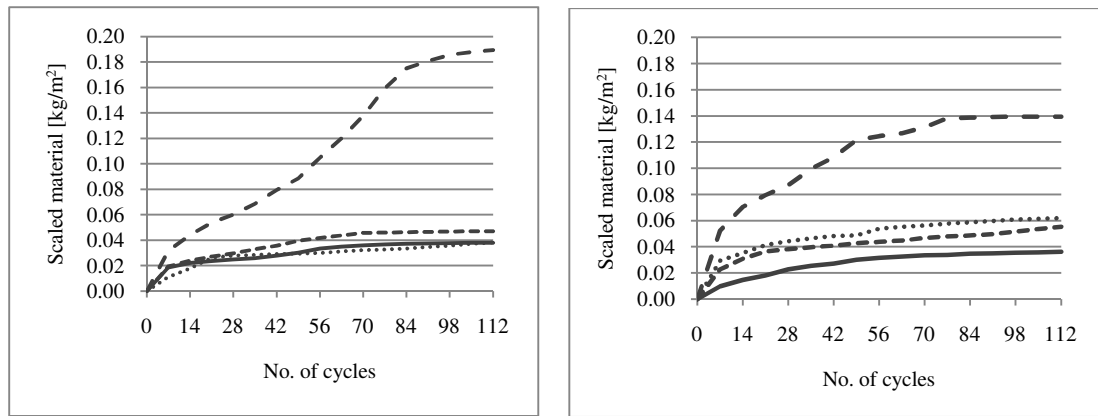


Figure 4.9 Scaled material for each specimen for the concrete without fly ash (mixture 6 and 7). Tested according to SS 13 72 44 (2005).

4.5.2 Curing regime according to the standard

As shown in Figure 4.10 the concrete containing 20% fly ash, did show slightly better durability regarding freezing and thawing, than the concrete with 6% and 0% fly ash. The resistance for the mixtures with 6% fly ash and without fly ash were similar.

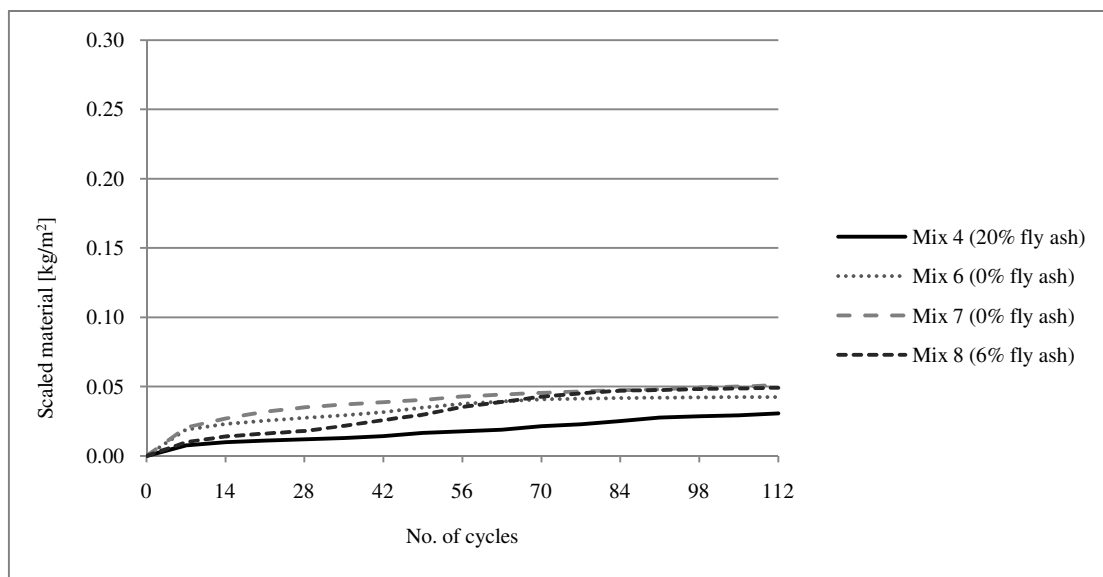


Figure 4.10 Mean values from scaling at freezing for concrete cured according to the standard with different amount of fly ash, measured after each seven cycles. Tested according to SS 13 72 44 (2005).

4.5.3 Different curing regimes for concrete with fly ash

When the concretes containing 20% fly ash, $k=0.4$, exposed to different curing conditions were compared, it was shown that the standard cured concrete, had less amount of scaled material, see Figure 4.11. The behaviour of the concretes with either extended curing period and/or cured at higher temperature, were all similar each other.

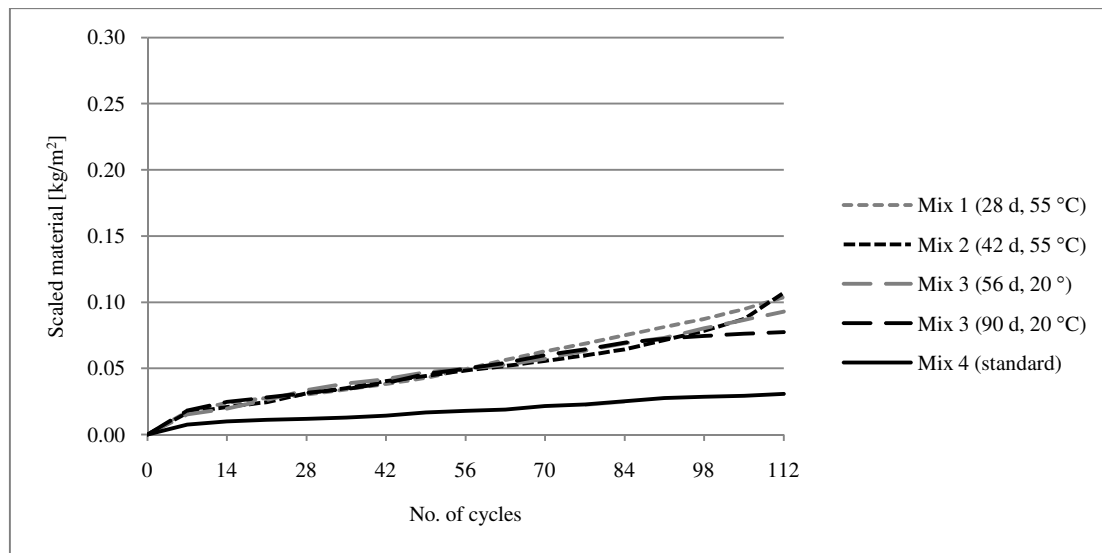


Figure 4.11 Mean values from scaling at freezing for mixtures with 20 % fly ash ($k=0.4$) cured according to different regimes, measured after each seven cycles. Tested according to SS 13 72 44 (2005).

The somewhat poorer performance for the specimens cured at 55 °C may be explained with that higher temperature may give micro cracks in the concrete. However, this theory does not explain the fact that scaled material is about the same for specimen with extended curing at 20 °C. Another, more agreeable, explanation, is that the concretes cured for prolonged duration and/or cured at 55 °C had higher maturity degree than the one cured according to the standard, which would give denser concrete. Neither the sizes nor the distances between the pores created by the air entraining agents are affected by the higher maturity degree. The capillary pores binding the larger air pores together will be finer with higher maturity degree, which will increase the hydraulic pressure, hence leading to larger disruptive pressure.

4.5.4 Different k -factors

According to the theory with increased hydraulic pressure due to finer capillary pores, the concrete with the k -factor equal to 1.0 should perform better than the concrete with k -factor equal to 0.4. This since the $(w/c)_{eq}$ is equal to 0.45 for both cases, but the total binder content for the mixture with higher k -factor is smaller, leading to a more porous pore structure with coarser capillary pores. With coarser capillary pores that the water can be transported through, the hydraulic pressure would decrease. On the other hand, concretes with higher k -factors are less dense, which leads to lower strength and more freezable water, thus a less durable concrete regarding freezing and thawing.

In Figure 4.12, the results from scaling under freeze/thaw for concretes with 20% fly ash and different k -factors are shown. The specimens from the concrete with $k=1.0$, which were cured for 63 days, showed to be less durable than those cured for 90 days at 20 °C and 28 days at 55 °C. This agrees with the later theory mentioned above.

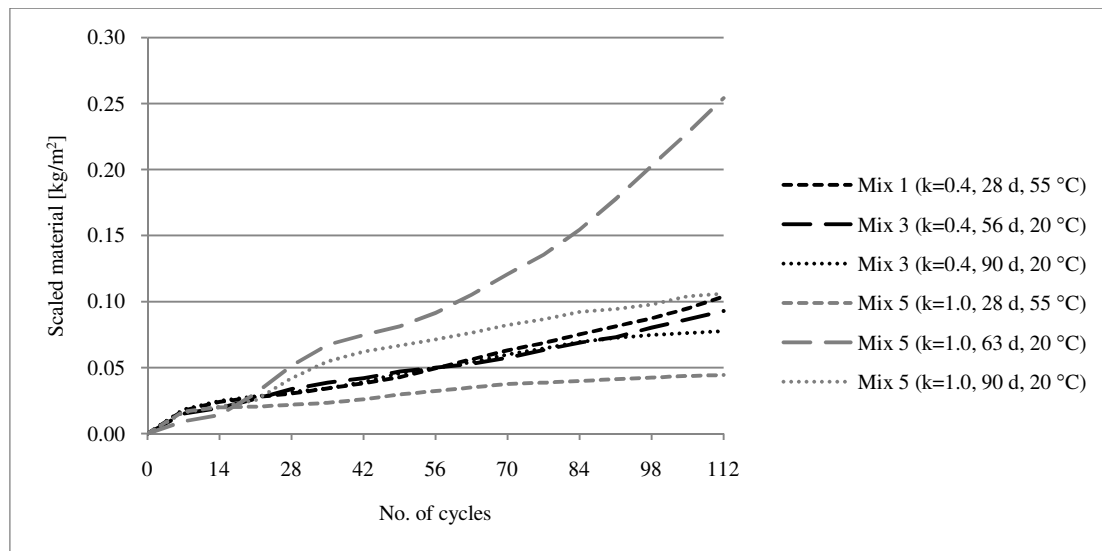


Figure 4.12 Mean values from scaling at freezing for mixtures with 20 % fly ash, different k -factors and cured under different regimes; measured after each seven cycles. Tested according to SS 13 72 44 (2005).

4.6 Air void analysis

The specimens tested for air void analysis, were chosen to correspond with the general behaviour of each concrete mixture regarding freeze/thaw durability. The analysis was performed on the corresponding surface of the specimen tested for scaling under freeze/thaw.

The results from the analysis, which are presented in Table 4.4, shows that the air void structures of all four specimens tested, are acceptable, even though the air content for concrete from mixture 5 is low. This is consistent with that concrete from all mixtures showed very good performance regarding scaling under freeze/thaw.

Table 4.4 Results from the air void analysis performed according to SS-EN 480-11 (2005).

	Accuracy of measurement	Mix 3 ^c	Mix 4 ^d	Mix 5 ^e	Mix 7 ^f
Air content [vol-%]	±0.7	5.1	4.0	2.9	5.9
Specific air void surface ^a [mm ⁻¹]	±3	27	32	30	21
Spacing factor ^b [mm]	±0.015	0.19	0.18	0.22	0.22
Assumed paste content [vol-%]	-	31.6	31.6	31.6	31.6

^a (surface area of air bubbles)/(volume of air bubbles)

^b distance between the air bubbles

^c 20% fly ash, $k=0.4$, cured 56 days at 20 °C

^d 20% fly ash, $k=0.4$, standard cured

^e 20% fly ash, $k=1.0$, cured 63 days at 20 °C

^f 0% fly ash, standard cured

The spacing factors of the concretes with 20% fly ash and $k=0.4$, i.e. mixtures 3 (56 d, 20 °C) and 4 (standard cured), are similar. This is in consistence with the theory presented in Section 4.5.3; higher maturity leads to an increase of the hydraulic pressure, thus reducing the freeze/thaw durability.

The air content, measured in the hardened concrete from mixture 5 (20% fly ash, $k=1.0$, 56 d, 20 °C) is lower than the air content measured in the fresh concrete (4.2%). However, this may be due to the high slump (class S4), leading to air leaving the concrete at casting and at the beginning of curing. The low air content may have made it more sensitive to the curing regime, regarding scaling under freeze/thaw, see Figure 4.8. The variation of the air content comparing the air content in the fresh concrete with the hardened concrete for mixtures 3, 4 and 7 could be explained by error of measurement.

5 Conclusions

The freeze/thaw durability of properly air entrained concrete with and without fly ash, is similar. Moreover, addition of 20% fly ash improves the resistance regarding chloride ingress. No effects on neither the freeze/thaw durability, nor the chloride ingress durability, was detected in the laboratory study, for concrete with only 6% fly ash, compared to concrete with plain Portland cement.

- The air void structure is important for a freeze/thaw durable concrete. In the laboratory study, results from the air void analysis showed that by increasing the amount of AEAs, properly air entrained concrete containing fly ash was achieved.
- Results from laboratory work indicates that concrete with 20% fly ash and $k=0.4$ showed slightly better resistance regarding freeze/thaw than concrete without fly ash. Results from literature studies showed that concrete with about 20% to 30% fly ash showed similar or slightly worse behaviour regarding freeze/thaw.
- According to the results from the laboratory work, prolonged curing and increased temperature for the concrete with 20% fly ash and $k=0.4$ did have a slightly negative effect on the freeze/thaw resistance. This was attributed to denser pore structure, thus increase of the hydraulic pressure. The amount of scaled material under freezing and thawing for the specimens exposed to either 55 °C or prolonged curing duration, were similar.
- In the laboratory study, the concretes with 20% fly ash and $k=1.0$ cured for 56 days and 90 days, showed less good resistant against freezing and thawing than the concrete with $k=0.4$. For the concretes cured at 55 °C, the relation was the inversed. Furthermore, the specimen cured 90 days showed improved durability compared to concrete cured 56 days.
- The results from chloride migration test were consistent with findings in the literature. Prolonged curing duration and higher temperature during curing had positive effect on the resistance against chloride migration. The concrete with 20% fly ash showed better performance than the reference concrete (0% fly ash), which was attributed to the fact that addition of fly ash gives denser concrete. Higher k -factor gave less resistant concrete, due to the increased w/c ratio which gives a more permeable concrete.
- The maturity equation 2.5, used in the laboratory study, underestimated the effect of temperature and/or overestimated the effect of extended curing period for concrete with fly ash.

6 Suggestions for future studies

In this project, the amount of fly ash was limited to 20% by weight of cement content. The effects, on the freeze/thaw durability, of different amounts of fly ash, could be studied in future studies. Also, concretes with different $(w/c)_{eq}$ and the effects of different k -factors could be studied. The structure of the air void system has major impact on the freeze/thaw durability; therefore its quality could be of interest. Also, the effects of different air entraining agents on the freeze/thaw durability could be of interest. Furthermore, the compatibility between air entraining agents and the fly ash is important to produce a stable air void system, therefore the compatibility between different types of air entraining agents and fly ashes from different sources could be analyzed.

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Appendix A: Compressive Strength

The results from compression strength and the density are presented in this appendix. The tests were performed at 7, 28, 56 and 90 days age for cubes (150 mm × 150 mm × 150 mm) according to EN 12390-3 for specimens cured at either 20 °C or 55 °C. In Tables A.1-A.4, the results from each specimen are presented. In Table A.5, the mean values of strength are shown. Furthermore, the strength classes have been evaluated in Table A.6 at 28 days age for concrete from all mixtures EN 206-1.

Table A.1 Results of 7-days compressive strength, tested according to EN 12390-3.

Mixture	Load [kN]	Weight [g]	Weight in water [g]	Compressive strength [MPa]	Density [kg/m ³]
1 (20% fly ash, 55 °C)	940	7 826	4 422	41.8	2 299
2 (20% fly ash, 55 °C)	1 003	7 865	4 449	44.6	2 302
3 (20% fly ash, 20 °C)	874	7 873	4 441	38.9	2 294
4 (20% fly ash, 20 °C)	941	7 812	4 417	41.8	2 301
5 (20% fly ash, $k=1.0$, 20 °C)	581	7 807	4 392	25.8	2 286
6 (0% fly ash, 20 °C)	847	7 960	4 523	37.7	2 316
7 (0% fly ash, 20 °C)	785	7 858	4 424	34.9	2 288
8 (6% fly ash, 20 °C)	854	7 985	4 541	38.0	2 319

Table A.2 Results of 28-days compressive strength, tested according to EN 12390-3.

Mixture	Load [kN]	Weight [g]	Weight in water [g]	Compressive strength [MPa]	Density [kg/m ³]
1 (20% fly ash, 55 °C)	1 444	7 774	4 387	64.2	2 295
	1 381	7 815	4 408	61.4	2 294
2 (20% fly ash, 55 °C)	1 409	7 801	4 417	62.6	2 305
	1 456	7 834	4 425	64.7	2 298
3 (20% fly ash, 20 °C)	1 141	7 788	4 400	50.7	2 299
4 (20% fly ash, 20 °C)	1 084	7 885	4 451	48.2	2 296
	1 042	7 827	4 424	46.3	2 300
	1 049	7 851	4 437	46.6	2 300
5 (20% fly ash, $k=1.0$, 20 °C)	913	7 878	4 430	40.6	2 285
6 (0% fly ash, 20 °C)	1 235	8 042	4 581	54.9	2 324
	1 216	7 963	4 513	54.0	2 308
	1 196	7 958	4 516	53.2	2 312
	1 213	7 947	4 493	53.9	2 301
7 (0% fly ash, 20 °C)	1 253	7 916	4 492	55.7	2 312
	1 266	7 912	4 492	56.3	2 313
8 (6% fly ash, 20 °C)	1 167	7 865	4 471	51.9	2 317
	1 159	7 963	4 505	51.5	2 303
	1 135	7 766	4 365	50.4	2 283

Table A.3 Results of 56-days compressive strength, tested according to EN 12390-3.

Mixture	Load [kN]	Weight [g]	Weight in water [g]	Compressive strength [MPa]	Density [kg/m ³]
1 (20% fly ash, 55 °C)	1 366	7 937	4 503	60.7	2 311
	1 488	7 836	4 457	66.1	2 319
2 (20% fly ash, 55 °C)	1 431	7 871	4 458	63.6	2 306
	1 369	7 793	4 410	60.8	2 304
3 (20% fly ash, 20 °C)	1 188	7 859	4 430	52.8	2 292
	1 218	7 859	4 446	54.1	2 303
4 (20% fly ash, 20 °C)	1 245	8 002	4 536	55.3	2 309
	1 263	7 951	4 512	56.1	2 312
5 (20% fly ash, $k=1.0$, 20 °C)	1 055	7 812	4 409	46.9	2 296
6 (0% fly ash, 20 °C)	1 348	8 040	4 559	59.9	2 310
7 (0% fly ash, 20 °C)	1 239	7 942	4 496	55.1	2 305
	1 225	7 981	4 500	54.4	2 293
	1 334	8 057	4 578	59.3	2 316
8 (6% fly ash, 20 °C)	1 316	7 927	4 508	58.5	2 319
	1 260	7 921	4 479	56.0	2 301

Table A.4 Results of 90-days compressive strength, tested according to EN 12390-3.

Mixture	Load [kN]	Weight [g]	Weight in water [g]	Compressive strength [MPa]	Density [kg/m ³]
3 (20% fly ash, 20 °C)	1 264	7 846	-	56.2	-
5 (20% fly ash, $k=1.0$, 20 °C)	1 200	7 847	4 435	53.3	2 300

Table A.5 Mean values of the compressive strength for 7, 28, 56 and 90 days.

Mixture	7 days		28 days		56 days		90 days	
	Compressive Strength [MPa]	Density [kg/m ³]	Compressive Strength [MPa]	Density [kg/m ³]	Compressive Strength [MPa]	Density [kg/m ³]	Compressive Strength [MPa]	Density [kg/m ³]
1	41.8	2 299	62.8	2 295	63.4	2 315	-	-
2	44.6	2 302	63.7	2 302	62.2	2 305	-	-
3	38.9	2 294	50.7	2 299	53.5	2 297	56.2	-
4	41.8	2 301	47.0	2 299	55.7	2 310	-	-
5	25.8	2 286	40.6	2 285	46.9	2 296	53.3	2 300
6	37.7	2 316	54.0	2 311	59.9	2 310	-	-
7	34.9	2 288	51.0	2 293	56.3	2 304	-	-
8	38.0	2 319	54.6	2 314	57.2	2 310	-	-

Table A.6 Evaluation of the strength classes at 28 days according to method in SS-EN 206-1.

Mixture	$f_{c,mean} - 4$ Mpa [MPa]	$f_{c,min} + 4$ Mpa [MPa]	$f_{ck,cube}$ [MPa]	Strength class
1	58.8	65.4	58.8	C45/55
2	59.7	66.6	59.7	C45/56
3	46.7	54.7	46.7	C35/45
4	43.0	50.3	43.0	C30/37
5	36.6	44.6	36.6	C30/37
6	50.0	57.2	50.0	C40/50
7	47.0	54.4	47.0	C35/45
8	50.6	55.9	50.6	C40/50

Appendix B: Rapid Chloride Migration

In this appendix, the testing procedure for rapid chloride migration (non-steady-state) according to NT Build 492, is described. Furthermore, the results from this test are presented in Tables B.1-B.17. The tests was performed at 28 and 56 days age for specimen cured at either 20 °C or 55 °C

Cast cylinders with the size $\text{Ø}100 \times 200$ mm were tested. The cylinders were sawn perpendicularly to its axis into two halves and then 50 ± 2 mm slices were sawn from the first cut surface of each half piece. The specimens were thereafter placed in a vacuum container, where the pressure was reduced to 10-50 mbar within a few minutes. After the vacuum had been maintained for three hours, the container was filled with saturated $\text{Ca}(\text{OH})_2$ solution. The vacuum was maintained for a further hour before the air was allowed to fill the container. The specimens were kept in the solution for 18 ± 2 hours.

The cylinders from mixtures 1, 2, 5 and 6 were put in the vacuum container the same day as they were sawn and the cylinders from mixtures 3, 4, 7 and 8, were sawn the day before they were placed in the vacuum container.

A rubber sleeve was fit and secured with two clamps on each specimen. The specimens were thereafter placed on the plastic support in the catholyte solution (10% NaCl by mass in tap water). The sleeves were filled with 300 ml of the anolyte solution (0.3 M NaOH in de-mineralized water) and then the anodes were immersed in the anolyte solutions. An initial voltage of 30 V was applied and the voltage as well as the test duration was adjusted. The arrangement of the migration set-up is shown in Figure B.1.

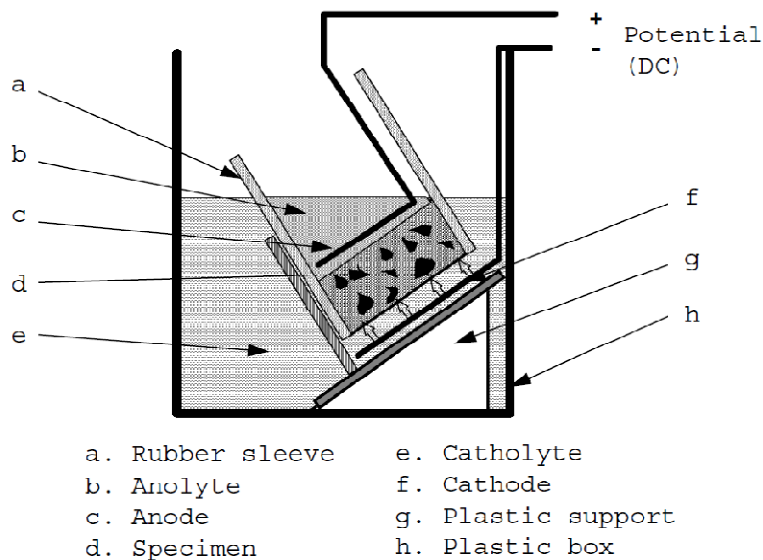


Figure B.1 Arrangement of the migration set-up [NORDTEST (1999)].

The specimens were disassembled and thereafter axially split into two pieces. Silver nitrate solution with 0.1 M was sprayed on both of the freshly split pieces. The penetration depths were measured at intervals of 10 mm and a mean value from the two pieces at each measured point were calculated. The depths closest to the edges were not measured, since possible leakage would give a higher value than the true.

The non-steady-state migration coefficients, D_{RCM} , were calculated from Equations (B.1)-(B.3):

$$D_{RCM} = \frac{RT}{zFE} \frac{x_d - \alpha \sqrt{x_d}}{t} \quad (B.1)$$

where

$$E = \frac{U-2}{L} \quad (B.2)$$

$$\alpha = 2 \sqrt{\frac{RT}{zFE}} \operatorname{erf}^{-1} \left(1 - \frac{2c_d}{c_0} \right) \quad (B.3)$$

D_{RCM} : non-steady-state migration coefficient, m^2/s ;

z : absolute value of ion valance, for chloride, $z=1$;

F : Faraday constant, $F=9.648 \times 10^4 \text{ J}/(\text{V} \cdot \text{mol})$;

U : absolute value of the applied voltage, V ;

R : gas constant, $R=8.314 \text{ J}/(\text{K} \cdot \text{mol})$;

T : average value of the initial and final temperatures in the anolyte solution, K ;

L : thickness of the specimen;

x_d : average value of the penetrations depths, m ;

erf^{-1} : inverse error function;

c_d : chloride concentration at which the colour changes, $c_d \approx 0.07 \text{ N}$ for OPC concrete

c_0 : chloride concentration in the catholyte solution, $c_0 \approx 2 \text{ N}$

The chloride concentration at which the colour of the concrete changes, when silver nitrate is sprayed on the specimens, is approximately the same for concrete with fly ash as for ordinary Portland cement concrete. Therefore, c_d is taken as 0.07 N for all specimens.

Table B.1 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 1 (20% fly ash, 55 °C) at 28 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 1 (20% fly ash, 55 °C)			
Age at the start of test, day:	28 days			
Mean value of D_{RCM}:	2.8	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	0.0	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	0.8	%		
Specimen No. * :	IIa	Ib	IIb	
Diameter d	100	100	100	mm
Thickness L	48.0	49.0	49.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	60.0	60.0	60.0	V
Current at start I_i	27.43	25.33	26.08	mA
Temperature at start T_i	294.16	294.16	294.16	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	48.8	41.2	49.5	mA
Temperature at end T_t	297.66	297.66	297.66	K
Average penetration depth x_d	13.0	12.6	12.6	mm
Migration coefficient D_{RCM}	2.8	2.8	2.8	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	13.5	12.0	14.0	mm
Penetration depth x_{d2}	13.0	12.0	12.5	mm
Penetration depth x_{d3}	12.5	12.0	12.5	mm
Penetration depth x_{d4}	12.5	12.5	12.5	mm
Penetration depth x_{d5}	13.0	13.0	12.5	mm
Penetration depth x_{d6}	13.0	13.0	12.0	mm
Penetration depth x_{d7}	13.5	14.0	12.5	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.2 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 2 (20% fly ash, 55 °C) at 28 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 2 (20% fly ash, 55 °C)			
Age at the start of test, day:	28 days			
Mean value of D_{RCM}:	2.8	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	0.2	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	6.7	%		
Specimen No. * :	Ib	IIa	IIb	
Diameter d	100	100	100	mm
Thickness L	50.0	48.0	51.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	60.0	60.0	60.0	V
Current at start I_i	23.72	24.39	22.75	mA
Temperature at start T_i	294.16	294.16	294.16	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	48.9	45.2	40.0	mA
Temperature at end T_t	297.56	297.56	297.56	K
Average penetration depth x_d	12.4	12.0	12.9	mm
Migration coefficient D_{RCM}	2.8	2.6	3.0	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	12.0	10.5	14.5	mm
Penetration depth x_{d2}	12.5	12.0	12.5	mm
Penetration depth x_{d3}	12.5	12.0	12.5	mm
Penetration depth x_{d4}	11.5	12.0	13.0	mm
Penetration depth x_{d5}	11.5	12.0	13.0	mm
Penetration depth x_{d6}	14.0	13.0	12.0	mm
Penetration depth x_{d7}	13.0	12.5	12.5	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.3 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 3 (20% fly ash, 20 °C) at 28 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 3 (20% fly ash, 20 °C)			
Age at the start of test, day:	28 days			
Mean value of D_{RCM}:	10.1	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	0.1	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	1.0	%		
Specimen No. * :	Ia	Ib	IIb	
Diameter d	100	100	100	mm
Thickness L	49.0	50.0	49.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	30.0	30.0	30.0	V
Current at start I_i	55.60	55.20	56.70	mA
Temperature at start T_i	295.66	295.66	295.66	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	58.3	55.4	58.2	mA
Temperature at end T_t	295.66	295.66	295.66	K
Average penetration depth x_d	21.9	21.9	22.2	mm
Migration coefficient D_{RCM}	10.0	10.2	10.1	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	21.0	22.5	22.5	mm
Penetration depth x_{d2}	22.5	22.0	23.0	mm
Penetration depth x_{d3}	21.5	22.0	22.0	mm
Penetration depth x_{d4}	22.5	22.0	22.0	mm
Penetration depth x_{d5}	22.5	22.0	22.0	mm
Penetration depth x_{d6}	21.0	22.0	22.0	mm
Penetration depth x_{d7}	22.0	20.5	22.0	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.4 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 4 (20% fly ash, 20 °C) at 28 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 4 (20% fly ash, 20 °C)			
Age at the start of test, day:	28 days			
Mean value of D_{RCM}:	12.3	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	0.7	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	5.5	%		
Specimen No. * :	Ib	IIa	IIb	
Diameter d	100	100	100	mm
Thickness L	49.0	48.0	50.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	25.0	25.0	25.0	V
Current at start I_i	54.80	56.40	57.20	mA
Temperature at start T_i	296.16	296.16	296.16	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	53.4	55.0	56.3	mA
Temperature at end T_t	295.66	295.66	295.66	K
Average penetration depth x_d	23.4	21.5	22.0	mm
Migration coefficient D_{RCM}	12.9	11.6	12.3	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	24.0	21.5	22.0	mm
Penetration depth x_{d2}	23.5	21.5	22.0	mm
Penetration depth x_{d3}	23.5	21.5	22.0	mm
Penetration depth x_{d4}	24.5	21.5	22.0	mm
Penetration depth x_{d5}	23.0	21.5	22.0	mm
Penetration depth x_{d6}	23.0	21.5	22.0	mm
Penetration depth x_{d7}	22.5	21.5	22.0	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.5 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 5 (20% fly ash, $k=1$, 20 °C) at 28 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 5 (20% fly ash, $k=1$, 20 °C)			
Age at the start of test, day:	28			
Mean value of D_{RCM}:	20.4	$\times 10^{-12}$ m ² /s		
Standard deviation:	0.6	$\times 10^{-12}$ m ² /s		
Coefficient of Variation:	2.8	%		
Specimen No. * :	IIa	Ib	IIb	
Diameter d	100	100	100	mm
Thickness L	47.0	48.0	49.5	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	15.0	15.0	15.0	V
Current at start I_i	60.20	60.00	59.50	mA
Temperature at start T_i	294.16	294.16	294.16	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	54.7	59.8	55.2	mA
Temperature at end T_t	295.16	295.16	295.16	K
Average penetration depth x_d	22.3	22.6	22.5	mm
Migration coefficient D_{RCM}	19.8	20.5	20.9	$\times 10^{-12}$ m ² /s
Individual chloride penetration depths				
Penetration depth x_{d1}	24.0	23.0	22.5	mm
Penetration depth x_{d2}	22.0	22.5	22.5	mm
Penetration depth x_{d3}	21.5	23.0	22.5	mm
Penetration depth x_{d4}	22.0	23.0	22.5	mm
Penetration depth x_{d5}	22.0	23.0	22.5	mm
Penetration depth x_{d6}	22.5	22.5	22.5	mm
Penetration depth x_{d7}	22.0	21.0	22.5	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.6 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 6 (0% fly ash, 20 °C) at 28 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 6 (0% fly ash, 20 °C)			
Age at the start of test, day:	28 days			
Mean value of D_{RCM}:	19.2	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	3.3	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	17.0	%		
Specimen No. * :	Ib	IIa	IIb	
Diameter d	100	100	100	mm
Thickness L	47.0	48.0	49.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	15.0	15.0	15.0	V
Current at start I_i	55.70	57.80	54.80	mA
Temperature at start T_i	294.16	294.16	294.16	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	45.9	47.5	50.3	mA
Temperature at end T_t	295.16	295.16	295.16	K
Average penetration depth x_d	19.0	20.3	24.6	mm
Migration coefficient D_{RCM}	16.6	18.2	22.9	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	19.5	21.0	25.0	mm
Penetration depth x_{d2}	19.0	20.0	24.5	mm
Penetration depth x_{d3}	19.0	20.5	24.5	mm
Penetration depth x_{d4}	19.0	20.5	25.0	mm
Penetration depth x_{d5}	19.0	20.5	24.5	mm
Penetration depth x_{d6}	19.0	20.0	24.5	mm
Penetration depth x_{d7}	18.5	19.5	24.0	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.7 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 7 (0% fly ash, 20 °C) at 28 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 7 (0% fly ash, 20 °C)			
Age at the start of test, day:	28 days			
Mean value of D_{RCM}:	16.6	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	1.0	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	6.2	%		
Specimen No. * :	Ib	IIa	Ia	
Diameter d	100	100	100	mm
Thickness L	46.5	51.0	49.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	20.0	20.0	20.0	V
Current at start I_i	80.70	67.40	78.20	mA
Temperature at start T_i	293.16	293.16	293.16	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	72.9	59.3	68.4	mA
Temperature at end T_t	296.16	296.16	296.16	K
Average penetration depth x_d	24.5	22.3	25.6	mm
Migration coefficient D_{RCM}	16.1	15.9	17.8	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	25.5	21.5	25.0	mm
Penetration depth x_{d2}	25.0	21.5	25.5	mm
Penetration depth x_{d3}	24.5	23.0	24.5	mm
Penetration depth x_{d4}	23.5	23.0	24.5	mm
Penetration depth x_{d5}	24.0	22.0	26.5	mm
Penetration depth x_{d6}	24.5	21.5	27.0	mm
Penetration depth x_{d7}		23.5	26.5	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.8 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 8 (6% fly ash, 20 °C) at 28 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 8 (6% fly ash, 20 °C)			
Age at the start of test, day:	28 days			
Mean value of D_{RCM}:	18.4	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	0.7	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	3.7	%		
Specimen No. * :	IIa	Ib	IIb	
Diameter d	100	100	100	mm
Thickness L	48.0	49.0	53.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	20.0	20.0	20.0	V
Current at start I_i	79.70	72.50	66.30	mA
Temperature at start T_i	293.16	293.16	293.16	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	67.4	60.1	58.1	mA
Temperature at end T_t	295.16	295.16	295.16	K
Average penetration depth x_d	26.0	26.4	25.6	mm
Migration coefficient D_{RCM}	17.7	18.3	19.1	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	29.0	28.0	25.0	mm
Penetration depth x_{d2}	27.0	25.5	25.5	mm
Penetration depth x_{d3}	27.0	24.5	25.5	mm
Penetration depth x_{d4}	25.5	26.0	26.0	mm
Penetration depth x_{d5}	25.5	26.0	25.5	mm
Penetration depth x_{d6}	24.0	26.5	25.5	mm
Penetration depth x_{d7}	24.0	28.0	26.5	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.9 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 5 (20% fly ash, $k=1.0$, $55\text{ }^{\circ}\text{C}$) at 28 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 5 (20% fly ash, $k=1.0$, $55\text{ }^{\circ}\text{C}$)		
Age at the start of test, day:	28 days		
Mean value of D_{RCM}:	7.1	$\times 10^{-12}$	m^2/s
Standard deviation:	0.0	$\times 10^{-12}$	m^2/s
Coefficient of Variation:	0.1	%	
Specimen No. * :	1	2	
Diameter d	100	100	mm
Thickness L	48.0	49.0	mm
Chloride concentration c_0	10	10	NaCl%
Applied potential U	30.0	30.0	V
Current at start I_i	50.00	60.00	mA
Temperature at start T_i	293	293	K
Test duration t	24.0	24.0	hr
Current at end I_t	110.0	170.0	mA
Temperature at end T_t	293	293	K
Average penetration depth x_d	16.3	16.0	mm
Migration coefficient D_{RCM}	7.1	7.1	$\times 10^{-12} \text{m}^2/\text{s}$
Individual chloride penetration depths			
Penetration depth x_{d1}	15.0	16.0	mm
Penetration depth x_{d2}	16.0	16.0	mm
Penetration depth x_{d3}	18.0	16.0	mm
Penetration depth x_{d4}	19.0	16.0	mm
Penetration depth x_{d5}	16.0	16.0	mm
Penetration depth x_{d6}	15.0	16.0	mm
Penetration depth x_{d7}	15.0	16.0	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.10 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 1 (20% fly ash, 55 °C) at 56 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 1 (20% fly ash, 55 °C)			
Age at the start of test, day:	56 days			
Mean value of D_{RCM}:	1.6	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	0.3	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	16.4	%		
Specimen No. * :	Ia	Ib	IIa	
Diameter d	100	100	100	mm
Thickness L	51.0	50.0	51.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	60.0	60.0	60.0	V
Current at start I_i	21	23	24	mA
Temperature at start T_i	294.16	294.16	294.16	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	37	47	45	mA
Temperature at end T_t	297.66	297.66	297.66	K
Average penetration depth x_d	6.4	7.0	8.5	mm
Migration coefficient D_{RCM}	1.4	1.5	1.9	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	7.0	7.0	7.0	mm
Penetration depth x_{d2}	6.5	7.0	8.0	mm
Penetration depth x_{d3}	6.5	7.0	9.0	mm
Penetration depth x_{d4}	6.5	7.0	9.0	mm
Penetration depth x_{d5}	6.5	7.0	9.0	mm
Penetration depth x_{d6}	6.0	7.0	9.0	mm
Penetration depth x_{d7}	6.0	7.0	8.5	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.11 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 2 (20% fly ash, 55 °C) at 56 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 2 (20% fly ash, 55 °C)			
Age at the start of test, day:	56 days			
Mean value of D_{RCM}:	1.5	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	0.1	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	8.3	%		
Specimen No. * :	Ia	Ib	IIa	
Diameter d	100	100	100	mm
Thickness L	51.0	50.0	51.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	60.0	60.0	60.0	V
Current at start I_i	21	22	21	mA
Temperature at start T_i	294.16	294.16	294.16	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	36	54	40	mA
Temperature at end T_t	297.66	297.66	297.66	K
Average penetration depth x_d	7.1	6.9	6.1	mm
Migration coefficient D_{RCM}	1.6	1.5	1.3	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	7.0	7.0	7.0	mm
Penetration depth x_{d2}	7.0	7.5	7.0	mm
Penetration depth x_{d3}	7.5	7.0	7.0	mm
Penetration depth x_{d4}	7.0	7.0	7.0	mm
Penetration depth x_{d5}	7.5	8.0	0.5	mm
Penetration depth x_{d6}	7.5	6.0	7.0	mm
Penetration depth x_{d7}	6.5	6.0	7.5	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.12 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 3 (20% fly ash, 20 °C) at 56 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 3 (20% fly ash, 20 °C)			
Age at the start of test, day:	56 days			
Mean value of D_{RCM}:	5.3	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	0.4	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	7.8	%		
Specimen No. * :	Ia	Ib	IIb	
Diameter d	100	100	100	mm
Thickness L	48.0	49.0	50.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	30.0	30.0	30.0	V
Current at start I_i	41	40	48	mA
Temperature at start T_i	294.66	294.66	294.66	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	40	39	49	mA
Temperature at end T_t	296.16	296.16	296.16	K
Average penetration depth x_d	12.8	12.8	11.0	mm
Migration coefficient D_{RCM}	5.5	5.6	4.8	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	14.0	12.0	13.5	mm
Penetration depth x_{d2}	14.5	12.0	11.5	mm
Penetration depth x_{d3}	13.0	12.5	10.0	mm
Penetration depth x_{d4}	11.5	13.0	10.0	mm
Penetration depth x_{d5}	12.5	13.5	10.0	mm
Penetration depth x_{d6}	12.5	13.5	10.0	mm
Penetration depth x_{d7}	11.5	13.0	12.0	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.13 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 4 (20% fly ash, 20 °C) at 56 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 4 (20% fly ash, 20 °C)			
Age at the start of test, day:	56 days			
Mean value of D_{RCM}:	7.8	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	0.2	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	2.9	%		
Specimen No. * :	Ia	Ib	IIb	
Diameter d	100	100	100	mm
Thickness L	52.0	49.0	50.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	30.0	30.0	30.0	V
Current at start I_i	45	49	39	mA
Temperature at start T_i	294.66	294.66	294.66	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	43	47	38	mA
Temperature at end T_t	296.16	296.16	296.16	K
Average penetration depth x_d	16.5	17.7	16.5	mm
Migration coefficient D_{RCM}	7.8	8.0	7.5	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	17.0	17.0	19.0	mm
Penetration depth x_{d2}	17.0	17.5	17.5	mm
Penetration depth x_{d3}	17.0	19.0	16.5	mm
Penetration depth x_{d4}	15.0	18.5	16.5	mm
Penetration depth x_{d5}	16.0	19.0	16.0	mm
Penetration depth x_{d6}	17.0	17.0	14.5	mm
Penetration depth x_{d7}	16.5	16.0	15.5	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.14 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 5 (20% fly ash, $k=1.0$, 20 °C) at 56 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 5 (20% fly ash, $k=1.0$, 20 °C)		
Age at the start of test, day:	56		
Mean value of D_{RCM}:	14.0	$\times 10^{-12}$ m ² /s	
Standard deviation:	1.4	$\times 10^{-12}$ m ² /s	
Coefficient of Variation:	10.1	%	
Specimen No. * :	Ia	Ib	
Diameter d	100	100	mm
Thickness L	51.0	53.0	mm
Chloride concentration c_0	10	10	NaCl%
Applied potential U	25.0	25.0	V
Current at start I_i	66	66	mA
Temperature at start T_i	294.16	294.16	K
Test duration t	24.0	24.0	hr
Current at end I_t	61	65	mA
Temperature at end T_t	296.16	296.16	K
Average penetration depth x_d	26.1	22.1	mm
Migration coefficient D_{RCM}	15.0	13.0	$\times 10^{-12}$ m ² /s
Individual chloride penetration depths			
Penetration depth x_{d1}	26.0	22.5	mm
Penetration depth x_{d2}	26.0	22.5	mm
Penetration depth x_{d3}	26.0	22.0	mm
Penetration depth x_{d4}	26.5	22.0	mm
Penetration depth x_{d5}	26.5	22.0	mm
Penetration depth x_{d6}	25.5	22.0	mm
Penetration depth x_{d7}	26.0	22.0	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.15 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 6 (0% fly ash, 20 °C) at 56 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 6 (0% fly ash, 20 °C)			
Age at the start of test, day:	56			
Mean value of D_{RCM}:	14.6	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	0.8	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	5.3	%		
Specimen No. * :	Ia	Ib	IIa	
Diameter d	100	100	100	mm
Thickness L	50.5	50.0	51.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	20.0	20.0	20.0	V
Current at start I_i	62	60	64	mA
Temperature at start T_i	294.16	294.16	294.16	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	52	51	52	mA
Temperature at end T_t	296.16	296.16	296.16	K
Average penetration depth x_d	21.1	19.8	21.4	mm
Migration coefficient D_{RCM}	14.8	13.7	15.2	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	21.5	18.5	22.0	mm
Penetration depth x_{d2}	21.0	19.5	21.5	mm
Penetration depth x_{d3}	21.0	20.0	21.5	mm
Penetration depth x_{d4}	20.0	20.5	21.5	mm
Penetration depth x_{d5}	20.5	20.5	21.5	mm
Penetration depth x_{d6}	21.5	19.5	20.5	mm
Penetration depth x_{d7}	22.0	20.0	21.5	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.16 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 7 (0% fly ash, 20 °C) at 56 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 7 (0% fly ash, 20 °C)			
Age at the start of test, day:	56			
Mean value of D_{RCM}:	13.3	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	1.1	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	8.2	%		
Specimen No. * :	Ia	Ib	IIb	
Diameter d	100	100	100	mm
Thickness L	51.0	51.0	51.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	20.0	20.0	20.0	V
Current at start I_i	62	61	64	mA
Temperature at start T_i	294.66	294.66	294.66	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	51	49	52	mA
Temperature at end T_t	294.66	294.66	294.66	K
Average penetration depth x_d	17.3	19.9	19.6	mm
Migration coefficient D_{RCM}	12.0	14.0	13.8	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	17.5	20.5	19.5	mm
Penetration depth x_{d2}	17.0	20.5	19.5	mm
Penetration depth x_{d3}	17.0	20.5	20.5	mm
Penetration depth x_{d4}	17.0	20.5	20.0	mm
Penetration depth x_{d5}	17.0	20.0	18.5	mm
Penetration depth x_{d6}	17.5	19.0	18.5	mm
Penetration depth x_{d7}	18.0	18.5	20.5	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Table B.17 Results from chloride migration coefficient, D_{RCM} , from non-steady state migration experiments for mixture 8 (6% fly ash, 20 °C) at 56 days age. Tested according to NT Build 492.

Specimen ID:	Mixture 8 (6% fly ash, 20 °C)			
Age at the start of test, day:	56			
Mean value of D_{RCM}:	13.4	$\times 10^{-12} \text{ m}^2/\text{s}$		
Standard deviation:	0.2	$\times 10^{-12} \text{ m}^2/\text{s}$		
Coefficient of Variation:	1.2	%		
Specimen No. *	Ia	Ib	IIb	
Diameter d	100	100	100	mm
Thickness L	52.0	50.0	49.0	mm
Chloride concentration c_0	10	10	10	NaCl%
Applied potential U	20.0	20.0	20.0	V
Current at start I_i	65	60	63	mA
Temperature at start T_i	295.16	295.16	295.16	K
Test duration t	24.0	24.0	24.0	hr
Current at end I_t	50	48	49	mA
Temperature at end T_t	294.66	294.66	294.66	K
Average penetration depth x_d	18.8	19.7	19.6	mm
Migration coefficient D_{RCM}	13.4	13.6	13.3	$\times 10^{-12} \text{ m}^2/\text{s}$
Individual chloride penetration depths				
Penetration depth x_{d1}	20.0	19.5	19.5	mm
Penetration depth x_{d2}	20.0	21.0	19.5	mm
Penetration depth x_{d3}	18.5	19.0	20.5	mm
Penetration depth x_{d4}	18.0	20.0	19.5	mm
Penetration depth x_{d5}	18.0	19.0	18.5	mm
Penetration depth x_{d6}	18.0	20.0	19.0	mm
Penetration depth x_{d7}	19.0	19.5	21.0	mm

*The specimen no. with the same roman numbers are sawn from the same cylinder.

Appendix C: Scaling under freeze/thaw

The results from scaling under freezing and thawing for concrete tested according to SS 13 72 44 are presented in this appendix:

- Measured values [g] after each seven cycles are presented in Table C.1.
- Accumulated values [kg/m^2] after each seven cycles are presented in Tables C.2-C.12.
- Diagrams with accumulated values for each specimen after each seven cycles are shown in Figures C.1-C.11
- Accuracy, by means of coefficient of variation, from each mixture, compared with the estimated accuracy of the method, is shown in Figures C.12-C.23.
- Photos of the specimen, after being exposed to 112 freeze/thaw cycles are shown in Figures C.24-C56.

Table C.1 Measured values from scaling at freezing.

Mixture	Curing regime	Specimen	Scaled material [g] (after each 7th cycle)															
			7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112
1 (20% FA, $k=0.4$)	28 d, 55 °C	I	0.360	0.155	0.047	0.079 ^b	0.087	0.164	0.171	0.171	0.195	0.211	0.143	0.168	0.155	0.165 ^a	0.173	0.244
		II	0.709	0.198	0.088	0.075 ^b	0.098	0.102	0.070	0.133	0.117	0.094	0.072	0.113	0.158	0.166	0.169	0.218
		III	0.191	0.158	0.066	0.058 ^b	0.126	0.070	0.122	0.224	0.247	0.211	0.211	0.179	0.154	0.124	0.226	0.226
		IV	0.321	0.061	0.127	0.033 ^b	0.032	0.028	0.056	0.072	0.061	0.085	0.088	0.113	0.088	0.087	0.108	0.121
2 (20% FA, $k=0.4$)	42 d, 55 °C	I	0.396	0.120 ^b	0.068	0.169	0.122	0.114	0.125	0.134	0.170	0.125	0.162	0.173	0.282	0.268	0.359	1.119
		II	0.379	0.065 ^b	0.085	0.033	0.033	0.162	0.092	0.155	0.133	0.187	0.211	0.231	0.320	0.351	0.445	0.645
		III	0.372	0.101 ^b	0.072	0.199	0.131	0.028 ^a	0.128	0.054	0.007	0.026	0.003	0.008	0.019	0.006	0.009	0.006
		IV	0.347	0.091 ^b	0.099	0.221	0.048 ^a	0.174 ^a	0.024	0.010 ^a	0.006	0.004	0.002	0.004	0.002	0.002	0.005	0.000 ^a
3 (20% FA, $k=0.4$)	56 d, 20 °C	I	0.397	0.114	0.127	0.242	0.132	0.091	0.166	0.044	0.052	0.140	0.128	0.152	0.106	0.136	0.193	0.169
		II	0.286	0.082	0.175	0.096	0.080	0.065	0.069	0.078	0.083	0.065	0.138	0.100	0.081	0.187	0.094	0.108
	90 d, 20 °C	I	0.352	0.144	0.068	0.096	0.047	0.047	0.090	0.068	0.082	0.139	0.079	0.179	0.134	0.090 ^a	0.088 ^a	0.056
		II	0.380	0.158	0.124	0.085	0.102	0.129	0.166	0.096	0.076	0.116	0.118	0.122 ^a	0.026 ^a	0.053	0.012	0.028
4 (20% FA, $k=0.4$)	Standard	III	0.498	0.140	0.037	0.048	0.036	0.143	0.191	0.112	0.139	0.141	0.101 ^a	0.040 ^a	0.038	0.006	0.006 ^a	0.006 ^a
		IV	0.040	0.036	0.012	0.019	0.021 ^b	0.046	0.073	0.044 ^a	0.019 ^a	0.013 ^a	0.017	0.014	0.006	0.006	0.011	0.013
		I	0.122	0.032	0.032	0.020	0.028 ^b	0.009	0.109	0.020 ^a	0.035	0.146	0.035	0.145	0.173	0.012 ^a	0.011	0.009
		II ^c	0.147	0.055	0.039	0.032	0.022 ^b	0.038	0.030	0.038	0.031	0.041	0.030	0.036	0.024	0.042	0.035	0.078
		III	0.379	0.086	0.018	0.005	0.017 ^b	0.026	0.006	0.004 ^a	0.017	0.027	0.037	0.016	0.028	0.011	0.014	0.030
		IV	0.040	0.036	0.012	0.019	0.021 ^b	0.046	0.073	0.044 ^a	0.019 ^a	0.013 ^a	0.017	0.014	0.006	0.006	0.011	0.013

^a Salt solution leaked.

^b Value measured one day before, e.g. the values at 28 cycles is measured after 27 cycles.

^c Tested for air void analysis

Table C.1 cont.

Mixture	Curing regime	Specimen	Scaled material [g] (after each 7th cycle)															
			7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112
5 (20% FA, $k=1.0$)	63 d, 20 °C	I	0.203	0.114	0.285	0.387	0.373	0.188	0.130	0.180	0.288	0.299	0.234	0.366	0.463	0.471	0.555	0.524
		II	0.209	0.105	0.447	0.565	0.333	0.152	0.169	0.271	0.340	0.397	0.434	0.485	0.578	0.659	0.576	0.657
	90 d, 20 °C	I	0.357	0.084	0.086	0.358	0.179	0.120	0.075	0.080	0.078	0.106	0.080	0.107	0.028 ^a	0.013 ^a	0.045 ^a	0.061
		II	0.363	0.114	0.133	0.398	0.386	0.220	0.126	0.131	0.146	0.163	0.116	0.140	0.069 ^a	0.143	0.235	0.032
	28 d, 55 °C	I	0.374	0.042	0.015 ^b	0.034	0.045	0.081	0.091	0.074	0.073	0.075 ^a	0.019 ^a	0.015 ^a	0.008 ^a	0.013 ^a	0.012	0.003
		II	0.383	0.092	0.017 ^b	0.022	0.030	0.035	0.067	0.051	0.050	0.038	0.028	0.043	0.053	0.048	0.038	0.029
6 (0% FA)	Standard	I	0.417	0.079	0.033	0.032 ^b	0.023	0.042	0.054	0.072 ^a	0.032	0.027	0.015	0.009 ^a	0.010	0.004	0.003 ^a	0.003
		II	0.248 ^a	0.153 ^a	0.187 ^a	0.042 ^{a,b}	0.007 ^a	0.016 ^a	0.006 ^a	0.012 ^a	0.029 ^a	0.022	0.011	0.018	0.030	0.021	0.032 ^a	0.028
		III	0.434	0.105	0.072	0.058 ^b	0.069	0.063	0.088	0.048 ^a	0.049 ^a	0.041	0.008 ^a	0.008 ^a	0.004 ^a	0.005 ^a	0.004	0.001 ^a
		IV	0.711	0.278	0.221	0.139 ^b	0.194	0.243	0.204	0.369	0.339	0.404	0.487	0.351 ^a	0.126 ^a	0.110	0.049	0.036
7 (0% FA)	Standard	I	0.220	0.111	0.078	0.101 ^b	0.064	0.035	0.065 ^a	0.033 ^a	0.024	0.024	0.006 ^a	0.021 ^a	0.005 ^a	0.009	0.005	0.013
		II ^c	0.658	0.132	0.137	0.066 ^b	0.050	0.039	0.013	0.117 ^a	0.031	0.024	0.033	0.021	0.021	0.028 ^a	0.013 ^a	0.007
		III	0.511	0.183	0.124	0.039 ^b	0.034	0.027	0.042	0.023	0.026	0.040	0.030	0.015 ^a	0.024	0.042	0.043	0.042
		IV	1.175	0.407	0.205	0.171 ^b	0.282 ^a	0.198 ^a	0.298	0.063	0.052	0.106	0.151 ^a	0.013 ^a	0.009 ^a	0.006	0.002	0.002
8 (6% FA, $k=0.4$)	Standard	I	0.183	0.048	0.052	0.037 ^b	0.074	0.086	0.090	0.096	0.091	0.073 ^a	0.052	0.050	0.011 ^a	0.013	0.012	0.007
		II	0.280	0.132	0.032	0.020 ^b	0.046	0.104	0.062	0.088 ^a	0.050	0.083	0.066 ^a	0.051	0.015 ^a	0.014	0.005	0.006
		III	0.211	0.099	0.045	0.075 ^b	0.122	0.096	0.118	0.181	0.121	0.091	0.042 ^a	0.032	0.011	0.015	0.011 ^a	0.013 ^a
		IV	0.538	0.137	0.031 ^b	0.004	0.007	0.011	0.011	0.013	0.024	0.020 ^a	0.078 ^a	0.009 ^a	0.001	0.000	0.000	0.001 ^a

^a Salt solution leaked.

^b Value measured one day before, e.g. the values at 28 cycles is measured after 27 cycles.

^c Tested for air void analysis

Table C.2 Results from scaling at freezing SS 13 72 44, method IA, for mixture 1 (20% fly ash, $k=0.4$, 55 °C, 28 d), accumulated values [kg/m^2]

Specimen	m ₇	m ₁₄	m ₂₁	m ₂₈	m ₃₅	m ₄₂	m ₄₉	m ₅₆	m ₆₃	m ₇₀	m ₇₇	m ₈₄	m ₉₁	m ₉₈	m ₁₀₅	m ₁₁₂	m ₅₆ /m ₂₈	m ₁₁₂ /m ₅₆
I	0.016	0.023	0.025	0.028	0.032	0.040	0.047	0.055	0.064	0.073	0.079	0.087	0.094	0.101	0.109	0.119		
II	0.032	0.040	0.044	0.048	0.052	0.056	0.060	0.065	0.071	0.075	0.078	0.083	0.090	0.097	0.105	0.115		
III	0.008	0.016	0.018	0.021	0.027	0.030	0.035	0.045	0.056	0.065	0.075	0.083	0.090	0.095	0.105	0.115		
IV	0.014	0.017	0.023	0.024	0.026	0.027	0.029	0.032	0.035	0.039	0.043	0.048	0.052	0.056	0.060	0.066		
Mean value	0.018	0.024	0.028	0.030	0.034	0.038	0.043	0.049	0.056	0.063	0.069	0.075	0.081	0.087	0.095	0.104	1.63	2.10
Standard deviation	0.010	0.011	0.011	0.012	0.012	0.013	0.013	0.014	0.015	0.017	0.017	0.018	0.020	0.021	0.023	0.025		
Coefficient of variation [%]	56.0	47.6	41.5	39.3	35.9	35.1	31.4	28.4	27.2	26.3	25.3	24.3	24.3	24.3	24.2	24.5		

Table C.3 Results from scaling at freezing SS 13 72 44, method IA, for mixture 2 (20% fly ash, $k=0.4$, 55 °C, 42 d), accumulated values [kg/m^2]

Specimen	m ₇	m ₁₄	m ₂₁	m ₂₈	m ₃₅	m ₄₂	m ₄₉	m ₅₆	m ₆₃	m ₇₀	m ₇₇	m ₈₄	m ₉₁	m ₉₈	m ₁₀₅	m ₁₁₂	m ₅₆ /m ₂₈	m ₁₁₂ /m ₅₆
I	0.018	0.023	0.026	0.033	0.039	0.044	0.050	0.055	0.063	0.069	0.076	0.083	0.096	0.108	0.124	0.174		
II	0.017	0.020	0.024	0.025	0.026	0.034	0.038	0.045	0.051	0.059	0.068	0.078	0.093	0.108	0.128	0.157		
III	0.017	0.021	0.024	0.033	0.039	0.040	0.046	0.048	0.049	0.050	0.050	0.050	0.051	0.051	0.052	0.052		
IV	0.015	0.019	0.024	0.034	0.036	0.044	0.045	0.045	0.045	0.046	0.046	0.046	0.046	0.046	0.046	0.046		
Mean value	0.017	0.021	0.024	0.031	0.035	0.040	0.044	0.048	0.052	0.056	0.060	0.064	0.071	0.078	0.087	0.107	1.54	2.22
Standard deviation	0.001	0.002	0.001	0.004	0.006	0.005	0.005	0.005	0.008	0.010	0.014	0.019	0.027	0.034	0.045	0.067		
Coefficient of variation [%]	5.4	7.6	4.4	13.5	16.8	11.8	11.1	10.4	14.9	18.4	24.2	29.8	37.3	43.9	51.0	62.9		

Table C.4 Results from scaling at freezing SS 13 72 44, method IA, for mixture 3 (20% fly ash, $k=0.4$, 20 °C, 56 d), accumulated values [kg/m^2]

Specimen	m_7	m_{14}	m_{21}	m_{28}	m_{35}	m_{42}	m_{49}	m_{56}	m_{63}	m_{70}	m_{77}	m_{84}	m_{91}	m_{98}	m_{105}	m_{112}	m_{56}/m_{28}	m_{112}/m_{56}
I	0.018	0.023	0.028	0.039	0.045	0.049	0.056	0.058	0.061	0.067	0.073	0.079	0.084	0.090	0.099	0.106		
II	0.013	0.016	0.024	0.028	0.032	0.035	0.038	0.041	0.045	0.048	0.054	0.059	0.062	0.070	0.075	0.079		
Mean value	0.015	0.020	0.026	0.034	0.038	0.042	0.047	0.050	0.053	0.057	0.063	0.069	0.073	0.080	0.087	0.093	1.48	1.86
Standard deviation	0.003	0.004	0.003	0.008	0.009	0.010	0.013	0.012	0.011	0.013	0.013	0.015	0.015	0.014	0.017	0.019		
Coefficient of variation [%]	23.0	23.0	11.4	22.4	23.9	23.9	27.7	24.1	20.9	23.3	20.6	21.3	21.2	17.3	19.6	20.4		

Table C.5 Results from scaling at freezing SS 13 72 44, method IA for mixture 3 (20% fly ash, $k=0.4$, 20 °C, 90 d), accumulated values [kg/m^2]

Specimen	m_7	m_{14}	m_{21}	m_{28}	m_{35}	m_{42}	m_{49}	m_{56}	m_{63}	m_{70}	m_{77}	m_{84}	m_{91}	m_{98}	m_{105}	m_{112}	m_{56}/m_{28}	m_{112}/m_{56}
I	0.016	0.022	0.025	0.029	0.031	0.034	0.038	0.041	0.044	0.050	0.054	0.062	0.068	0.072	0.076	0.078		
II	0.017	0.024	0.029	0.033	0.038	0.043	0.051	0.055	0.058	0.064	0.069	0.074	0.075	0.078	0.078	0.080		
III	0.022	0.028	0.030	0.032	0.034	0.040	0.049	0.054	0.060	0.066	0.070	0.072	0.074	0.074	0.074	0.075		
Mean value	0.018	0.025	0.028	0.032	0.034	0.039	0.046	0.050	0.054	0.060	0.064	0.069	0.072	0.075	0.076	0.078	1.58	1.56
Standard deviation	0.003	0.003	0.003	0.002	0.003	0.005	0.007	0.008	0.009	0.008	0.009	0.007	0.004	0.003	0.002	0.002		
Coefficient of variation [%]	18.9	13.1	9.6	6.3	9.3	13.0	15.6	16.1	16.0	14.1	14.2	9.6	5.6	4.1	2.6	3.2		

Table C.6 Results from scaling at freezing SS 13 72 44, method IA for mixture 4 (20% fly ash, $k=0.4$, standard), accumulated values [kg/m^2]

Specimen	m ₇	m ₁₄	m ₂₁	m ₂₈	m ₃₅	m ₄₂	m ₄₉	m ₅₆	m ₆₃	m ₇₀	m ₇₇	m ₈₄	m ₉₁	m ₉₈	m ₁₀₅	m ₁₁₂	m ₅₆ /m ₂₈	m ₁₁₂ /m ₅₆
I	0.005	0.007	0.008	0.009	0.010	0.011	0.016	0.017	0.018	0.025	0.026	0.033	0.040	0.041	0.041	0.042		
II	0.007	0.009	0.011	0.012	0.013	0.015	0.016	0.018	0.019	0.021	0.022	0.024	0.025	0.027	0.028	0.032		
III	0.017	0.021	0.021	0.022	0.022	0.024	0.024	0.024	0.025	0.026	0.028	0.028	0.030	0.030	0.031	0.032		
IV	0.002	0.003	0.004	0.005	0.006	0.008	0.011	0.013	0.014	0.014	0.015	0.016	0.016	0.016	0.017	0.017		
Mean value	0.008	0.010	0.011	0.012	0.013	0.014	0.017	0.018	0.019	0.021	0.023	0.025	0.028	0.029	0.029	0.031	1.49	1.72
Standard deviation	0.006	0.007	0.007	0.007	0.007	0.007	0.005	0.005	0.005	0.005	0.006	0.007	0.010	0.010	0.010	0.010		
Coefficient of variation [%]	84.5	75.2	67.3	60.1	54.7	48.4	32.1	26.0	23.9	24.2	24.5	28.6	36.4	35.4	34.3	32.7		

Table C.7 Results from scaling at freezing SS 13 72 44, method IA for mixture 5 (20% fly ash, $k=1.0$, 20 °C, 63 d), accumulated values [kg/m^2]

Specimen	m ₇	m ₁₄	m ₂₁	m ₂₈	m ₃₅	m ₄₂	m ₄₉	m ₅₆	m ₆₃	m ₇₀	m ₇₇	m ₈₄	m ₉₁	m ₉₈	m ₁₀₅	m ₁₁₂	m ₅₆ /m ₂₈	m ₁₁₂ /m ₅₆
I	0.009	0.014	0.027	0.044	0.061	0.069	0.075	0.083	0.095	0.109	0.119	0.135	0.156	0.177	0.202	0.225		
II	0.009	0.014	0.034	0.059	0.074	0.080	0.088	0.100	0.115	0.133	0.152	0.174	0.199	0.229	0.254	0.283		
Mean value	0.009	0.014	0.030	0.051	0.067	0.075	0.081	0.091	0.105	0.121	0.136	0.155	0.178	0.203	0.228	0.254	1.78	2.78
Standard deviation	0.000	0.000	0.005	0.011	0.009	0.008	0.009	0.012	0.014	0.017	0.023	0.027	0.031	0.037	0.037	0.041		
Coefficient of variation [%]	2.1	0.7	16.5	20.6	13.9	11.0	11.6	13.5	13.2	14.1	17.2	17.5	17.2	18.0	16.3	16.3		

Table C.8 Results from scaling at freezing SS 13 72 44, method IA for mixture 5 (20% fly ash, $k=1.0$, 20 °C, 90 d), accumulated values [kg/m^2]

Specimen	m ₇	m ₁₄	m ₂₁	m ₂₈	m ₃₅	m ₄₂	m ₄₉	m ₅₆	m ₆₃	m ₇₀	m ₇₇	m ₈₄	m ₉₁	m ₉₈	m ₁₀₅	m ₁₁₂	m ₅₆ /m ₂₈	m ₁₁₂ /m ₅₆
I	0.016	0.020	0.023	0.039	0.047	0.053	0.056	0.060	0.063	0.068	0.071	0.076	0.077	0.078	0.080	0.083		
II	0.016	0.021	0.027	0.045	0.062	0.072	0.077	0.083	0.090	0.097	0.102	0.108	0.111	0.118	0.128	0.130		
Mean value	0.016	0.020	0.025	0.042	0.055	0.062	0.067	0.071	0.076	0.082	0.087	0.092	0.094	0.098	0.104	0.106	1.70	1.49
Standard deviation	0.000	0.001	0.003	0.004	0.010	0.014	0.015	0.017	0.019	0.021	0.022	0.023	0.024	0.028	0.034	0.033		
Coefficient of variation [%]	1.2	5.5	10.3	9.2	19.0	21.7	22.7	23.4	24.7	25.1	25.1	24.8	25.6	28.8	32.9	31.4		

Table C.9 Results from scaling at freezing SS 13 72 44, method IA for mixture 5 (20% fly ash, $k=1.0$, 55 °C, 28 d), accumulated values [kg/m^2]

Specimen	m ₇	m ₁₄	m ₂₁	m ₂₈	m ₃₅	m ₄₂	m ₄₉	m ₅₆	m ₆₃	m ₇₀	m ₇₇	m ₈₄	m ₉₁	m ₉₈	m ₁₀₅	m ₁₁₂	m ₅₆ /m ₂₈	m ₁₁₂ /m ₅₆
I	0.017	0.018	0.019	0.021	0.023	0.026	0.030	0.034	0.037	0.040	0.041	0.042	0.042	0.043	0.043	0.043		
II	0.017	0.021	0.022	0.023	0.024	0.026	0.029	0.031	0.033	0.035	0.036	0.038	0.040	0.043	0.044	0.046		
Mean value	0.017	0.020	0.021	0.022	0.023	0.026	0.030	0.032	0.035	0.038	0.039	0.040	0.041	0.043	0.044	0.044	1.48	1.38
Standard deviation	0.000	0.002	0.002	0.002	0.001	0.000	0.001	0.002	0.003	0.004	0.003	0.003	0.001	0.000	0.001	0.002		
Coefficient of variation [%]	1.7	9.4	9.3	7.1	4.6	1.5	3.8	5.7	7.4	10.0	9.0	6.5	2.8	0.1	1.7	3.5		

Table C.10 Results from scaling at freezing SS 13 72 44, method IA for mixture 6 (0% fly ash, standard), accumulated values [kg/m²]

Specimen	m ₇	m ₁₄	m ₂₁	m ₂₈	m ₃₅	m ₄₂	m ₄₉	m ₅₆	m ₆₃	m ₇₀	m ₇₇	m ₈₄	m ₉₁	m ₉₈	m ₁₀₅	m ₁₁₂	m ₅₆ /m ₂₈	m ₁₁₂ /m ₅₆
I	0.019	0.022	0.024	0.025	0.026	0.028	0.030	0.033	0.035	0.036	0.037	0.037	0.038	0.038	0.038	0.038		
II ^a	0.011	0.018	0.026	0.028	0.028	0.029	0.029	0.030	0.031	0.032	0.033	0.033	0.035	0.036	0.037	0.038		
III	0.019	0.024	0.027	0.030	0.033	0.036	0.040	0.042	0.044	0.046	0.046	0.046	0.047	0.047	0.047	0.047		
IV	0.032	0.044	0.054	0.060	0.069	0.079	0.088	0.105	0.120	0.138	0.160	0.175	0.181	0.186	0.188	0.189		
Mean value	0.023	0.030	0.035	0.038	0.042	0.048	0.053	0.060	0.066	0.073	0.081	0.086	0.088	0.090	0.091	0.091	1.57	1.52
Mean value 2 ^b	0.019	0.023	0.025	0.027	0.029	0.032	0.035	0.038	0.039	0.041	0.041	0.042	0.042	0.042	0.042	0.042	1.37	1.13
Standard deviation	0.007	0.012	0.017	0.019	0.023	0.028	0.031	0.039	0.047	0.056	0.068	0.077	0.080	0.083	0.084	0.085		
Standard deviation 2 ^b	0.001	0.001	0.003	0.003	0.005	0.005	0.007	0.006	0.006	0.007	0.007	0.007	0.006	0.006	0.006	0.006		
Coefficient of variation [%]	31.7	40.5	47.5	49.7	53.9	58.4	59.3	65.2	70.6	76.8	84.7	89.5	90.8	92.1	92.5	92.9		
Coefficient of variation 2 ^b [%]	2.8	5.9	10.2	12.4	16.5	17.3	18.8	15.5	16.1	16.6	15.9	15.7	15.1	15.1	15.1	14.9		

^aLeakage during the 63 first cycles, therefore not included in mean value, standard deviation or coefficient of variation.

^bResults from specimen IV not included in because it deviated too much from the other values.

Table C.11 Results from scaling at freezing SS 13 72 44, method IA for mixture 7 (0% fly ash, standard), accumulated values [kg/m²]

Specimen	m ₇	m ₁₄	m ₂₁	m ₂₈	m ₃₅	m ₄₂	m ₄₉	m ₅₆	m ₆₃	m ₇₀	m ₇₇	m ₈₄	m ₉₁	m ₉₈	m ₁₀₅	m ₁₁₂	m ₅₆ /m ₂₈	m ₁₁₂ /m ₅₆
I	0.010	0.015	0.018	0.023	0.026	0.027	0.030	0.031	0.032	0.034	0.034	0.035	0.035	0.035	0.036	0.036		
II	0.029	0.035	0.041	0.044	0.046	0.048	0.049	0.054	0.055	0.056	0.058	0.059	0.060	0.061	0.061	0.062		
III	0.023	0.031	0.036	0.038	0.040	0.041	0.043	0.044	0.045	0.047	0.048	0.049	0.050	0.052	0.053	0.055		
IV	0.052	0.070	0.079	0.087	0.100	0.108	0.122	0.124	0.127	0.131	0.138	0.139	0.139	0.139	0.139	0.140		
Mean value	0.028	0.038	0.044	0.048	0.053	0.056	0.061	0.063	0.065	0.067	0.069	0.070	0.071	0.072	0.073	0.073	1.32	1.16
Mean value 2*	0.021	0.027	0.032	0.035	0.037	0.039	0.040	0.043	0.044	0.045	0.047	0.047	0.048	0.049	0.050	0.051	1.23	1.19
Standard deviation	0.018	0.023	0.026	0.028	0.032	0.036	0.041	0.042	0.042	0.044	0.047	0.047	0.047	0.046	0.046	0.046		
Standard deviation 2*	0.010	0.011	0.012	0.011	0.011	0.011	0.010	0.011	0.011	0.011	0.012	0.012	0.012	0.013	0.013	0.013		
Coefficient of variation [%]	62.4	62.1	58.8	57.4	61.4	64.1	68.1	65.9	65.2	65.6	67.5	66.5	65.8	64.4	63.4	62.2		
Coefficient of variation 2 [%]*	48.1	40.0	38.0	31.7	28.6	27.6	23.6	26.1	25.8	25.1	25.9	25.4	25.8	26.2	26.4	26.1		

*Results from specimen IV not included because it deviated too much from the other values.

Table C.12 Results from scaling at freezing SS 13 72 44, method IA for mixture 8 (6% fly ash, standard), accumulated values [kg/m²]

Specimen	m ₇	m ₁₄	m ₂₁	m ₂₈	m ₃₅	m ₄₂	m ₄₉	m ₅₆	m ₆₃	m ₇₀	m ₇₇	m ₈₄	m ₉₁	m ₉₈	m ₁₀₅	m ₁₁₂	m ₅₆ /m ₂₈	m ₁₁₂ /m ₅₆
I	0.008	0.010	0.013	0.014	0.018	0.021	0.025	0.030	0.034	0.037	0.039	0.041	0.042	0.042	0.043	0.043		
II	0.012	0.018	0.020	0.021	0.023	0.027	0.030	0.034	0.036	0.040	0.043	0.045	0.046	0.046	0.047	0.047		
III	0.009	0.014	0.016	0.019	0.025	0.029	0.034	0.042	0.047	0.052	0.053	0.055	0.055	0.056	0.056	0.057		
IV*	0.024	0.030	0.031	0.032	0.032	0.032	0.033	0.033	0.034	0.035	0.039	0.039	0.039	0.039	0.039	0.039		
Mean value	0.010	0.014	0.016	0.018	0.022	0.026	0.030	0.035	0.039	0.043	0.045	0.047	0.048	0.048	0.049	0.049	1.96	1.39
Standard deviation	0.002	0.004	0.004	0.003	0.004	0.004	0.004	0.006	0.007	0.008	0.007	0.007	0.007	0.007	0.007	0.007		
Coefficient of variation [%]	22.2	28.6	22.4	18.6	16.9	15.3	14.6	18.0	18.8	18.1	16.3	14.7	14.5	14.4	14.3	14.5		

*Water was poured onto the surface one week too late, therefore are the results from this specimen is not included in the mean value.

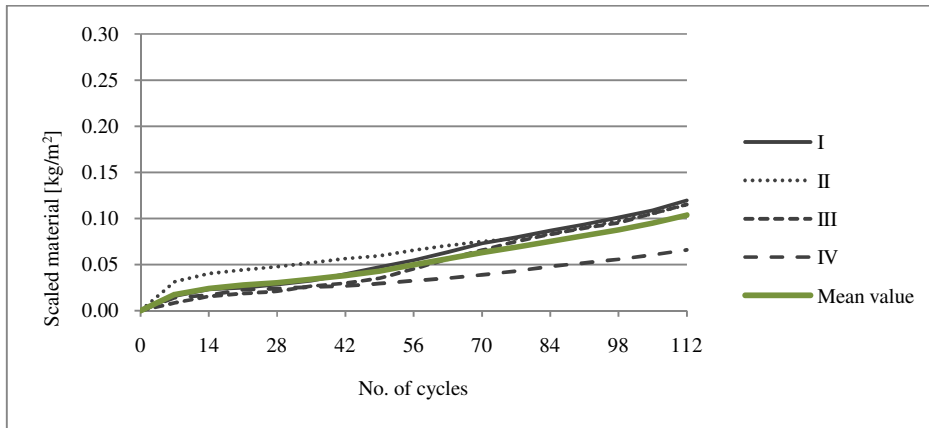


Figure C.1 Scaling at freezing according to SS 13 72 44:2005 for Mixture 1 (20% fly ash, cured 28 days in 55 °C).

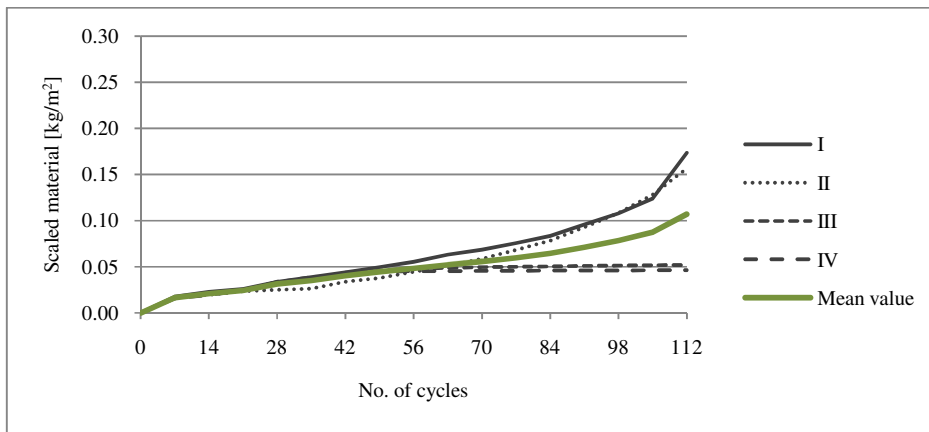


Figure C.2 Scaling at freezing according to SS 13 72 44:2005 for Mixture 2 (20% fly ash, cured 42 days in 55 °C).

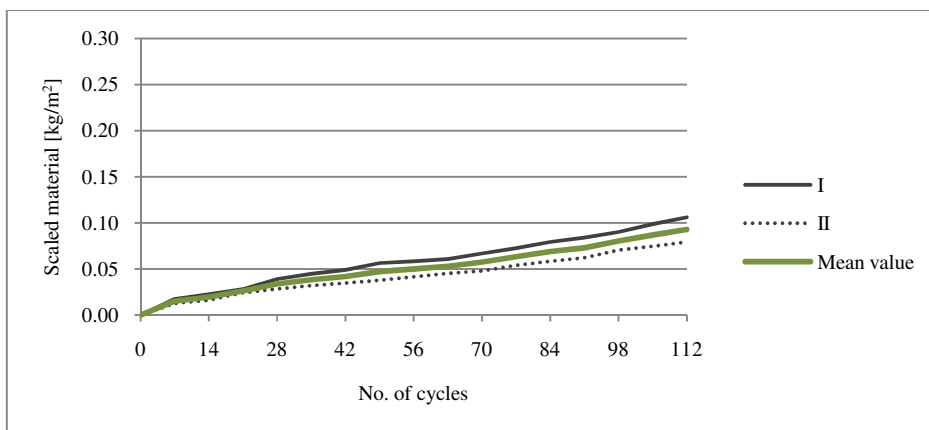


Figure C.3 Scaling at freezing according to SS 13 72 44:2005 for Mixture 3 (20% fly ash, cured 56 days in 20 °C).

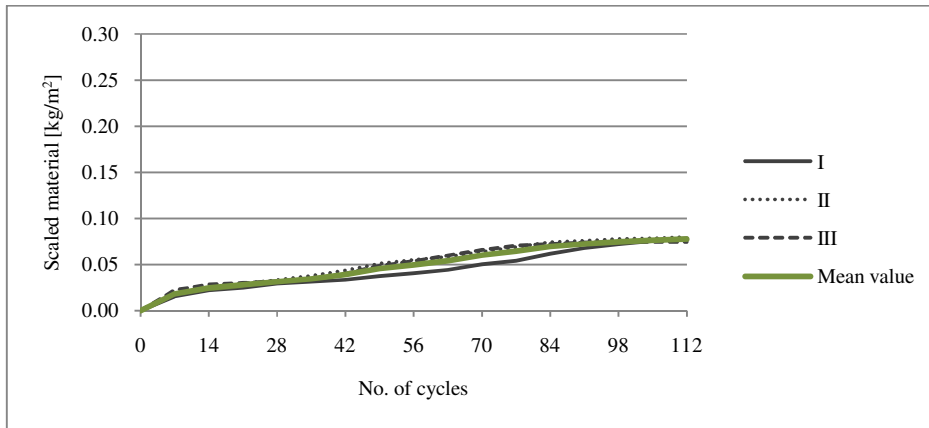


Figure C.4 Scaling at freezing according to SS 13 72 44:2005 for Mixture 3 (20% fly ash, cured 90 days in 20 °C).

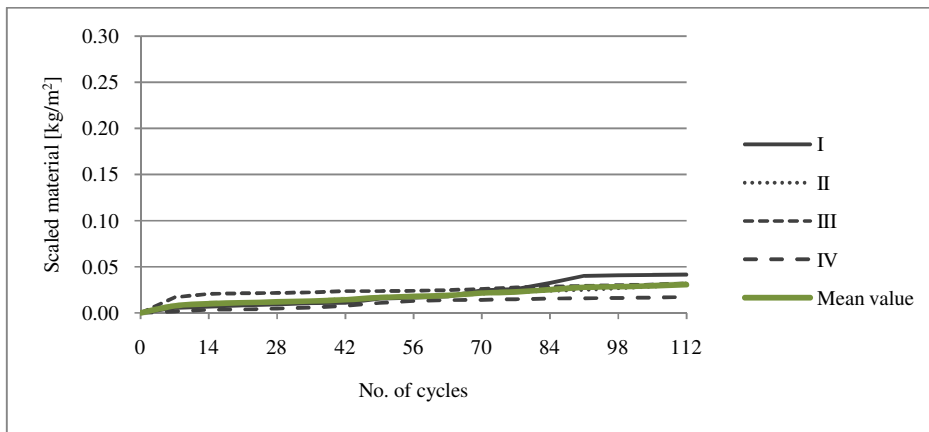


Figure C.5 Scaling at freezing according to SS 13 72 44:2005 for Mixture 4 (20% fly ash, standard curing).

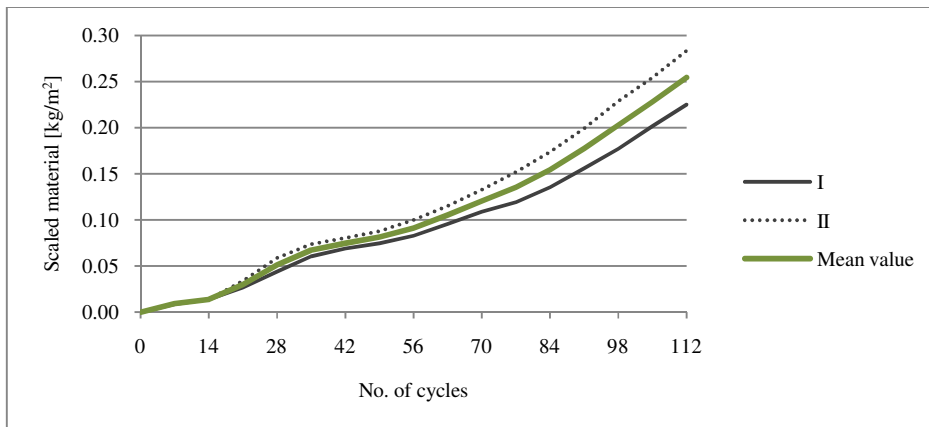


Figure C.6 Scaling at freezing according to SS 13 72 44:2005 for Mixture 5 (20% fly ash, $k=1.0$, cured 63 days in 20 °C).

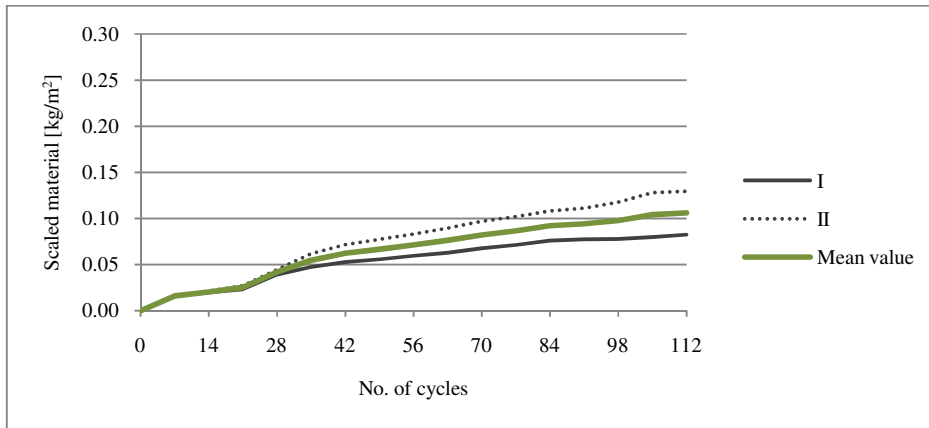


Figure C.7 Scaling at freezing according to SS 13 72 44:2005 for Mixture 5 (20% fly ash, $k=1.0$, cured 90 days in 20 °C).

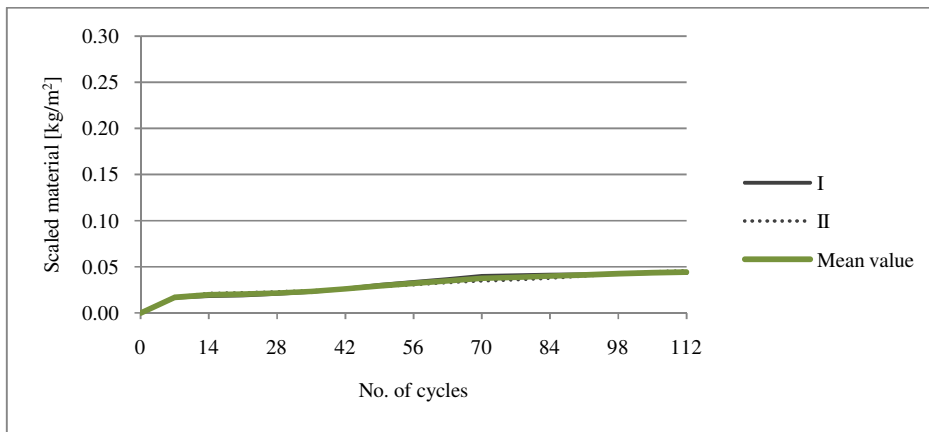


Figure C.8 Scaling at freezing according to SS 13 72 44:2005 for Mixture 5 (20% fly ash, $k=1.0$, cured 28 days in 55 °C).

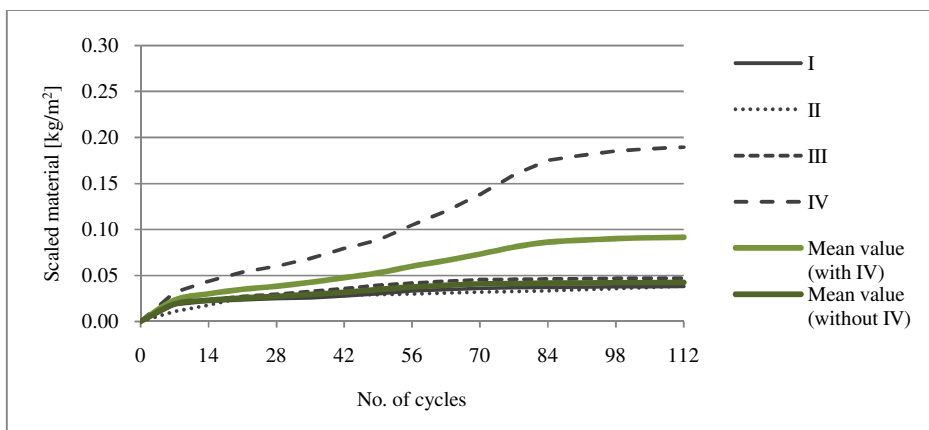


Figure C.9 Scaling at freezing according to SS 13 72 44:2005 for Mixture 6 (0% fly ash, cured according to the standard).

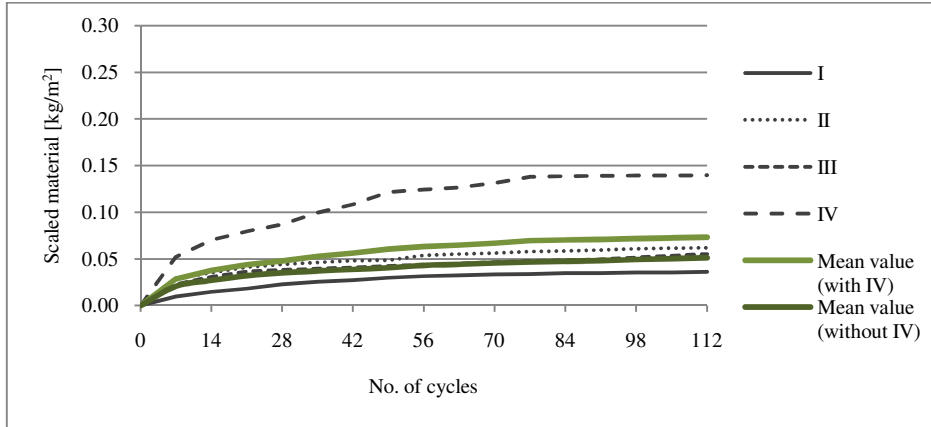


Figure C.10 Scaling at freezing according to SS 13 72 44:2005 for Mixture 7 (0% fly ash, cured according to the standard).

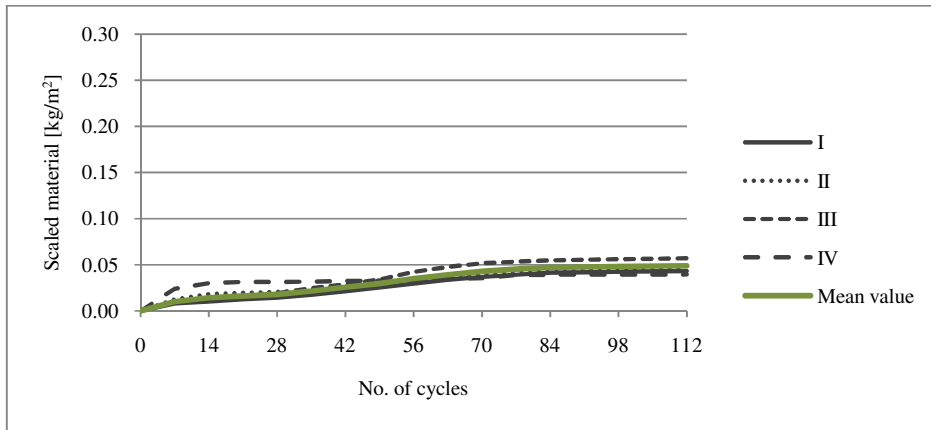


Figure C.11 Scaling at freezing according to SS 13 72 44:2005 for Mixture 8 (6% fly ash, cured according to the standard).

An estimation of the accuracy of the method, is given in SS 13 72 44 by the coefficients of variation in terms of repeatability, v_r , and reproducibility, v_R , respectively. The equation to calculate the coefficients are shown below:

$$v = a \cdot m^b \quad (7.1)$$

where

m : the mass of scaled material, kg/m^2

a, b : constants, values shown in Table 7.1

Table 7.1 Values of a and b for coefficient of variation according to SS 13 72 44.

	a	b	R^2
Repeatability coefficient of variation, v_r	17.0	-0.24	0.99
Reproducibility coefficient of variation, v_R	31	-0.23	0.95

R^2 : coefficient of determination

The coefficients of variation, for both the repeatability and the reproducibility, are decreasing as the scaled material increases, see Figure C.12. This means that in this method better resistance against scaling involves larger variations.

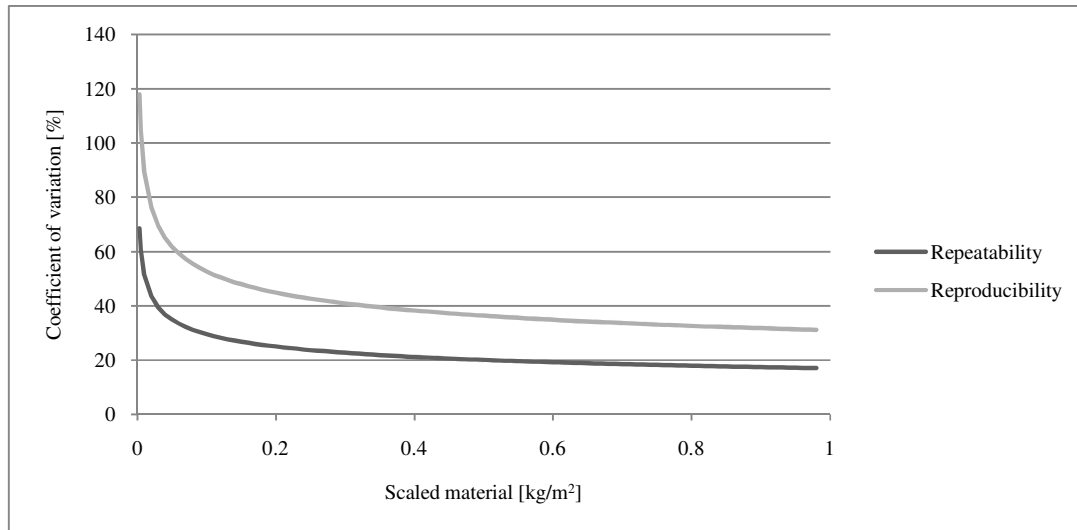


Figure C.12 Repeatability and reproducibility coefficients of variation.

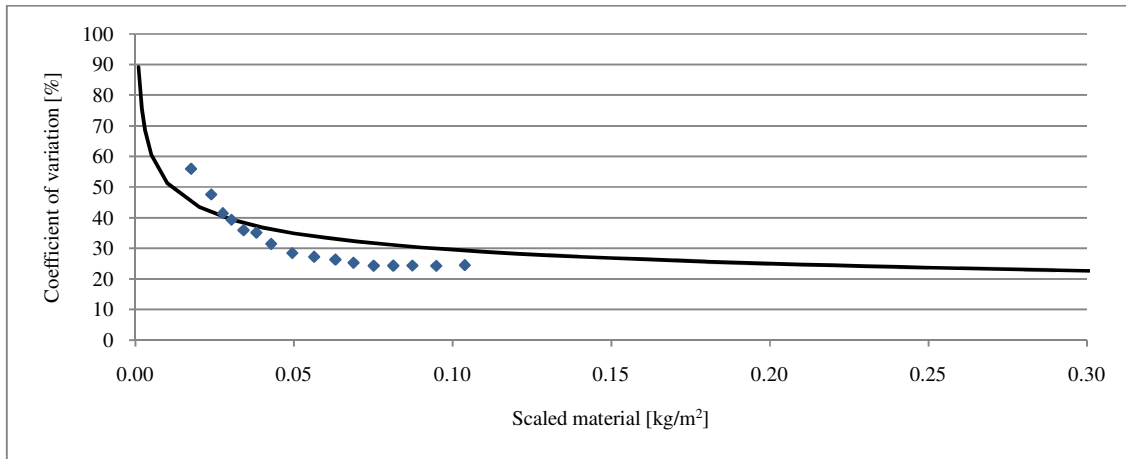


Figure C.13 The coefficient of variation for Mixture 1 (20% fly ash, 55 °C, 28 d) compared with the repeatability coefficient of variation.

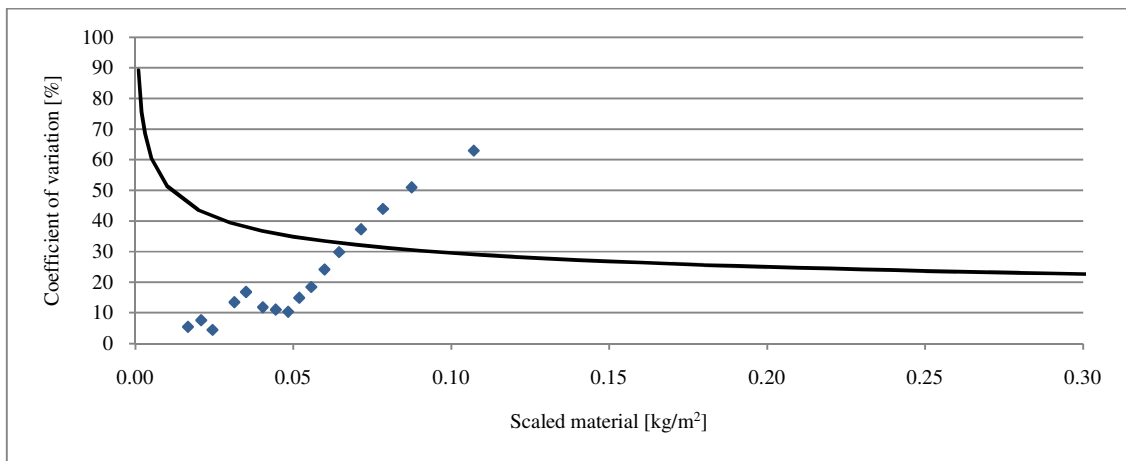


Figure C.14 The coefficient of variation for Mixture 2 (20% fly ash, 55 °C, 42 d) compared with the repeatability coefficient of variation.

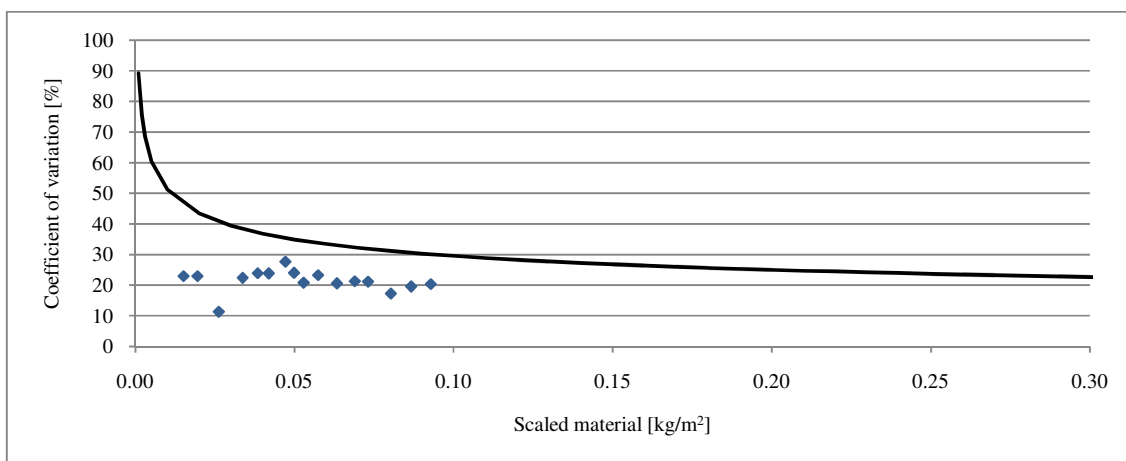


Figure C.15 The coefficient of variation for Mixture 3 (20% fly ash, 20 °C, 56 d) compared with the repeatability coefficient of variation.

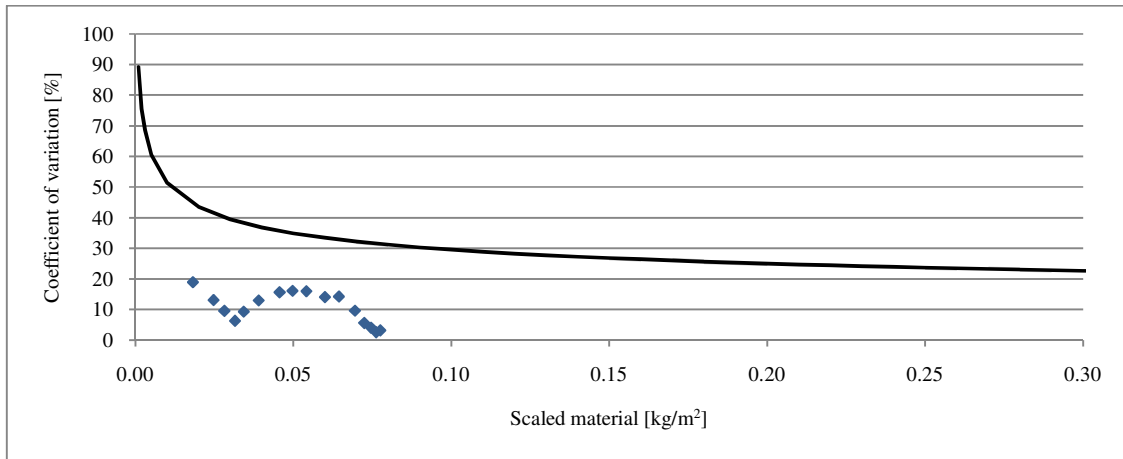


Figure C.16 The coefficient of variation for Mixture 3 (20% fly ash, 20 °C, 90 d) compared with the repeatability coefficient of variation.

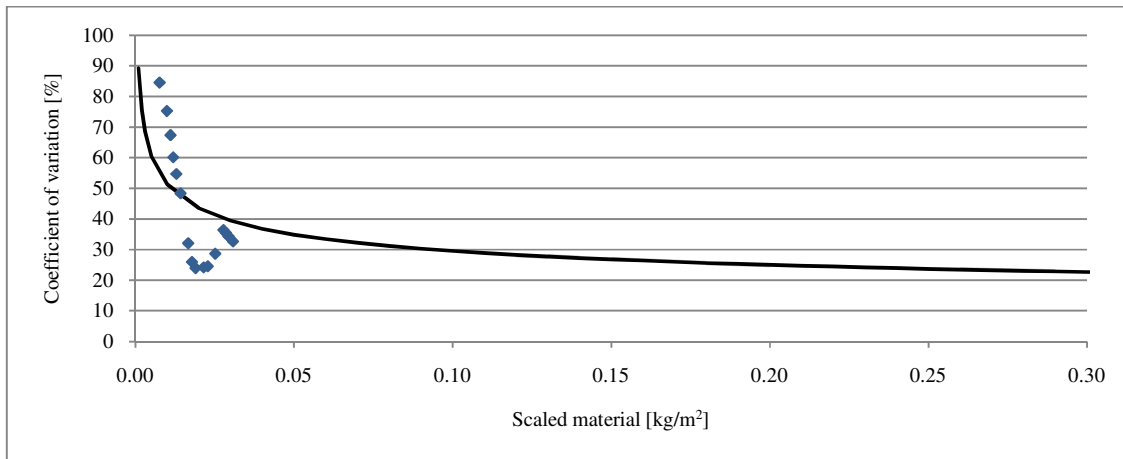


Figure C.17 The coefficient of variation for Mixture 4 (20% fly ash, std) compared with the repeatability coefficient of variation.

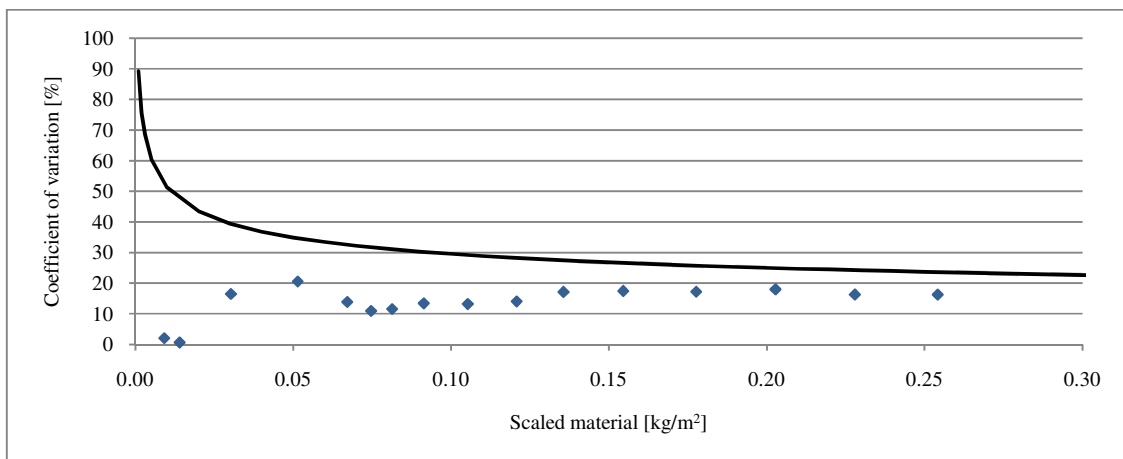


Figure C.18 The coefficient of variation for Mixture 5 (20% fly ash, $k=1.0$, 20 °C, 63 d) compared with the repeatability coefficient of variation.

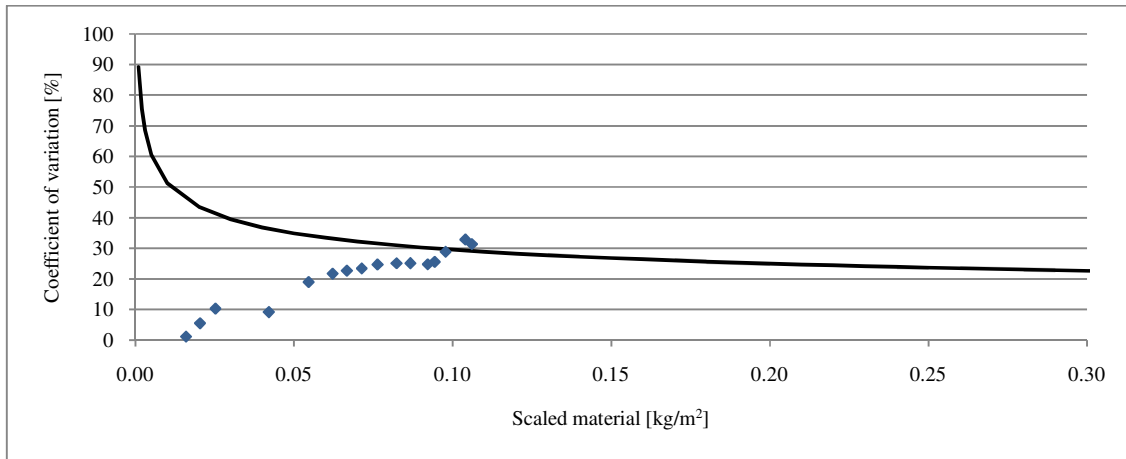


Figure C.19 The coefficient of variation for Mixture 5 (20% fly ash, $k=1.0$, 20 °C, 90 d) compared with the repeatability coefficient of variation.

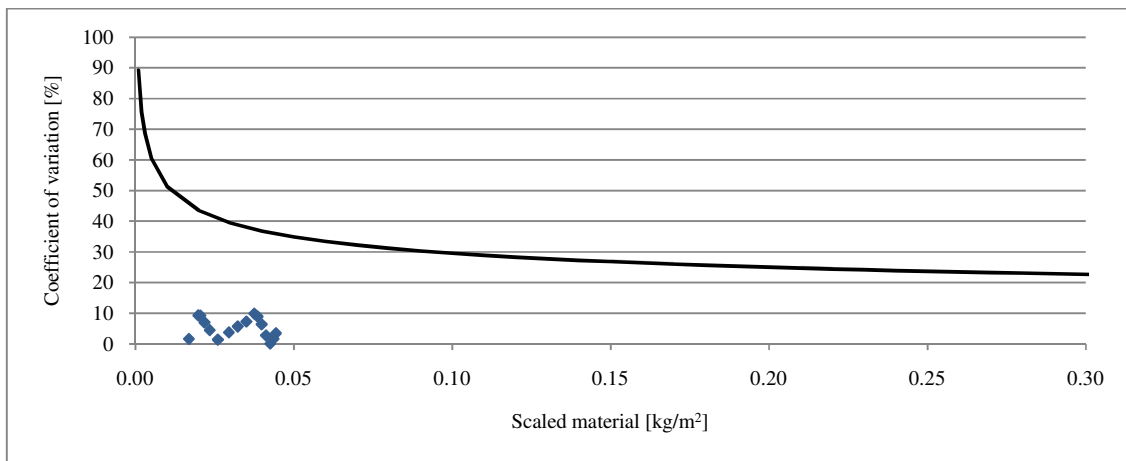


Figure C.20 The coefficient of variation for Mixture 5 (20% fly ash, $k=1.0$, 55 °C, 28 d) compared with the repeatability coefficient of variation.

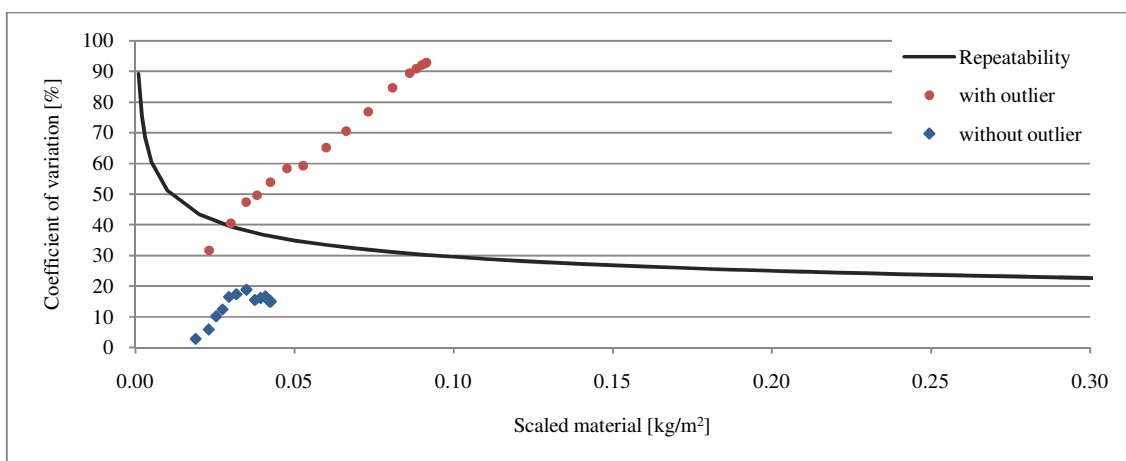


Figure C.21 Coefficient of variation for Mixture 6 (0% fly ash) compared with the repeatability coefficient of variation.

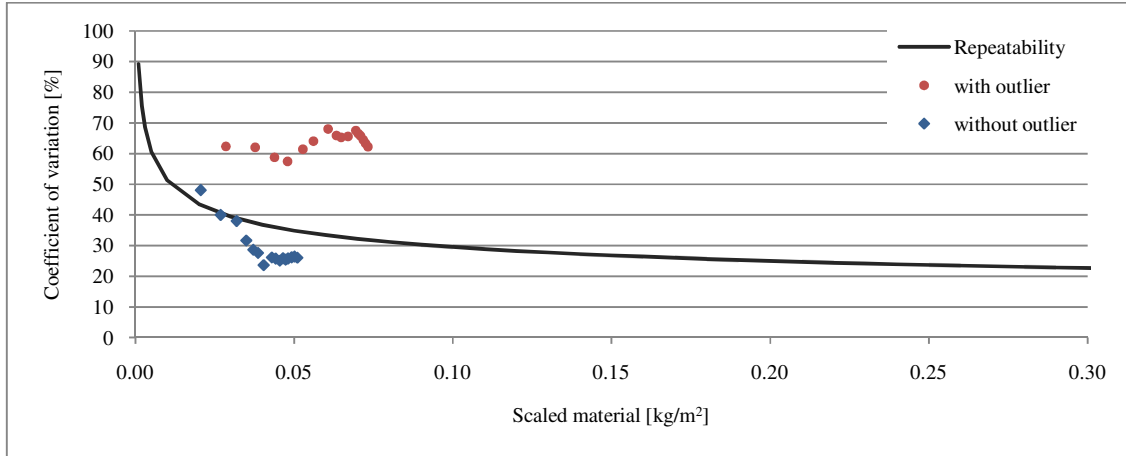


Figure C.22 Coefficient of variation for mixture 7 (0% fly ash) compared with the repeatability coefficient of variation.

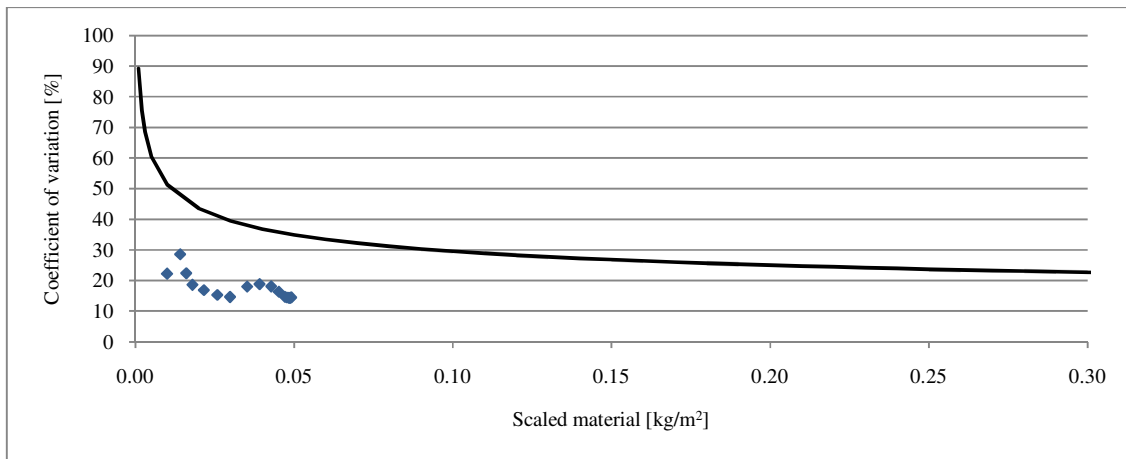


Figure C.23 The coefficient of variation for Mixture 8 (6% fly ash, std) compared with the repeatability coefficient of variation.



Figure C.24 Photo after 112 cycles of freeze/thaw for mixture 1 (20% FA, 28 d, 55 °C), specimen I.



Figure C.26 Photo after 112 cycles of freeze/thaw for mixture 1 (20% FA, 28 d, 55 °C), specimen III.

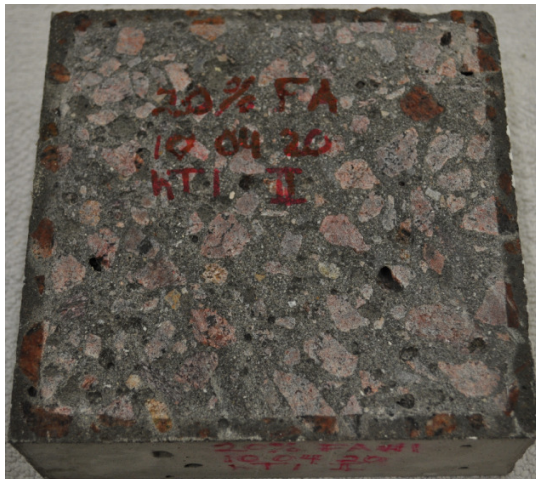


Figure C.25 Photo after 112 cycles of freeze/thaw for mixture 1 (20% FA, 28 d, 55 °C), specimen II.

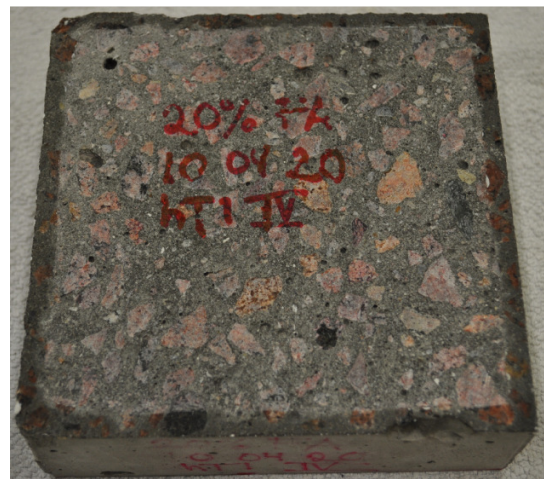


Figure C.27 Photo after 112 cycles of freeze/thaw for mixture 1 (20% FA, 28 d, 55 °C), specimen IV.



Figure C.28 Photo after 112 cycles of freeze/thaw for mixture 2 (20% FA, 42 d, 55 °C), specimen I.



Figure C.30 Photo after 112 cycles of freeze/thaw for mixture 2 (20% FA, 42 d, 55 °C), specimen III.



Figure C.29 Photo after 112 cycles of freeze/thaw for mixture 2 (20% FA, 42 d, 55 °C), specimen II.



Figure C.31 Photo after 112 cycles of freeze/thaw for mixture 2 (20% FA, 42 d, 55 °C), specimen IV.



Figure C.32 Photo after 112 cycles of freeze/thaw for mixture 3 (20% FA, 90 d, 20 °C), specimen I.

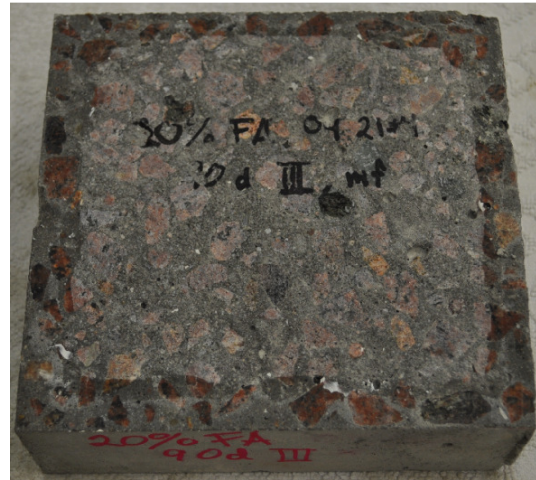


Figure C.34 Photo after 112 cycles of freeze/thaw for mixture 3 (20% FA, 90 d, 20 °C), specimen III.



Figure C.33 Photo after 112 cycles of freeze/thaw for mixture 3 (20% FA, 90 d, 20 °C), specimen II.



Figure C.35 Photo after 112 cycles of freeze/thaw for mixture 4 (20% FA, standard), specimen I.

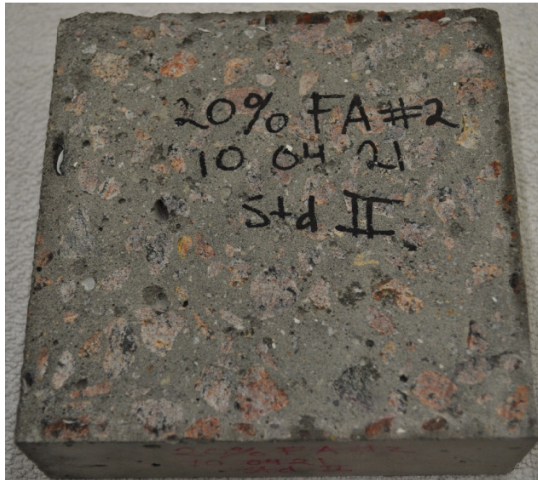


Figure C.36 Photo after 112 cycles of freeze/thaw for mixture 4 (20% FA, standard), specimen II.



Figure C.38 Photo after 112 cycles of freeze/thaw for mixture 4 (20% FA, standard), specimen IV.



Figure C.37 Photo after 112 cycles of freeze/thaw for mixture 4 (20% FA, standard), specimen III.

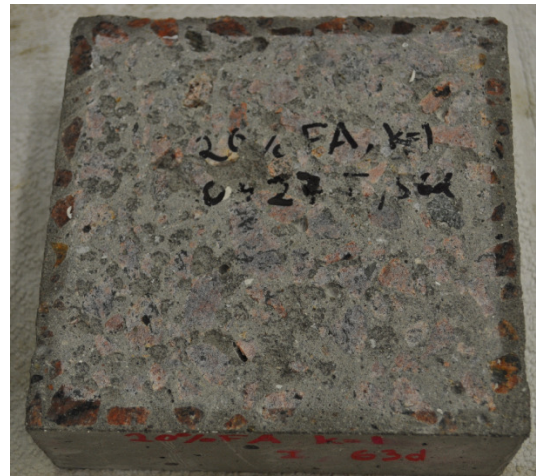


Figure C.39 Photo after 112 cycles of freeze/thaw for mixture 5 (20% FA, $k=1.0$, 63 d, 20 °C), specimen I.

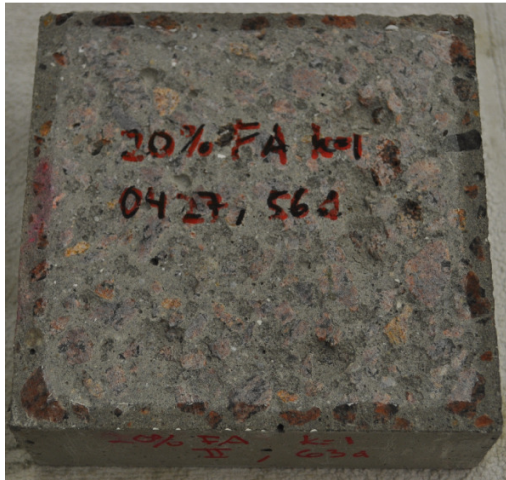


Figure C.40 Photo after 112 cycles of freeze/thaw for mixture 5 (20% FA, $k=1.0$, 63 d, 20 °C), specimen II.



Figure C.42 Photo after 112 cycles of freeze/thaw for mixture 5 (20% FA, $k=1.0$, 90 d, 20 °C), specimen II.



Figure C.41 Photo after 112 cycles of freeze/thaw for mixture 5 (20% FA, $k=1.0$, 63 d, 20 °C), specimen II.

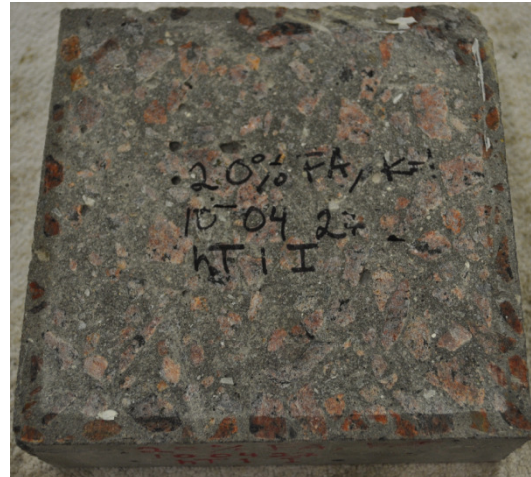


Figure C.43 Photo after 112 cycles of freeze/thaw for mixture 5 (20% FA, $k=1.0$, 28 d, 55 °C), specimen I.

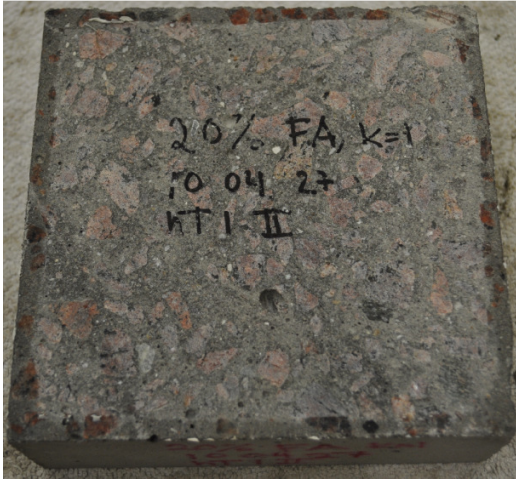


Figure C.44 Photo after 112 cycles of freeze/thaw for mixture 5 (20% FA, $k=1.0$, 28 d, 55 °C), specimen I.

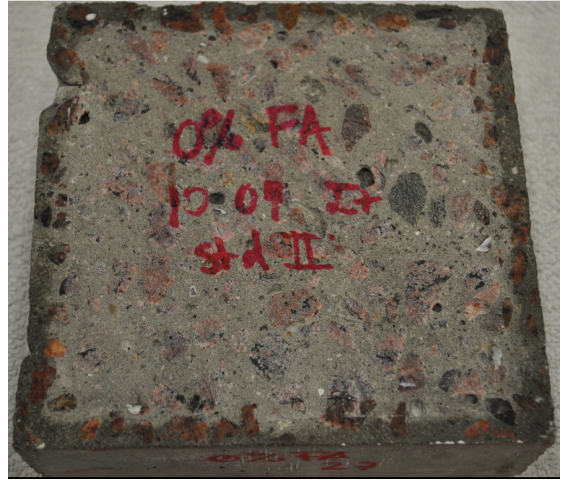


Figure C.46 Photo after 112 cycles of freeze/thaw for mixture 6 (0% FA), specimen II.

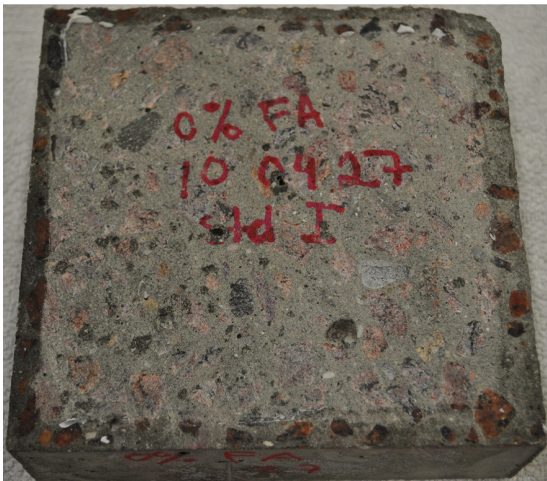


Figure C.45 Photo after 112 cycles of freeze/thaw for mixture 6 (0% FA), specimen I.

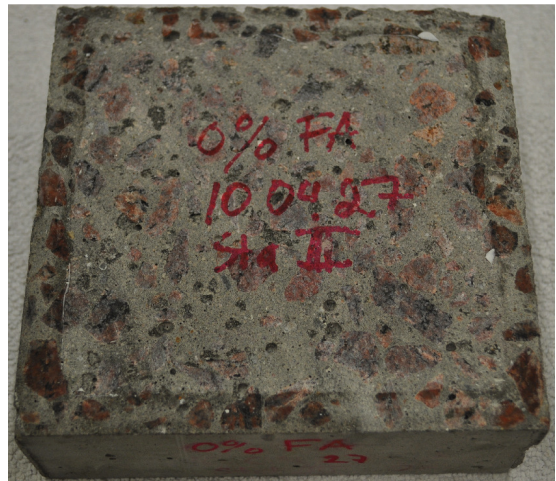


Figure C.47 Photo after 112 cycles of freeze/thaw for mixture 6 (0% FA), specimen III.

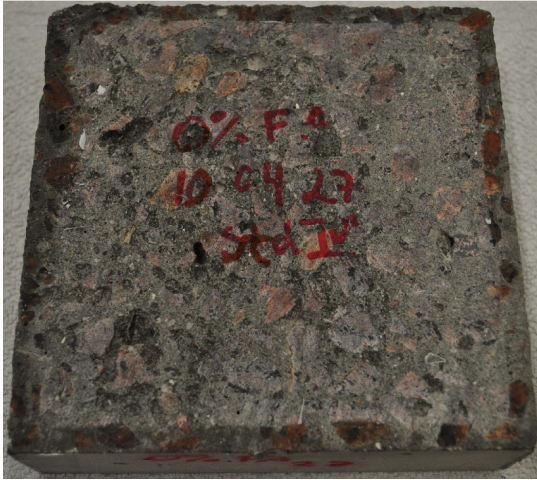


Figure C.48 Photo after 112 cycles of freeze/thaw for mixture 6 (0% FA), specimen IV.

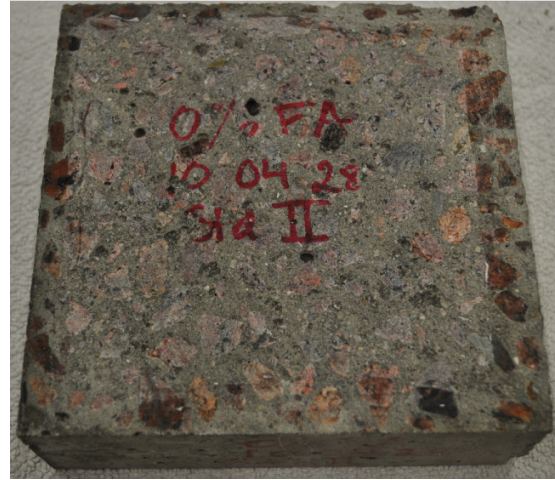


Figure C.50 Photo after 112 cycles of freeze/thaw for mixture 7 (0% FA), specimen II.

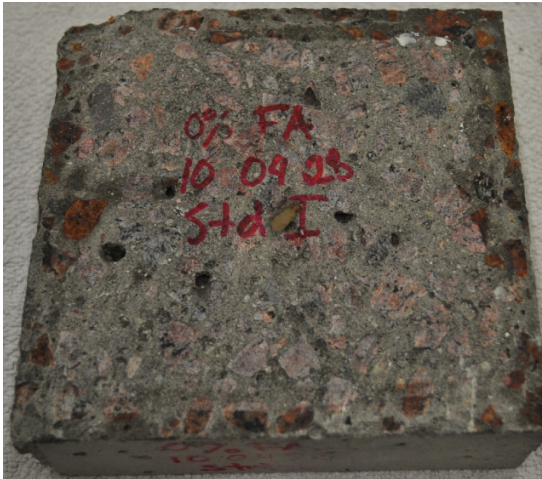


Figure C.49 Photo after 112 cycles of freeze/thaw for mixture 7 (0% FA), specimen I.



Figure C.51 Photo after 112 cycles of freeze/thaw for mixture 7 (0% FA), specimen III.



Figure C.52 Photo after 112 cycles of freeze/thaw for mixture 7 (0% FA), specimen IV.

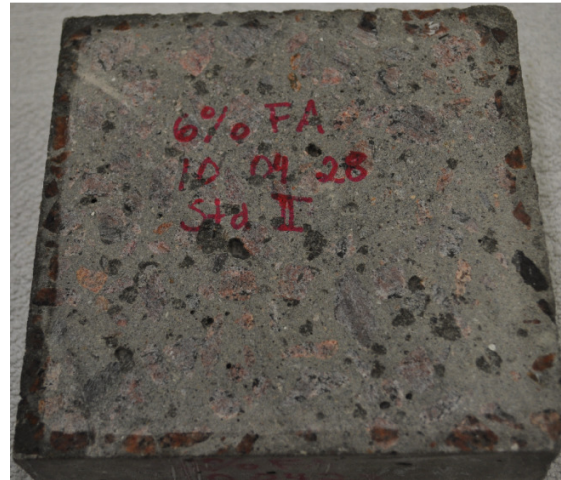


Figure C.54 Photo after 112 cycles of freeze/thaw for mixture 8 (6% FA), specimen II.



Figure C.53 Photo after 112 cycles of freeze/thaw for mixture 8 (6% FA), specimen I.

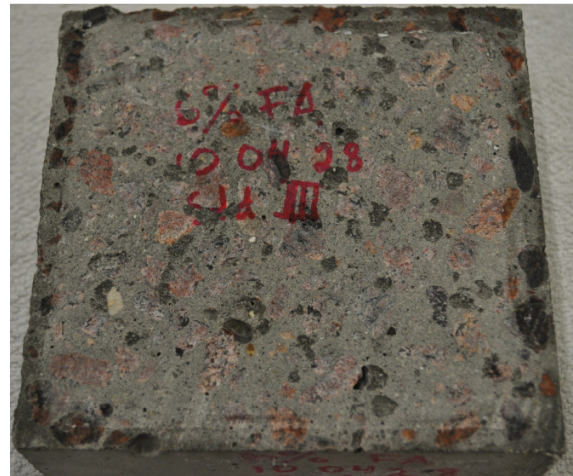


Figure C.55 Photo after 112 cycles of freeze/thaw for mixture 8 (6% FA), specimen III.



Figure C.56 Photo after 112 cycles of freeze/thaw for mixture 8 (6% FA), specimen IV.

Appendix D: Exposure Classes

Table D.1 Description of the exposure classes defined in SS-EN 206-1

Exposure class	Description of environment	
X0	No risk of corrosion attack	Dry
XC1 XC2 XC3 XC4	Corrosion induced by carbonation	Dry or permanently wet Wet, rarely dry Moderate humidity Cyclic wet and dry
XD1 XD2 XD3	Corrosion induced by chlorides other than from sea water	Moderate humidity Wet, rarely dry Cyclic wet and dry
XS1 XS2 XS3	Corrosion induced by chlorides from sea water	Exposed to airborne salt Permanently submerged Tidal, splash and spray zones
XF1 XF2 XF3 XF4	Freeze/thaw attack with or without de-icing salts	Moderate water saturation, without de-icing salts Moderate water saturation, with de-icing salts High water saturation, without de-icing salts High water saturation, with de-icing salts
XA1 XA2 XA3	Chemical attack	Slightly aggressive chemical environment Moderately aggressive chemical environment Highly aggressive chemical environment

