Climate change effect on freeze-thaw cycles in Nordic climate

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ABSTRACT: In Finland one of the most considerable durability issues for outdoor structures is freeze-thaw cycles which can occur all year round. The biggest problems with freeze-thaw cycles occur while at the same time ambient conditions are wet. That is conventional in Finland during autumn, spring and warm winter when daytime temperature is slightly above 0 ^{o}C and by night below. The number of freeze-thaw cycles is slightly higher in inland than in southern Finland and coastal areas but the higher amount of rain and sleet in the latter makes the number of the freeze-thaw cycles needed for the same degree of frost damage much lower. This paper studies how the chance of freeze-thaw cycle occurrence effect on durability properties of concrete facades and balcony structures based on actual freeze-thaw durability studies by Tampere University of Technology and climate change projections made by the Finnish Meteorological Institute.

1 INTRODUCTION

1.1 *Finnish building stock*

Finnish building stock consists of 2.4 million buildings which include over 1.2 million residential buildings. Most of the residential buildings are detached houses in which almost half of the Finnish population live. Apartment houses are concentrated in big cities and they cover only 4.5 % of the total amount of the residential buildings. However 34 % of the population of Finland live in these housings. (ROTI 2011).

The volume of the renovation is increasing because the Finnish building stock is homogenous and fairly new compared to e.g. South and Middle Europe. Most of the stock is built after the 1960s. For example construction with precast concrete panels increased at that time because of the urbanization and most of it is built during the 1960s and 1970s. Buildings constructed at that time are coming at the end of their service life and they need to be renovated. Although the share of precast concrete panels and other concrete facades is only 18 % of all the facades its renovation volume is and will be significant within near future. (Lahdensivu 2010)

1.2 *Prefabricated concrete structures*

Since 1970s almost all prefabricated concrete structures in Finland are based on the Concrete Element System (BES 1969). That open system defines, for instance, the recommended floor-to-floor height and the types of prefabricated panels used. In principle, the system allows using the prefabricated panels made by all manufacturers in any single multi-storey building.

The concrete facade panels used in exterior walls of multi-storey residential buildings were, and still are, chiefly prefabricated sandwich-type panels with thermal insulation placed between two concrete layers. Facade panels are made up of two relatively thin reinforced concrete layers connected to each other by steel trusses. The thermal insulation between the layers is most often mineral wool of 240 mm nominal thickness according to the building regulations in force. It should also be noted that usually there is no ventilation gap behind the outer layers of precast exterior wall panels. Thus, if the thermal insulation gets wet e.g. due to leakage through the joints, the structure dries slowly. The drying of the outer layers is also slow because of the efficient thermal insulation that limits the drying heat flow through the wall. This means that the concrete may remain moist for long periods.

The most common balcony type in Finland from the late 1960's until today consists of a floor slab, side panels and a parapet panel of precast concrete. These stacked balconies have their own foundations, and the whole stack is connected to the building frame only to brace it against horizontal loads. All structural members of a precast balcony are load-bearing.

1.3 *Climate in Finland*

Finland is located between 60th and 70th northern latitudes. Its maximum length on north-south direction is over 1100 km and maximum width over 500 km. Yet Finnish climate is much milder than its location on mid-latitude predicts, mostly due to the warm and steady Atlantic Ocean. Also Scandinavian Peninsula prevents Finland for the most extreme conditions of e.g. coastal areas of Norway. In the Köppen Climate Classification system Finland locates in the subarctic climate zone in which warm summers and freezing winters are typical.

Although the climate is relatively steady for the latitudes and compared to size, it still varies considerably. However, the Finnish building stock is mainly focused on the few biggest cities and certain growth areas near them. Due to both the climate differences and the concentration areas of the population Finland can be divided to four main areas: coastal area, southern Finland, inland and northern Finland (Lapland region). Coastal area includes 30 km wide sector of the coast from the city of Vaasa to Russian border. Southern Finland includes the rest of southern parts to the level of the Tampere city (150 km north from Helsinki). Inland area includes the rest of the country except Lapland.

Prevailing wind directions and wind speeds also have a strong influence on the distribution of rainfall across a building. In Finland most of the rain and sleet in wintertime comes with southerly to westerly winds. Rain events with wind from other directions have been rare. Due to stronger winds, about 60% of the rain and sleet load in the coastal area hits the facades and balconies; the corresponding share inland is about 40%. Combined with the higher amount of precipitation in coastal areas, facades and balconies there are subject to considerably higher moisture stress than inland resulting in clearly more corrosion and frost damage. Winds are stronger at higher reaches of buildings than close to ground level which naturally leads to upper sections of high buildings receiving more rain and sleet stress than lower buildings, and lower sections of buildings in general. (Lahdensivu et al. 2013).

1.4 *Frost attack on concrete*

Frost attack due to a high moisture load is a common reason for the deterioration of concrete structures in Nordic outdoor climate. Concrete is a porous material whose pore system may, depending on the conditions, hold varying amounts of water. As the water in the pore system freezes, it expands about 9% by volume creating hydraulic pressure in the system. If the level of water saturation of the system is high, the overpressure cannot escape into air-filled pores and thus damage the internal structure of the concrete resulting in its degradation. More than 15 different theories or explanations for frost attack on porous materials have been presented (Kuosa & Vesikari 2000). That proves that frost attack is a complex process and frost damage can take many different forms.

The early phase of frost damage is manifested as inner cracking of concrete or scaling of the concrete surface when the hydraulic pressure caused by freezing pore water exceeds the tensile strength of concrete. Cracking will decrease the strength of concrete and increase capillary water absorption. Continuing freeze-thaw cycles and a high moisture content of concrete will finally lead to frost damage (Neville 1995). Early phase frost damage is not visible and cannot be detected by hammering the surface of concrete. Detection of such inner cracking of concrete requires a more sophisticated research method like thin-section analysis (Pentti et al. 1996).

Far advanced frost damage is manifested as a reduction in strength of concrete, loss of adhesion, or crazing or chipping off of the surface due to internal expansion. Disintegration of concrete also accelerates carbonation of concrete due to cracking and consequently also steel corrosion.

The degree of frost damage may vary in different parts of structures depending, for instance, on the moisture load and variation in material properties and thickness of the concrete structure. Frost damage due to a high local moisture load may affect only a very limited area. On the other hand, improper surface treatment of non-frost-resistant concrete may result in deterioration across most of the side wall surface.

2 RESEARCH MATERIAL

2.1 *Concrete facades and balconies database*

Research material for this study is composed of data on concrete durability assembled in condition assessments conducted on prefabricated concrete facades and balconies. The information has been collected as a database that includes the condition assessments of 947 buildings built in 1961–1996. As this study discusses the current concrete codes, only the data concerning buildings built 1990 or after are taken into consideration. There are in all 72 buildings from this era in the database. The database withholds measurements of concrete pore structure, tensile strength, chloride content, carbonation depths as well as concrete cover depths of reinforcement. In addition it includes results from thin section analyses and visual observations made from the building facades and balconies.

Practical design of concrete structures is in Finland governed by national concrete codes (BY50 2012). Besides guidelines for structural design, it also gives recommendation on durability properties and service life design. These requirements are compared to the actual observed degradation processes and their progress in the future.

2.2 *Climate data and projections*

The Finnish Meteorological Institute (FMI) has weather data since 1961 in digital form from several meteorological stations covering all of Finland. The data consist of temperature, relative humidity, rain intensity, wind speed and direction, solar radiation variables, etc. These observations have been collected at least daily and three times a day at best.

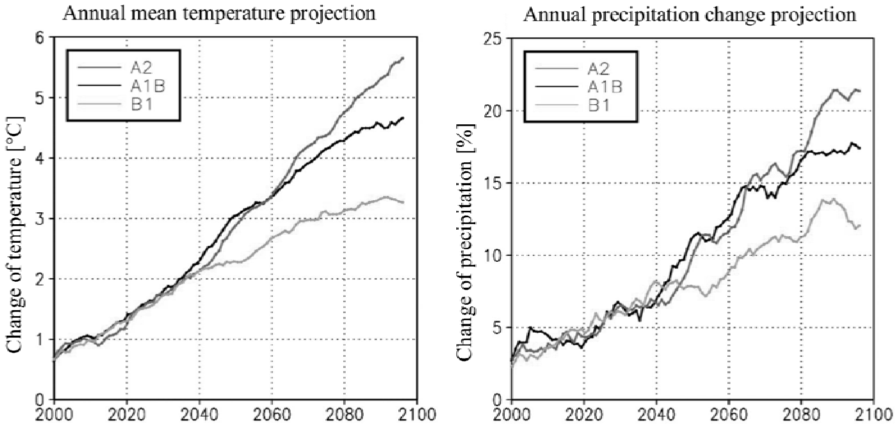

Figure 1. Projections for (a) the annual mean temperature and (b) the precipitation change for the period 2000–2100, relative to the mean of the reference period 1971–2000. The curves depict 11 year running means, averaged over Finland and the responses of 19 global climate models. Projections are given separately for the three greenhouse gas scenarios (A2, A1B and B1) (Jylhä et al. 2009).

In the ACCLIM project (Jylhä et al. 2009) the FMI examined the different climate models, built models for Finnish climate conditions and adaptation to climate change based on three IPCC (2007) scenarios for the evolution of greenhouse gas and aerosol particle emissions. Based on the scenarios the FMI has prepared their effects on weather conditions critical to concrete degradation (Fig. 1). In the REFI-B project (Jylhä et al. 2011), the FMI also forecast the climates of four localities (coastal area, southern Finland, inland, Lapland) in three periods (2030, 2050 and 2100). The forecasts are based on an average of 19 different models which are all based on greenhouse gas emission scenario A2. The A2 scenario involves a situation where greenhouse gases are assumed to increase significantly − it is a sort of worst-case scenario. The FMI also has other significant greenhouse gas emission scenarios: A1B (quite large emissions) and B1 (small emissions).

2.3 *Number of annual freeze-thaw cycles*

The number of annual freeze-thaw cycles in Finnish outdoor climate has been studied in four different weather stations: Helsinki-Vantaa (south coastal area), Jokioinen (south inland), Jyväskylä (inland) and Sodankylä (Lapland) with following criteria (Jylhä et al 2011):

- Raining or wet snowing at the most 2 days before freezing
- The number of freeze-thaw cycles when temperature goes under 0 °C, -2 °C, -5 °C, -10 °C, -15 °C, and -20 °C
- Counting the annual freeze-thaw cycles for the years 2000, 2030, 2050 and 2100

Table 1. Number of annual freeze-thaw cycles at four different observation stations at most 2 days after rain or sleet events (Jylhä et al. 2011)

Year and place	Temperature under (at most 2 days after rain or sleet)					
	0 °C	-2 °C	-5 °C	-10 °C	-15 °C	-20 °C
Vantaa (south coastal area)						
2000	37.8	23.5	11.7	4.0	1.3	0.2
2030	25.9	15.2	7.7	2.3	0.7	0
2050	21.4	12.9	6.1	1.8	0.3	0
2100	14.5	9.4	3.9	0.4	0	0
Jokioinen (south inland)						
2000	34.6	22.3	11.1	4.2	1.3	0.4
2030	26.5	16.0	8.2	3.0	1.0	0.1
2050	23.8	14.8	7.6	2.5	0.6	0
2100	17.2	11.3	5.8	1.1	0	0
Jyväskylä (inland)						
2000	30.4	20.2	10.4	4.2	1.6	0.5
2030	25.4	17.5	9.6	3.3	1.3	0.4
2050	24.8	17.0	9.4	3.2	0.9	0.2
2100	19.8	13.9	7.2	2.1	0.2	0
Sodankylä (Lapland)						
2000	23.4	18.1	10.4	5.0	2.7	0.8
2030	20.6	15.5	9.9	4.7	2.5	0.9
2050	22.3	16.7	11.4	5.8	2.5	0.9
2100	25.2	20.0	13.3	5.7	1.8	0

In table 1 the basic level of the number of annual freeze-thaw cycles in the year 2000 has been counted from the one hour intervals interpolated observations made during basic period of 1980-2009. Future scenarios bases model estimations where observed data has been changed to represent future climate.

Based on the research made by FMI, the annual rainfall will increase according to table 2. The change in the amount of rainfall will be higher during autumn and winter when drying of structures is slower in general.

Table 2. Average change [%] in precipitation compared to present climate (2000) in four different observation station.

	Vantaa (south coastal area			Jokioinen (south inland)			Jyväskylä (inland)			Sodankylä (Lapland)		
Month	2030	2050	2100	2030	2050	2100	2030	2050	2010	2030	2050	2100
1	4.1	9.9	29.6	4.3	9.3	24.7	3.8	9.7	32.6	6.2	11.5	37.9
2	6.4	9.5	29.3	5.7	9.5	26.0	6.3	10.8	30.5	8.4	14.4	31.4
3	3.9	6.5	20.6	2.7	4.1	15.3	3.9	6.6	21.5	3.3	8.4	26.7
4	3.4	6.5	19.1	0.7	4.1	14.1	2.3	5.8	16.4	5.2	9.3	21.2
5	3.5	5.9	16.6	2.2	3.7	11.4	3.9	5.3	14.9	3.4	5.5	22.0
6	-1.2	3.5	9.6	-0.8	4.3	11.2	-0.6	3.8	12.3	-0.9	5.0	17.7
7	2.6	4.4	11.3	2.6	5.4	12.8	2.1	5.1	11.1	2.9	4.7	8.4
8	3.8	4.9	5.7	3.6	3.1	4.3	3.5	4.5	5.8	4.6	5.4	12.2
9	3.5	5.8	9.5	2.7	4.5	10.0	4.4	6.7	11.0	2.3	3.4	13.2
10	3.1	8.4	18.6	2.9	8.3	17.9	2.8	8.0	20.1	2.2	8.8	22.6
11	7.1	10.9	24.4	6.3	9.5	22.3	7.9	10.6	27.6	7.1	13.1	30.6
12	5.4	9.0	28.7	4.8	8.1	23.7	6.5	12.0	34.0	8.1	15.3	38.6
Whole year	3.8	7.1	17.7	3.1	6.1	15.2	3.6	7.1	18.2	3.9	7.9	21.3

Again, according to FMI, the prevailing wind directions during rain events will stay same as present. It intends that facades faced from South-East to West will get more rainfall also in the future.

3 RESULTS AND DISCUSSION

3.1 *Frost resistance of concrete*

The frost resistance of concrete used in facades or balconies will be determined, in the first place, during concrete mixing process. Air entrainment to fresh concrete has been recommended since 1976 and demanded since 1980 in Finnish concrete codes. The compressive strength of concrete has been increased to present level (C30/37) as early as 1989 (BY32 1989).

Success of air entrainment of concrete used in facades and balconies was studied from the samples in the database taken on the buildings built 1990 or afterwards. In the database the information related to used air entrainment and its success has been reported as a protective pore ratio (p_r), which was common practice in Finland until the year 2004. According to concrete codes (1980), protective pore ratio should be at least 0.20, which intends that at least 20 % of total porosity of concrete never will be fulfilled by capillary water. Protective pore ratio 0.20 corresponds spacing factor 0.25 mm (Koskiahde 2004). The durability demands in different stress class according to Finnish concrete codes are shown in table 3.

Table 3. Demands for frost resistant hardened concrete in different stress class when designed service life is 50 or 100 years (BY50 2012).

Designed service life [a]	Stress class	Spacing factor [mm]	Freeze-thaw test	
			number of cycles	remaining bending strength after test [%]
50	XF 1	≤ 0.27	100	≥ 67
	XF 3	≤ 0.23	300	≥ 67
100	XF 1	≤ 0.25	300	≥ 67
	XF 3	≤ 0.22	-	-

Facades and balcony side panels and parapets belong to stress class XF 1 and balcony slab in stress class XF 3. The most common design service life is 50 years in ordinary buildings.

As can be found from figures 2 and 3, the air entrainment in fresh concrete has been made with varying success both in facades and balconies. The demand for frost resistance fulfills only approximately in 50 % of made panels. If the protective pore ratio is less than 0.1, concrete is not frost resistant in moisture conditions, i.e. in ordinary Finnish outdoor during winter time.

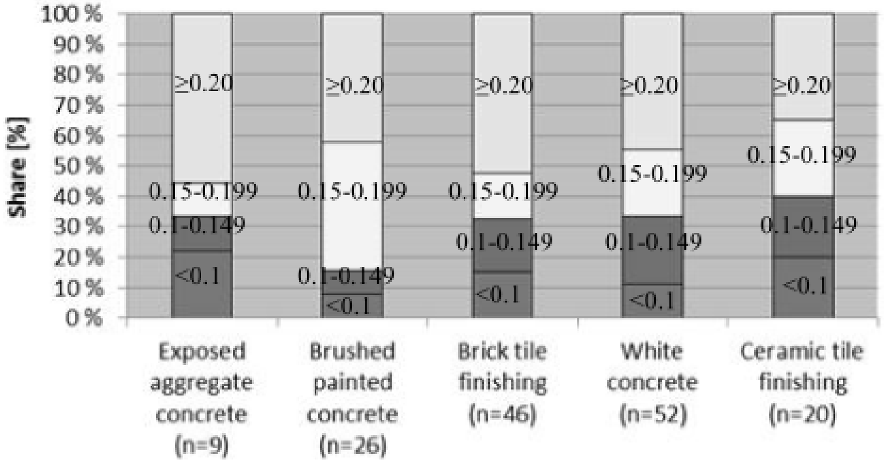

Figure 2. Distribution of protective pore ratios in different facade types according to database. The facades are made from 1990 to 1996. Total number of samples is 153.

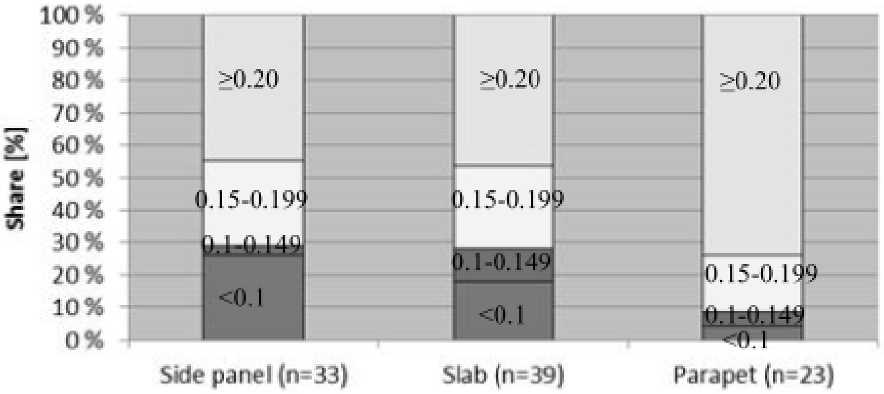

Figure 3. Distribution of protective pore ratios in different balcony elements according to database. The balconies are made from 1990 to 1996. Total number of samples is 95.

3.2 *Frost weathering of concrete*

Prerequisites for frost damage are that pore structure of concrete has been capillary fulfilled over critical point (Fagerlund 1977) and freezing of pore water will happen in the temperatures low enough (Pigeon & Pleau 1995). Thus, even if concrete is not frost resistant there will not occur any frost damage if concrete is dry or temperature does not go low enough. In practice, frost damage needs the concrete to freeze to temperatures of -5 ºC or lower.

The number of freeze-thaw cycles of existing concrete facades and balconies has been studied with following criteria (Lahdensivu 2012):

- raining or wet snowing at most 2 days before freezing
- the number of freeze-thaw cycles when the temperature goes under -5 °C
- studying the existence and state of frost damage with thin-section analyses (245 samples)
- samples from exposed aggregate concrete facades (no paint or other disturbing surface treatment).

Concrete can be very durable in Nordic climate if it has been successfully air-entrained. There were no signs of frost damage in the concrete samples according to thin-section analyses when concrete was frost resistant ($p_r \geq 0.20$) after over 500 freeze-thaw cycles in real outdoor environment.

On the opposite, if the protective pore ratio measured from hardened concrete is less than 0.10, the air-entrainment of concrete has failed. Even insufficiently air-entrained concrete has a service life of some years. Cracking indicating frost damage is the result of an average of 388 freeze-thaw cycles (t ≤ -5 °C) inland (Jyväskylä) and 307 cycles in the southern coastal area (Vantaa). If the freezing temperature criterion is t ≤ -10 °C, incipient frost damage occurs on average after 189 and 140 freeze-thaw cycles, respectively. On the southern coastal area this translates into about 22 years and inland into about 24 years. General frost damage revealed by thin sections begins to occur in exposed aggregate facades in the southern coastal area on average after 330 freeze-thaw cycles (t ≤ -5 °C) and after 416 cycles inland (Lahdensivu 2012). The number of freeze-thaw cycles is slightly higher in inland than in Southern Finland but the higher amount of rain and sleet in South Finland makes the number of the freeze-thaw cycles needed for the same degree of frost damage much lower. General frost damage in concrete samples revealed in thin-section analyses only approximately 20 freeze-thaw cycles more than incipient frost damage. So, the frost damage will proceed quite fast when it ever begins.

In table 4 has been calculated an estimation of the time needed for incipient frost damage revealed with thin-section analyses from inadequate frost resistant concrete both inland (Jyväskylä) and south coastal area (Vantaa) based on forecast of the future and above mentioned research.

Table 4. Time to incipient frost damage to reveal in thin-section analyses in different temperature criteria when rain or sleet has come ≤ 2 days before freezing (pr ≤ 0.10).

Building	South coastal area [years]		Inland [years]	
year	t ≤ -5 °C	t ≤ -10 °C	t ≤ -5 °C	t ≤ -10 °C
2000	26	35	37	45
2030	40	61	40	58
2050	50	78	41	59
2100	79	350	53	90

In consequence of climate change outdoor circumstances when concrete freezes wet will ease remarkably already 2030 in southern Finland. In inland outdoor climate remains in the present level and those will get even harder with increasing amount of rain and sleet almost to the end of century. The complete failure with air entraining fresh concrete ($p_r \leq 0.10$) will surely lead to frost damage of concrete structure before eligible service life of the structure (usually at least 50 years).

If the spacing factor is less than 0.20 mm concrete can be generally considered as frost resistant in all cases (Pigeon & Pleau 1995). However, in several tests it has been found that concrete made of ordinary Portland cement is frost resistant if spacing factor is less than 0.50 mm (Powers & Helmuth 1953, Pigeon et al. 1986, Aitcin & Mindess 2011). In Finnish concrete codes required spacing factor is always 0.27 or less. It can be stated that according to present concrete codes tested durable concrete will stand well also in real outdoor climate for eligible service life.

4 CONCLUSIONS

The number of freeze-thaw cycles is slightly higher in inland than in Southern Finland but the higher amount of rain and sleet in South Finland makes the number of the freeze-thaw cycles needed for the same degree of frost damage much lower. In practice, frost damage needs the concrete to freeze to temperatures of -5 ºC or lower. Freezing events to -5 ºC are significantly fewer than freezing events to just below 0 ºC.

In consequence of climate change outdoor circumstances when concrete freezes wet will ease remarkably already 2030 in southern Finland. In inland outdoor climate remains in the present level and will get even harder with increasing amount of rain and sleet almost to the end of the century. The complete failure with air entraining fresh concrete ($p_r \leq 0.10$) will surely lead to frost damage of concrete structure before eligible service life of the structure (usually at least 50 years).

Concrete can be very durable in Nordic climate if it has been successfully air-entrained. The present requirement for frost resistance of concrete is enough also in the future climate. However, the attention must be paid to successful air entrainment of fresh concrete. It must always succeed.

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