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Delayed ettringite formation (DEF) and its effect on freeze-thaw damage in Finnish concrete façades

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ABSTRACT

The strongest drivers causing delayed ettringite formation (DEF) and its impact as a cause of freeze-thaw damage in Finnish concrete façades is still poorly known as it has been only briefly touched as a part of one dissertation [1] and one master's thesis [2]. The conclusion of both studies was that DEF might slightly accelerate freeze-thaw damage of concrete, but how strongly or how rapidly was not stated. To complement the knowledge on that matter, this article analyses Finnish façade structures built between 1960 and 2003 using large case-study databases, weather history data and statistical methods.

As a result, it was found that DEF occurs in more than half of the Finnish concrete façades, but it significantly increases the freeze-thaw damage only when it has spread widely in the pore structure of concrete. Such case has been quite rare, since the amount of widespread DEF covers only 4.4% of all observations. Wind-driven rain (WDR) was found to be one of the most significant drivers for DEF, and if the façades are either completely protected from it or oriented in the direction which are least exposed to WDR, DEF was not observed extensively at all. Façades where no DEF was detected had WDR exposure an average of 1852 mm per year. The facades where DEF was found extensively had 68% more exposure, an average of 3127 mm per year.

1. Introduction

One factor that might weaken the freeze-thaw resistance of concrete is delayed ettringite formation (DEF). It has been presented that DEF can cause degradation either due to its decreasing effect on freeze-thaw resistance or even in such a way that the pressure generated in filled pores causes cracks in concrete [3]. In many reports, DEF has been detected in degradation cases of concrete structures. The phenomenon often occurs in combination with, for example, alkali-silica reaction (ASR) or freeze-thaw damage caused by other drivers, so it is difficult to state how big role DEF plays in the degradation of concrete [4].

The impact of DEF as a cause of freeze-thaw damage is still poorly known. Very few publications study this certain issue concerning the Finnish building stock and Finnish climate as it has been only briefly addressed in one dissertation [1] and one master's thesis [2]. Both studies have suggested to complement the knowledge on that matter to predict better the rate of freeze-thaw damage in old concrete structures. The objective of this study, by analysing large case-study databases of Finnish façade structures built between 1960 and 2003 and WDR data history, is to answer the following questions:

- Is DEF considerably increasing the freeze-thaw damage in Finnish concrete façades?

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- What is the most significant individual factor that cause DEF in concrete?
- How have construction guidelines, requirements and regulations influenced to formation of delayed ettringite?
- How large part of the Finnish building stock is affected by DEF and how widely?

2. Background

2.1. Freeze-thaw damage of concrete and delayed ettringite formation

Freeze-thaw damage is caused by water expanding by about 9% when freezing and thawing in the pore network of concrete. The smaller the volume of the pore network of concrete, the more susceptible it is to degradation by freezing water. The concrete pore network can be divided into gel pores, capillary pores, and compaction pores, see Fig. 1. The amount, distribution and size of different pores are affected by, for example, the degree of hydration, water-cement ratio as well as the mixing and curing of concrete [5,6].

Ettringite, i.e. hydrated tricalcium-aluminate sulphate $Ca_6Al_2(SO_4)_3(OH)_{12}*26H_2O$ is a substance formed in the first hours of hydration process when Portland cement and water is mixed. In this process cement's tricalcium aluminate (C_3A) reacts with calcium sulphate (gypsum). When gypsum is consumed, the remaining C_3A reacts with ettringite and turns into calcium monosulphoaluminate hydrate $3CaO*Al_2O_3*CASO_4*12H_2O$ [6]. This so called primary ettringite is not harmful, and it plays an essential role in the development of concretes short term strength and its long-term stability [8].

The presence of ettringite turns harmful when it's formed in mature concrete uncontrollably because of one or more of the following phenomena:

- long-term and severe moisture exposure [9].
- excessive heat development because of heat curing treatment [9].
- excessive heat generation during the hydration process [9].
- internal or external sulphate source [10,11].

This type of ettringite is called, depending on the source, late ettringite, secondary ettringite or delayed ettringite formation (DEF). In the delayed ettringite formation process, ettringite crystallises on the walls of the concrete's pores or cracks which decreases the volume of concrete's pore network and thereby is suggested to decrease freeze-thaw resistance [12]. The volume increase of crystallised ettringite can be 130–140% compared to its starting substances and it can theoretically cause a pressure up to 55.5 MPa in concrete [13]. DEF can thus cause degradation either by accelerating freeze-thaw damage caused by other phenomena or by creating unbearable internal pressures in concrete [3].

2.2. DEF, freeze-thaw damage and their relation in guidelines and requirements

In Finland and other Nordic countries, freeze-thaw resistance of concrete is ensured with air-entrainment agents in the concrete mixture [14]. The purpose of such manoeuvre is to create evenly distributed, so-called protective pores with a diameter of about 50 μm in the pore network of concrete, which can take the pressure of freezing and thawing water causes [5,6]. Air-entrainment agents have been used in Finland since the 1960s [1], but the first recommendations were made in 1976 [14] and the requirement for

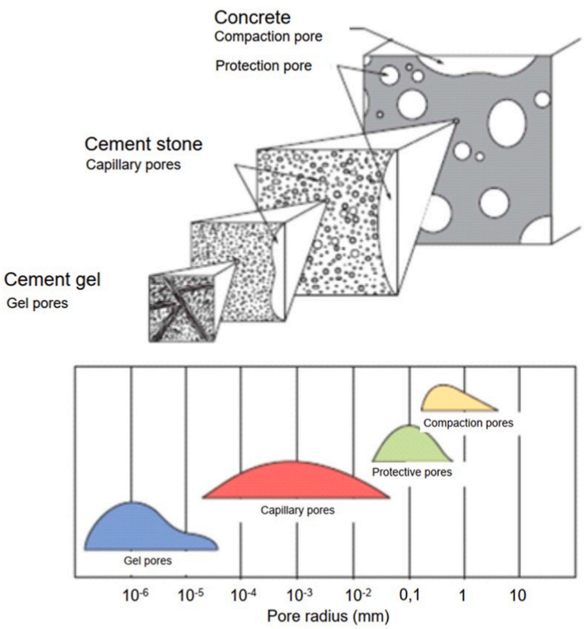


Fig. 1. Distribution and size of different pores in concrete [7].

its use was not set until 1980 [10]. In 1976, the protective pore ratio was recommended to be at least 0.15 in environmental class Y2 (normal conditions) and at least 0.2 in severe conditions (environmental class Y1) [14]. The protective pore ratio was changed from a recommendation to a requirement having a value of 0.2 for both environmental classes in 1989 [15]. In 2000 it was raised to 0.25 for environmental class Y1. In 2004, the environmental classes were replaced by exposure classes since Finland started to use European standards. At the same time, the protective pore ratio requirement was replaced by the spacing factor. For concrete façades, the spacing factor should be ≤ 0.27 mm (exposure class XF1, design service life 50 years) or ≤0.25 mm (exposure class XF1, design service life 100 years) [16].

The purpose of the heat curing treatment of concrete elements (even up to 60–80 °C) is to speed up the hardening process, thus making the mold cycle faster at the production plant [6]. In Finland, this method was used to harden concrete from 1965 onwards, but when the connection between heat treatment and decreased ultimate strength was found, the upper limit of heat treatment was set to 60 °C in 1977. Excessive heat generation of concrete may also have occurred during the in-situ casting phase at winter times, where the hazardous heat development can occur with massive cast-in place structures due to the uncontrollable heat development of the hydration process itself. In general, the critical temperature for the DEF is considered to be above 70 °C in hardening concrete. At such temperatures, the reaction between tricalcium aluminate and gypsum produces unstable monosulphate (instead of ettringite), which can later crystallise to ettringite [7].

In a sulphate attack, the sulphates react with portlandite ($Ca(OH)_2$) to form gypsum. Sulphate ions continue to react with gypsum and calcium aluminate hydrates, monosulphates or unhydrated C_3A to form ettringite. External sulphate attack usually occurs in industrial buildings, bridges or in structures which are in contact with certain types of sulphate-containing soil, groundwater or seawater [7,11]. In Finland, concrete is considered as sulphate-resistant when the tricalcium aluminate content of the cement is limited to a maximum of 3 wt-%. This is often done by using at least 70% blast furnace slag as a binder, as it does not contain tricalcium aluminate [16].

2.3. Finnish building stock

In Finland, the first concrete structures were built in the mid-1800s and the first frame structures of buildings in the 1930s. Post-World War II reconstruction, the large increase in the birth rate and, at the same time, the intensive migration from countryside to cities increased the demand for housing production. The increasing use of precast concrete elements provided a solution for the demand from the 1950s onwards, and Finland experienced a huge precast concrete construction boom in the 1960s and '70s. Today a considerable part of the building stock is from that era, see Fig. 2 [17,18]. Since those years, the pace of construction slowed down, but started to grow again for residential buildings in the 2010s [18]. Most of the facades of residential, commercial and office buildings are made of concrete [19].

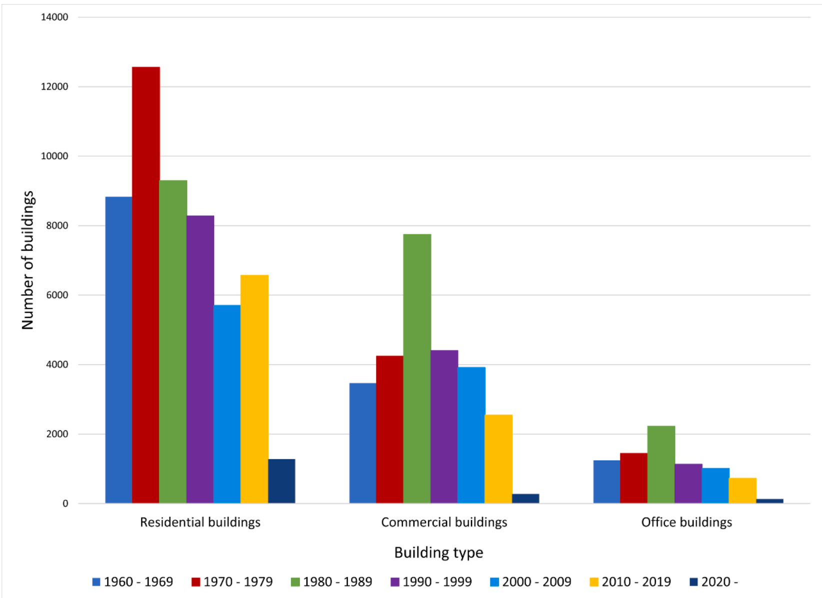


Fig. 2. The number of residential, commercial and office buildings in Finland built during different decades [18].

3. Research data and methods

3.1. Research data

3.1.1. Condition investigation database

The research data consists mainly of two databases. The first of them is a database for deterioration and material properties of existing Finnish concrete façades built between 1960 and 1996, assembled by Tampere University in 2006–2009. The database includes information of 422 condition investigation reports from 947 precast concrete element buildings. The second database has been compiled by corresponding author (as an employee of Ramboll Finland Oy) and it's based on field condition investigations made between 2016 and 2022. This database consists of information from 175 individual thin-section analyses. The initial data from these two databases have been combined in the statistical analysis, and the latter collected data serves as a complementary study to the previous database. Investigation reports includes basic information such as year of construction, year of sampling, façade surface type, geographical location, and orientation of the façade as well as information from thin-section analyses (degree of freeze-thaw damage, degree of DEF). The buildings in this combined database were on average 24 years old at the time of their investigation (min = 7 years, max = 49 years, deviation = 8 years). The numbers of measured data from taken concrete core samples are presented in Table 1.

Analysis based on these databases have been supported by results from the aforementioned master's thesis [2], in which degree of DEF in Finnish façades built in 1990s has been examined from a total of 291 thin-section analyses.

3.1.2. Climate data

Finland is divided in four geographical areas based on both the climatic conditions and the population distribution, see Fig. 3. The division and its fundaments are presented more precisely in Pakkala's dissertation [20]. The geographical areas and the weather stations (with their geographical coordinates) representing them are:

- coastal area, Helsinki-Vantaa airport (60.31, 24.97)
- southern Finland, Jokioinen observatory (60.81, 23.50)
- inland, Jyväskylä airport (62.40, 25.67)
- Lapland (northern Finland), Sodankylä observatory (67.37, 26.63)

The climate data has been obtained from the weather observation data of the Finnish Meteorological Institute. For this article, the data is collected every hour between 1980 and 2022 and it consists of wind direction and precipitation (rain and sleet).

3.2. Research methods

All condition investigation reports carried out after 1997 are made in accordance with *Condition investigation manual for concrete façade panels,* which is firstly published in 1997 and updated in 2002, 2013 and 2019 [21]. Laboratory tests (thin-section analysis and protective pore ratio tests) are made according to standards ASTM C856/C856M – 20 and SFS 4475 [22,23].

This article uses descriptive statistics to summarise and sort data for cross tabulating the following combinations:

- DEF and freeze-thaw damage indicating cracking
- DEF and protective pore ratio
- DEF and orientation of the façade
- DEF and the amount of precipitation
- DEF and different surface types
- DEF and different construction years
- DEF and age of the building at the time of sampling

In addition, the statistical significance between DEF and freeze-thaw damage indicating cracking is analysed with Student's one-way *t*-test of two independent samples. Observations of DEF and freeze-thaw damage indicating cracking have been presented in verbal form in the thin-section analyse reports. For statistical processing, they have been classified on a four-tier classification based on a system presented by Koskiahde [24], see Table 2.

In the condition investigation reports, the orientation of each sample has been reported in an eight-tier classification (main and intermediate orientations) and the collected weather observation data has been reported separately for every 1/10°. For statistical analysis, the amount of precipitation has been changed to an eight-tier classification.

3.3. Validation of research data and methods

In Finland, the condition investigations of concrete façade structures have become more systematic from early 1990′s onwards and the first guidelines were published in *Condition investigation manual for concrete façade panels* in 1997 [21]. The condition investi-

Table 1
The amounts of measured data from taken concrete core samples.

Measured data	Number
Freeze-thaw damage indicating cracking	1533
Degree of DEF	1517
Protective pore ratio	2362

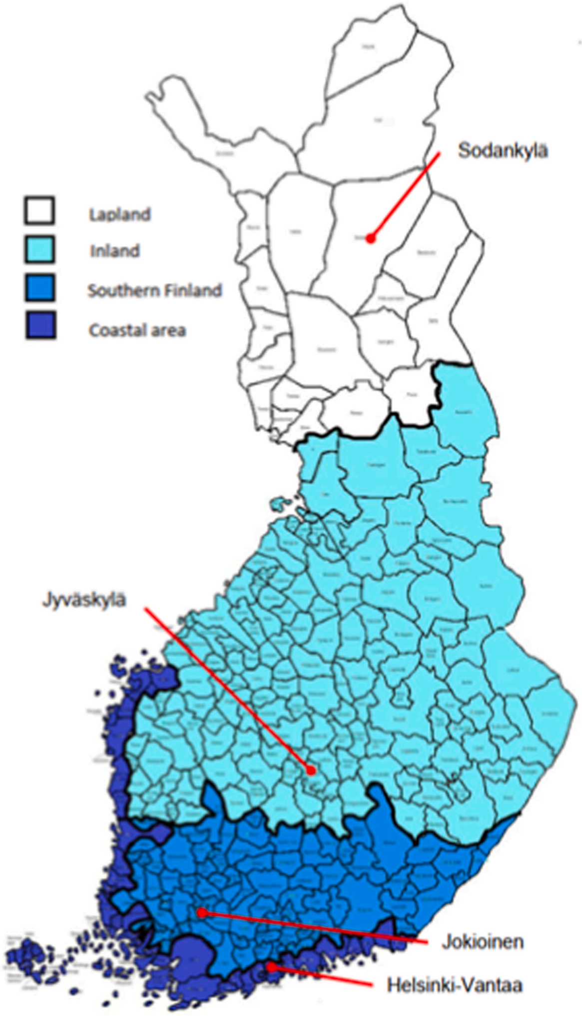


Fig. 3. Four geographical areas based on both the climatic conditions and the population distribution [20].

Table 2
Classification of DEF and freeze-thaw damage indicating cracking [24].

Class/ designation	Degree of DEF	Freeze-thaw damage indicating cracking
1	None.	None.
2	Incipient filling, small individual crystals.	Incipient. Crack widths < 0.01 mm and lengths < 10 mm
3	Continuous, circular filling. Thickness of deposit 0.01–0.05 mm.	Frequent. Crack widths 0.01–0.1 mm and lengths ≥10 mm. Frequency < 0.25 cracks/mm and < 50% of aggregate loosened.
4	Widespread filling of pores, systematic deposit > 0.05 mm.	Severe. many cracks > 0.1 mm wide and > 25 mm long. Frequency ≥0.25 cracks/mm or ≥50% of aggregate loosened.

gation reports made before that are executed by those individuals who have written the aforementioned manual and they can therefore, on the basis of their reliability, be assimilated to subsequent reports. The condition investigation methods for old structures have always their uncertainties, but they can be considered as reduced as possible since the data analysed consists of thousands of individual laboratory samples.

Previous studies [1] have shown that the geographical location of the building has no effect on the properties of concrete structures and the production of concrete elements has been of uniform quality throughout Finland. Also, different surface types have been used relatively evenly across Finland. The amount of precipitation varies considerably in different parts of Finland [20] and it has been taken into account in this study by collecting data from four different geographical locations.

4. Results and discussion

4.1. DEF and observed freeze-thaw damage indicating cracking

Observations of DEF and the freeze-thaw damage indicating cracking are shown in a cross tabulated form in Fig. 4. The overwhelming majority (34%) of the observations are cases where no DEF or freeze-thaw damage indicating cracking has been observed. The share of cases where both widespread cracking and DEF occurs, is only 0.5% of all observations. Only when widespread DEF has been observed, the amount of widespread cracking is also clearly higher.

The statistical significance of this difference was examined using a Student's one-way *t*-test of two independent samples with the following null hypothesis: "Freeze-thaw damage indicating cracking does not occur significantly more in cases where widespread DEF is observed".

Student's t-test analyses whether the means of two populations are different. As a result, it gives a p-value which tells how likely the null hypothesis is true. The significance level is often considered to be 0.05 [5%], at values below the null hypothesis can be rejected, and the difference is considered statistically significant. With the data used in this article, the test gives a p-value of 0.005, see Table 3. The null hypothesis can then be rejected, and the difference is considered statistically significant.

This partly confirms the conclusions stated in previous publications [5–9,11,12,17] that DEF lowers the freeze-thaw resistance of concrete by filling pores and preventing porewater escaping to large pores. However, based on the analysis with the initial data, it seems that there should be really plenty of filling before DEF significantly participates in freeze-thaw damage cracking.

Cracking of concrete allows soaking of WDR easier and deeper in the pore structure. It also retains water longer in pore structure, which might explain higher amount of widespread DEF, too. However, results shown later in chapter 4.4 does not support this hypothesis. In condition investigation samples are not taken from far damaged facades, so the possible cracking in samples can be seen

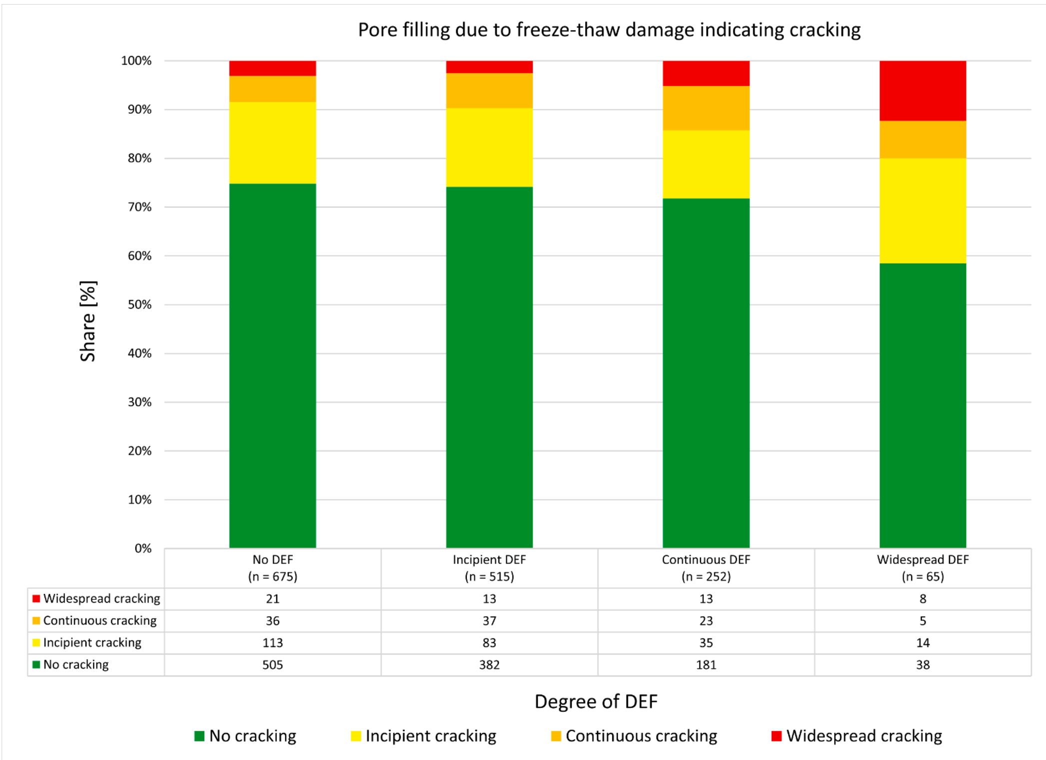


Fig. 4. Shares of DEF and freeze-thaw damage indicating cracking observations.

Table 3
Results from the Student's t-test.

Group statistics				
Group	Sample size	Mean	Std. Deviation	Std. Error Mean
No DEF - continuous DEF	1442	1.3911	0.75316	0.01983
Widespread DEF	65	1.7385	1.04995	0.13023
Independent Samples Test				
	T	**df**	**Significance (p-value), one sided**	
Unequal variances	−2.637	67.002	0.005	

only with microscope. Due to very narrow cracking during the incipient freeze-thaw damage phase the water absorption is not significantly higher.

4.2. DEF and the protective pore ratio

Observations of DEF and protective pore ratio are shown in cross tabulated form in Fig. 5. Most widespread DEF observations (86%) have been made in cases where the protective pore ratio is less than 0.1, meaning poor freeze-thaw resistance of concrete. Widespread DEF has not been observed at all in cases where the protective pore ratio has been 0.15 or higher. This means that insufficient air-entrainment increases the risk of damage to concrete not only due to freeze-thaw damage by other drivers like moisture exposure or surface type, but also due to the pressure generated by DEF. It seems that DEF should not have a significant effect on the freeze-thaw damage when successful air-entrainment is ensured.

4.3. DEF, the orientation of the façade and the amount of precipitation

Observations of DEF in different sampling orientations are shown in cross tabulated form in Fig. 6. The amount of precipitation towards different facade orientations is shown in Figs. 7 and 8. Presented precipitation is as an average annual amount between year of built and sampling year.

The orientation of the façade (the amount of precipitation) has a clear relationship with the degree of DEF. Widespread DEF was observed most in the south (34.4%), west (17.2%), and southwest (14.1%) façades of all widespread DEF observations. Same façades are also the most exposed to wind-driven rain. Samples with widespread DEF have received nearly twice as much WDR exposure than samples where no DEF has been observed at all.

The findings confirm the conclusions of previous studies that the DEF requires sufficient moisture exposure to occur [8]. It can now be refined how much it is in a certain orientation in order to detect different degrees of DEF.

4.4. DEF and different surface types

Widespread DEF observations are heavily concentrated on uncoated plain concrete façades and on façades with ceramic tile or brick tile cladding, see Fig. 9. This is because uncoated concrete surfaces get the most severe exposure during rain. In clinker tile and brick tile cladded façades, water enters deeper into the structure through the porous mortar joints of the tiles (clinker tile claddings), as well as through porous brick tiles and their mortar joints, but these structures cannot dry as fast as other surface types. White concrete samples are younger than others, mostly made 1990's. The guideline with requirements for durable concrete similar to present were published in 1989 [15]. Since then, using air-entrainment in concrete has been more common. So, the freeze-thaw resistance of white concrete is remarkable better than earlier concrete [1,2].

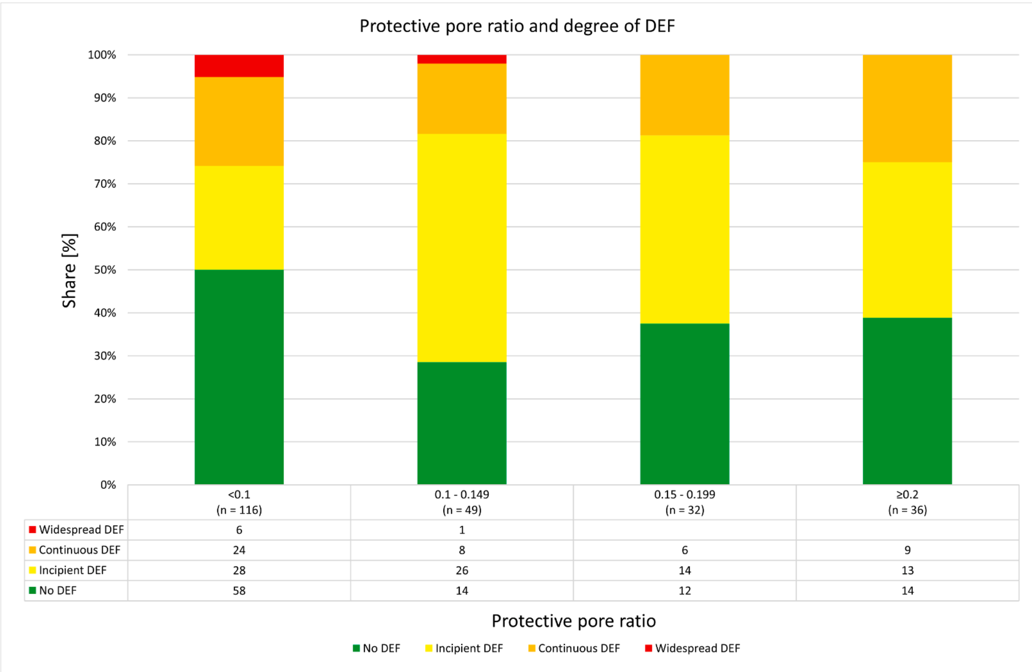


Fig. 5. Shares of DEF and protective pore ratio observations.

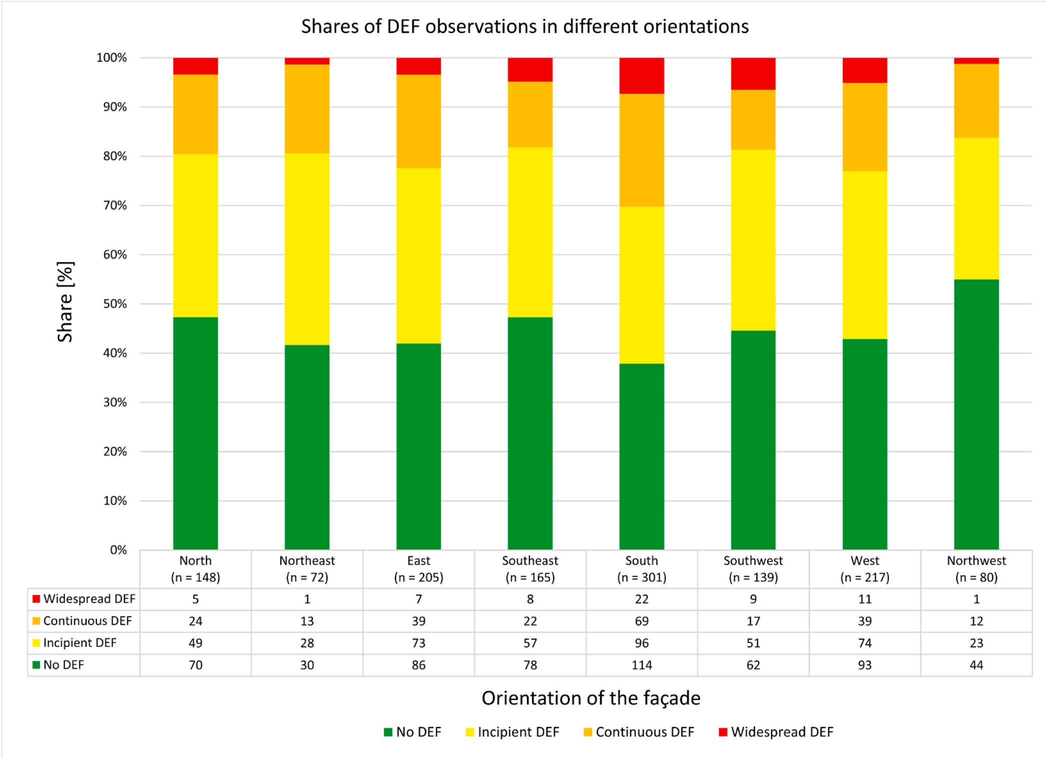


Fig. 6. Shares of DEF observations in different orientations.

Exposed aggregate concrete was common in 1970s and ‘80s. The freeze-thaw resistance of it is very poor [1]. In most cases freeze-thaw damage was so far-advanced and widespread that no samples were taken from those facades during condition investigation. The damage could be seen by naked eye.

4.5. DEF, different construction years and age of the building

Figs. 10 and 11 show the observed degree of DEF in buildings of different age and from different construction era. The age of the building is the time from construction year to the sampling year. The share of widespread DEF observations from all cases is just 4.4%. This is because that the façade structure must meet certain properties and conditions for DEF to be extensively occur. As discussed in the previous chapters, if the façade is protected from WDR or has the sufficient surface type, DEF will not occur in concrete structure. If the DEF observations are generalised to cover the entire residential, commercial, and office building stock in Finland (87 027 buildings built since 1960) [18], it can be estimated that widespread DEF will affect 3786 of these buildings. Incipient DEF will affect 29 946 buildings and continuous DEF 14 571 buildings.

From the 1980s onwards, the total share of DEF observations compared to older buildings is 9–20% higher. Newer concretes contain more cement than before (higher compression strength), which means that there is also more material that allows delayed ettringite to form compared to older concrete grades. Typical compression strength of concrete until 1980s was C20, and onwards C25 to C35. Cement used in Finnish precast concrete panels has been Portland cement (OPC) until present days.

5. Conclusions

This study investigated the occurrence and impact of DEF in Finnish concrete façades. Many previous studies have confirmed the different formation mechanisms of DEF. The purpose of this study was to produce a deeper understanding of the mechanisms and exposure causing DEF and quantitatively determine the extent and significance of it by using statistical analysis. Based on the results, the following conclusions were drawn:

- DEF does reduce the freeze-thaw resistance of concrete, but it must have been formed extensively before it causes freeze-thaw damage.
- DEF is detected in approximately 50% of all samples, but the number of widespread filling observations is very low.
- DEF requires specific conditions to occur, and it does not occur extensively at all if the structure is protected from WDR, protective pore ratio is > 0.15 or if the used surface type either prevents the structure from getting wet and/or allows it to dry sufficiently.
- The most susceptible façade surface types to DEF are plain, uncoated concrete surfaces, and façades with ceramic or brick tile cladding.

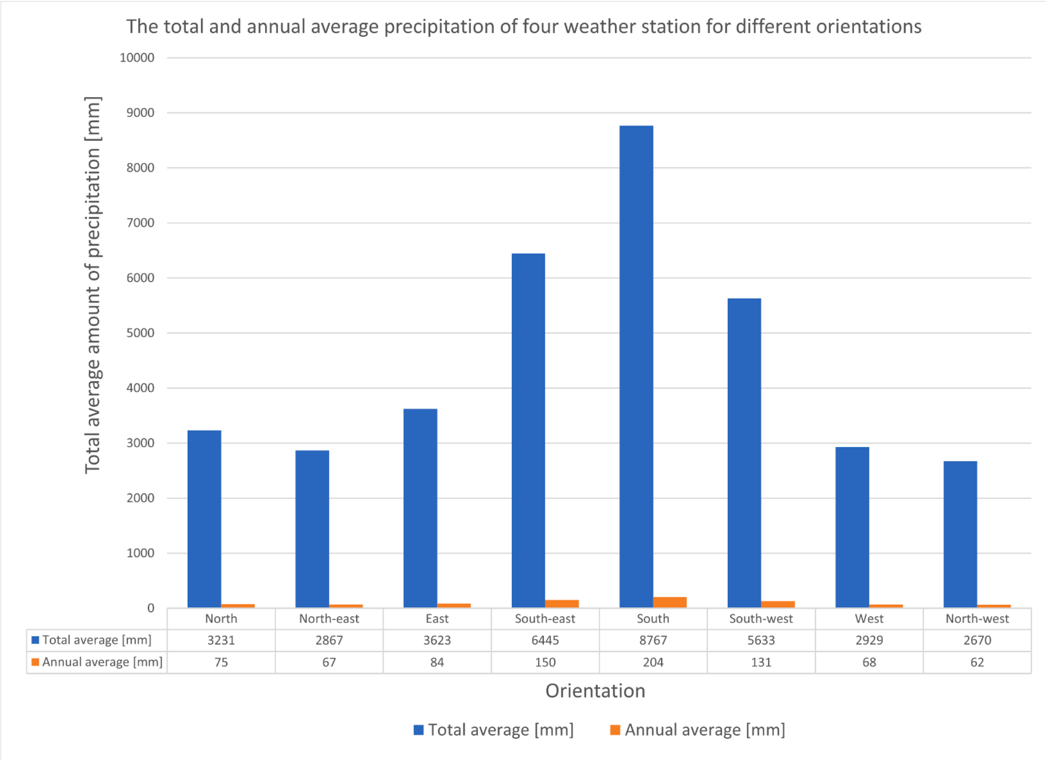


Fig. 7. The total and annual average precipitation of four weather station for different orientations.

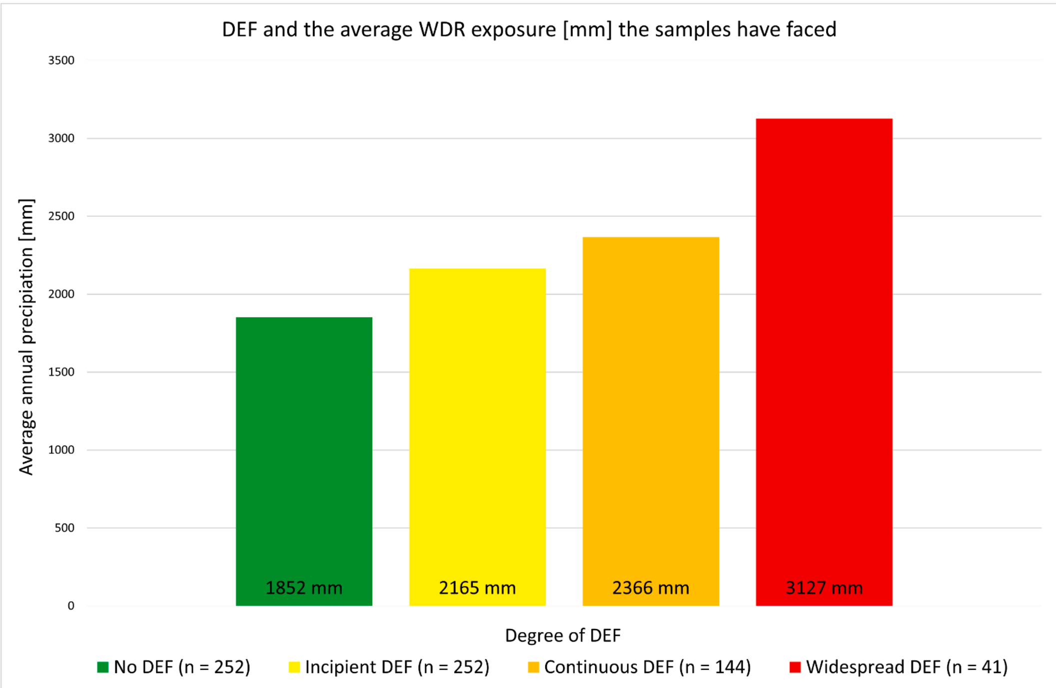
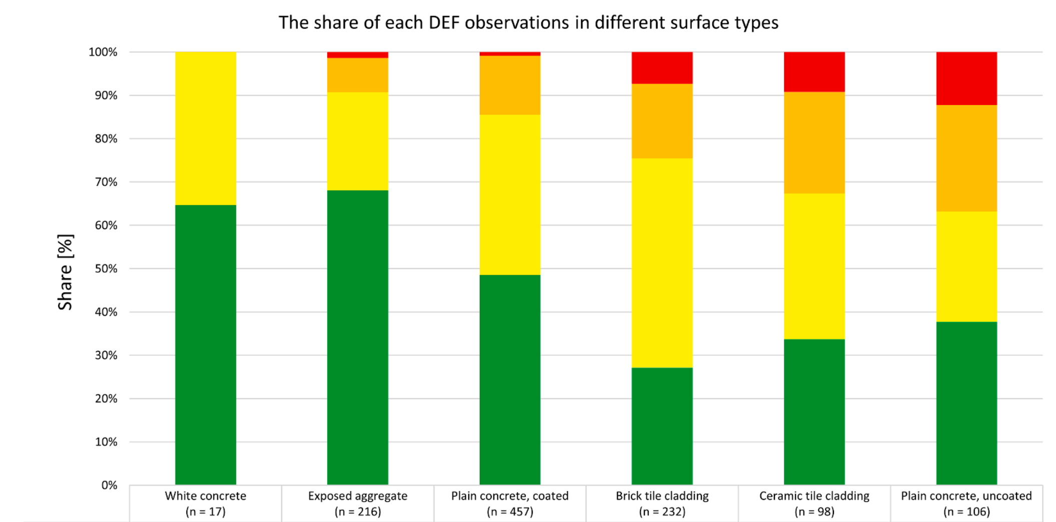
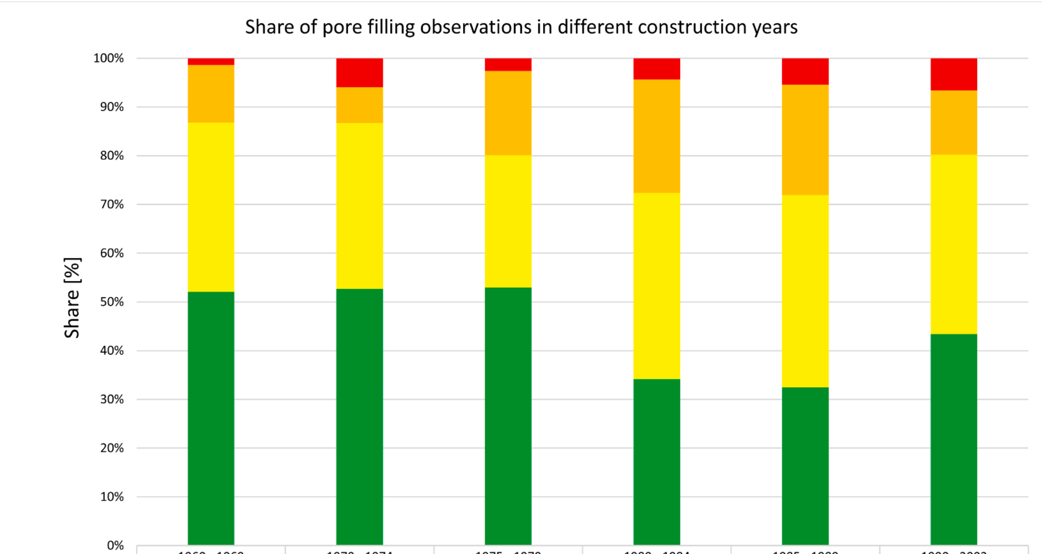


Fig. 8. DEF and the average WDR exposure [mm] the samples have faced.



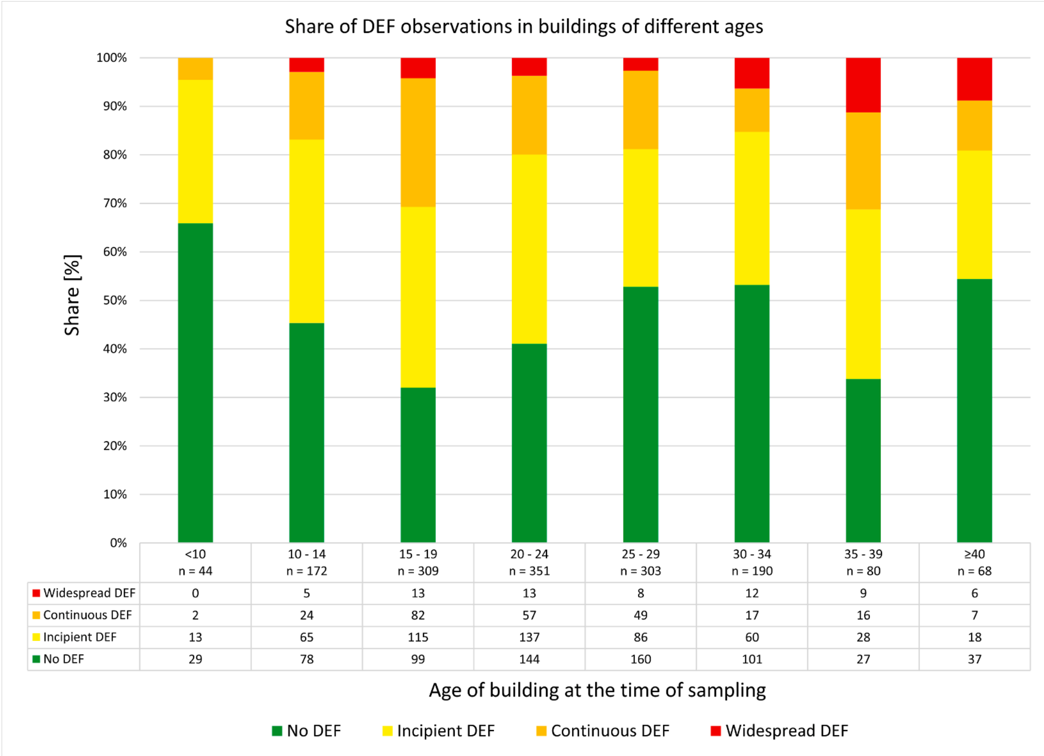
	White concrete (n = 17)	Exposed aggregate (n = 216)	Plain concrete, coated (n = 457)	Brick tile cladding (n = 232)	Ceramic tile cladding (n = 98)	Plain concrete, uncoated (n = 106)
Widespread DEF		3	4	17	9	13
Continuous DEF		17	62	40	23	26
Incipient DEF	6	49	169	112	33	27
No DEF	11	147	222	63	33	40

Fig. 9. The share of each DEF observations in different surface types.



	1960 - 1969 n = 144	1970 - 1974 n = 203	1975 - 1979 n = 387	1980 - 1984 n = 322	1985 - 1989 n = 203	1990 - 2003 n = 258
Widespread DEF	2	12	10	14	11	17
Continuous DEF	17	15	67	75	46	34
Incipient DEF	50	69	105	123	80	95
No DEF	75	107	205	110	66	112

Fig. 10. Share of pore filling observations in different construction years.



	<10 n = 44	10 - 14 n = 172	15 - 19 n = 309	20 - 24 n = 351	25 - 29 n = 303	30 - 34 n = 190	35 - 39 n = 80	≥40 n = 68
Widespread DEF	0	5	13	13	8	12	9	6
Continuous DEF	2	24	82	57	49	17	16	7
Incipient DEF	13	65	115	137	86	60	28	18
No DEF	29	78	99	144	160	101	27	37

Fig. 11. Share of void filling observations in buildings of different ages.

- WDR is the main exposure type affecting DEF in Finland and it occurs mostly on façades facing south-southwest.
- Façade elements are no longer heat-treated at harmful temperatures and external sulphate sources can be considered negligible as a cause for DEF in Finnish façade structures.
- Newer cement-rich concretes produce more DEF than before. Increased using of air-entrainment agents and thus the larger volume of pore network, DEF must also be formed more in order to significantly reduce the freeze-thaw resistance of concrete.

The main limitation is the fact that the data used in this article does not provide information about the water-cement ratio or the amount of cement in old concrete façades. Because of this, DEF and the drivers causing it will have to be examined indirectly, as in this article. New laboratory tests cannot draw direct conclusions about the water-cement ratio, or the amount of cement used in old structures.

The authors identified two things that should be studied in more detail in the future. Since water is transferred mainly capillary in the pore network of concrete, the total capillary porosity of concrete certainly plays a role in the formation of delayed ettringite. In addition, from the point of view of the frost resistance of concrete, it would be worth examining whether freeze-thaw damage has a higher weight due to moisture stress or the number of freeze thaw cycles in the Finnish climate.

CRediT author statement

Niko Lindman: Methodology, Formal analysis, Investigation, Resources, Data Curation, Writing - Original draft, Visualization.
Elina Lahdensivu: Investigation, Resources, Writing - Review & Editing.
Jukka Lahdensivu: Conceptualization, Project administration, Validation, Writing - Review & Editing, Supervision.
Toni Pakkala: Writing – Review & Editing, Visualization.

Declaration of competing interest

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Data availability

The authors do not have permission to share data.

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