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## Predicting the Freeze-Thaw Damage Initiation in Concrete Facades with Different Surface Types



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## ABSTRACT

With statistical methods and by analysing a comprehensive database of concrete facade condition investigation reports and utilising the newly developed Relative Freeze-Thaw Exposure (RFE) Index, this article presents a novel service life model to estimate the probability of freeze-thaw damage initiation as a function of time. The model provides property owners with cost-effective baseline information for scheduling facade repairs and planning the extent of necessary restoration work.

The model considers different geographical locations, facade directions and used surface type. It was initially applied to current climate conditions, but it also allows to calculate the probability of freeze-thaw damage initiation with future climate scenarios.

The results showed that freeze–thaw damage initiates most rapidly in painted concrete facades. In contrast, the damage occurs significantly later in unpainted plain concrete facades, due to their greater ability to dry between rain events. This highlights the issue of neglected maintenance in painted concrete facades, as they should be recoated approximately every 15 years. The second shortest service life was predicted for clinker-tiled surfaces. This is due to their characteristic tendency to allow wind-driven rain to penetrate the concrete through the seams, while the dense tiles prevent the concrete dry efficiently.

**Key words:** service life model, freeze-thaw damage, climatic exposure, durability of concrete

## 1. INTRODUCTION

The main degradation mechanisms of concrete facades in cold climates are carbonation-induced corrosion and freeze-thaw damage [1 - 3]. While the propagation of corrosion has been extensively studied with significant success [4 - 7], numerous studies have emphasised that no practical solution currently exists for predicting the evolution of freeze-thaw damage in existing concrete structures [3, 8 - 14]. Several challenges contribute to this gap, including:

- Existing service life models have been primarily developed for new construction design.
- These models often require expensive and/or time-consuming laboratory tests, limiting their practical application.
- Many models have been developed and validated using concrete grades that are not currently used in Finland.
- They do not adequately consider the actual number of freeze-thaw cycles or the influence of wind-driven rain exposure.

In Finland, one-third of the building stock's floor area consists of residential, commercial, and office buildings [15]. These buildings are now between 36 – 65 years old, and most of their facades are made of concrete [16]. Although concrete structures built following the current concrete codes are theoretically freeze-thaw durable, studies indicate that the actual quality of concrete in many cases has not met the required standards [3, 17]. This underscores the importance of assessing the impact of present and changing climate conditions to estimate their remaining service life and inform maintenance strategies and future repair cost projections.

With statistical methods and by analysing a comprehensive database of concrete facade condition investigation reports and utilising the newly developed Relative Freeze-Thaw Exposure Index (RFE) introduced by Pakkala et al. [18], this article presents a novel service life model to estimate the probability of freeze-thaw damage initiation as a function of time with different surface types. In addition, a similar approach was employed to study the decrease in tensile strength of concrete as a function of time.

## 2. BACKGROUND

Simply put, freeze-thaw damage in concrete refers to cracking caused by the pressure of freezing pore water. Each concrete structure has a critical degree of water saturation above which freeze-thaw damage can occur. Concrete itself can withstand repeated freeze-thaw cycles, but damage arises only when sufficient free water is present in its pore system [19 - 22]. For concrete facades, this water primarily comes from Wind-Driven Rain (WDR). Thus, the main stress factors for freeze-thaw damage are the number of cycles and the amount of water in the concrete's pore system. Although the relationship between freeze-thaw damage and these stress factors has been established, the significance of each factor has remained unclear. Moreover, no standardised method has existed to estimate the severity of freeze-thaw loads.

Lisø et al. [23] introduced a combination of the Frost Decay Exposure Index (FDEI) and Freezing Point Crossings (FPC) to characterize the risk of freeze-thaw damage in porous, mineral-based materials. In their research, freeze-thaw cycles were defined as temperature crossings over the freezing point ( $0^{\circ}\text{C}$ ), with the number of cycles calculated as the annual average number of days with such crossings. The FDEI correlated FPC to the amount of liquid precipitation recorded on the day of a freezing point crossing and the preceding two to four days. By presenting FDEI and FPC in the same diagram, Lisø et al. [23] estimated freeze-thaw damage risk by analysing their relationship.

However, Pakkala [11] identified several issues with this approach. The actual freezing point in a concrete pore structure is typically lower than  $0^{\circ}\text{C}$ , often below  $-5^{\circ}\text{C}$  depending on pore size [21]. Consequently, freezing point crossings should be calculated with a lower temperature threshold and only after rain events to reflect the presence of free water in the pores. Pakkala [11] investigated freeze-thaw cycles in Finland using a  $-5^{\circ}\text{C}$  threshold. This study included the average annual rainfall and sleet within 72 hours before a cycle, as well as the average amount of WDR within the same period. Using recorded climate data from 1980 to 2009 and projections for 2050 and 2100 based on the IPCC SRES A2 scenario [24], Pakkala analysed four geographical regions and different facade directions, accounting for wind direction during rain events. The findings showed a general decrease in the number of freeze-thaw cycles across all studied locations, except in northernmost Finland (Lapland). The annual average WDR before freeze-thaw cycles decreased in coastal and southern areas but increased elsewhere. The intensity of freeze-thaw loads, defined as the average amount of WDR within 72 hours before a cycle, slightly decreased in coastal areas but increased in all other locations. Coastal areas consistently experienced the highest freeze-thaw loads, with inland locations projected to approach present coastal load levels in future climates.

In his doctoral thesis, Pakkala [11] emphasised the need for improved methods to evaluate freeze-thaw stress severity, specifically by comparing the number of cycles following rain events, the annual WDR before cycles, and the WDR before individual cycles. Building on this, Pakkala et al. [18] compared these situations with freeze-thaw damage observations from thin-section

analyses taken from facades and found that the amount of WDR before an individual freeze-thaw cycle explained the damage most significantly. As a result, they introduced the RFE index, which describes the relative annual freeze-thaw stress on facades in different orientations, geographical locations, and climate scenarios, see Table 1. The climate change effect was studied by using updated climate change scenarios (Representative Concentration Pathways, RCPs) produced by Finnish Meteorological Institute (FMI) in a RASMI-project [25], where present and projected future climates for the time series 2050 and 2080 were produced. RCP2.6, RCP4.5, and RCP8.5 are representing small, medium, and very large greenhouse-gas emissions, respectively.

*Table 1 – RFE index in different geographical locations and facade directions [18]*

Location	Direction	Used climate scenario						
		Present	2050			2080		
			RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Coastal area	North	12	15	15	15	15	15	20
	East	23	26	29	26	27	26	33
	South	38	39	43	39	40	39	34
	West	19	20	21	21	20	21	24
Southern Finland	North	9	9	10	12	9	12	11
	East	18	18	20	22	18	23	18
	South	22	22	22	24	22	25	20
	West	13	14	16	17	14	18	13
Inland	North	9	9	9	9	9	10	13
	East	12	14	16	16	14	16	19
	South	14	14	15	15	15	16	23
	West	9	8	9	9	8	9	14
Lapland	North	10	9	8	8	9	8	7
	East	12	11	11	10	11	11	11
	South	13	12	11	12	12	11	11
	West	7	5	5	4	5	5	5

The RFE index shows an increase in coastal areas across all scenarios and directions, with one exception: under the 2080 RCP8.5 scenario for the southern direction, the index decreases significantly. Despite this anomaly, the RFE index remains highest in coastal areas compared to other studied locations. Only a few individual values from other locations exceed the lowest RFE index values recorded in coastal areas, such as southern-facing structures in southern Finland and inland regions under the 2080 RCP8.5 scenario compared to northern-facing structures in coastal areas. In southern Finland, the RFE index remains generally at present levels regardless of the scenario. In inland areas, it also remains at current levels except for notable increase under the 2080 RCP8.5 scenario. Lapland is the only location where the RFE index decreases across all directions and scenarios compared to the present climate.

Inland is unique in that the RFE index shows greater variability between directions compared to current conditions, particularly under the 2080 RCP8.5 scenario. In other locations, the differences in RFE index across directions remain similar to present levels or even out.

### 3. RESEARCH DATA AND METHODS

#### 3.1 Research data

The research data consist of a database compiled from concrete facade condition investigation reports, including laboratory analyses (see Table 2), collected by Tampere University and Ramboll Finland Oy. These reports provide essential information, such as the year of construction (1960 - 2003), the date of the condition investigation (1993 - 2022), the geographical location, and the sampling direction, specified to main and intermediate compass directions.

*Table 2 – Research data*

Laboratory analysis	Standard	number	Age of buildings [years]			
			Average	Min.	Max.	Std. deviation
Thin-section analysis	ASTM C856/C856M-20	744	22.5	7	49	9.2
Tensile strength	SFS 5445	1722	24.9	7	49	8.1

The data from thin-section analyses were initially processed by converting qualitative observations of freeze-thaw damage indicating cracking into numerical classifications. This conversion was necessary because the original laboratory test reports described these observations in verbal form. The classification system applied for this conversion is based on the approach outlined by Koskiahde [26] and is detailed in Table 3.

*Table 3 – Conversion of verbal freeze-thaw damage observations [26]*

Class	Freeze-thaw damage indicating cracking
1	No sign of cracks due to freeze-thaw damage.
2	Initial freeze-thaw cracking. Sporadic microcracks observed, typically <0.01 mm in width and <10 mm in length. No cracks exceeding 0.1 mm in width and 25 mm in length allowed.
3	Frequent freeze-thaw cracking. Crack pattern commonly parallel to the surface. Typical crack widths 0.01 - 0.1 mm and lengths $\geq 10$ mm. Incidence <0.25 cracks/mm and <50% of paste-aggregate (coarse-grained aggregate) interfaces detached.
4	Severe freeze-thaw cracking. Several cracks >0.1 mm in width and >25 mm in length. Incidence $\geq 0.25$ cracks/mm or $\geq 50\%$ of paste-aggregate interfaces detached.

#### 3.2 Research methods

In the initial phase of the calculation, each sample in the database was assigned an RFE index based on its geographic location and exposure direction. Since Pakkala et al. [18] have only used the main compass directions in their analysis, for samples collected from intermediate compass directions, the RFE index was calculated as the average of the values for the adjacent main compass directions, see Table 4. By examining the weather observation data, averaging the RFE index of the main compass directions appears to slightly overestimate the northern intermediate directions and slightly underestimate the southern intermediate directions. The annual extremes of freeze-thaw exposure remain still unchanged in the analysis.

Table 4 – RFE index in different geographical locations and facade directions

Location	Direction	Used climate scenario						
		Present	2050			2080		
			RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Coastal area	North	12	15	15	15	15	15	20
	Northeast	17.5	20.5	22	20.5	21	20.5	26.5
	East	23	26	29	26	27	26	33
	Southeast	30.5	32.5	36	32.5	33.5	32.5	33.5
	South	38	39	43	39	40	39	34
	Southwest	28.5	29.5	32	30	30	30	29
	West	19	20	21	21	20	21	24
	Northwest	15.5	17.5	18	18	17.5	18	22
Southern Finland	North	9	9	10	12	9	12	11
	Northeast	13.5	13.5	15	17	13.5	17.5	14.5
	East	18	18	20	22	18	23	18
	Southeast	20	20	21	23	20	24	19
	South	22	22	22	24	22	25	20
	Southwest	17.5	18	19	20.5	18	21.5	16.5
	West	13	14	16	17	14	18	13
	Northwest	11	11.5	13	14.5	11.5	15	12
Inland	North	9	9	9	9	9	10	13
	Northeast	10.5	11.5	12.5	12.5	11.5	13	16
	East	12	14	16	16	14	16	19
	Southeast	13	14	15.5	15.5	14.5	16	21
	South	14	14	15	15	15	16	23
	Southwest	11.5	11	12	12	11.5	12.5	18.5
	West	9	8	9	9	8	9	14
	Northwest	9	8.5	9	9	8.5	9.5	13.5
Lapland	North	10	9	8	8	9	8	7
	Northeast	11	10	9.5	9	10	9.5	9
	East	12	11	11	10	11	11	11
	Southeast	12.5	11.5	11	11	11.5	11	11
	South	13	12	11	12	12	11	11
	Southwest	10	8.5	8	8	8.5	8	8
	West	7	5	5	4	5	5	5
	Northwest	8.5	7	6.5	6	7	6.5	6

The RFE index was subsequently multiplied by the sample's age (calculated from the building's completion to the condition investigation date). The resulting  $RFE_{total}$  index represents the cumulative climate exposure experienced by the facade over its lifetime. Cross-tabulations were conducted to compare the  $RFE_{total}$  index between samples with no freeze-thaw damage observed in thin-section analysis and those where freeze-thaw damage had initiated (incipient, continuous, or widespread). These analyses were performed for all samples collectively and separately for different facade surface types. In addition to freeze-thaw damage observed in thin-section analyses, a similar approach was employed to study the decrease in tensile strength of concrete as a function of  $RFE_{total}$  index. This calculation shows the probability of that tensile strength has decreased below 1.0 MPa and below 0.5 MPa as a function of  $RFE_{total}$  index. Based on the cross-tabulation, an exponential equation can be determined using the following formula:

$$y_{predicted} = a * e^{bx} \tag{1}$$

where,  $a$  is the scaling factor,  $b$  is the rate parameter that defines the speed of deterioration, and  $e$  denotes the base of the natural logarithm (approximately 2.718). The coefficient of determination  $R^2$  can be further calculated by applying the least squares method to estimate  $a$  and  $b$ , ensuring that the sum of squared residuals ( $SSR$ ) is minimised:

$$R^2 = 1 - \frac{SSR}{SST} \quad (2)$$

where,  $SSR$  is the sum of squared residuals (difference between observed and predicted values):

$$SSR = \sum_{i=1}^n (y_i - y_{predicted,i})^2 \quad (3)$$

$SST$  is the total sum of squares (variability of observed values around the mean):

$$SST = \sum_{i=1}^n (y_i - \bar{y})^2 \quad (4)$$

Using the equations derived from the cross-tabulations, the proportion of damaged samples can be determined for any given  $RFE_{total}$  index. This enables the translation of  $RFE_{total}$  index into years when the age and geographical location of the facade, and sampling direction are known. Consequently, this approach allows the progression of freeze-thaw damage to be analysed as a function of time.

### 3.3 Validation of research material and methods

In Finland, facade condition investigations have been systematically conducted since the early 1990's, enabling comparability across reports from different parties and years. The laboratory tests referenced in this article were carried out by accredited research laboratories using standardised methods [3]. These tests, commonly employed in Finland for facade condition investigations, ensure reliable and consistent data. Previous studies have shown that the geographical location of buildings does not significantly affect the properties of the concrete pore structure in Finland. Therefore, the quality of concrete production can be considered uniform across the country. Facade surface types are evenly distributed throughout Finland, meaning that the intensity of climate stress can primarily be attributed to geographical location and facade orientation [3, 11].

## 4. RESULTS AND DISCUSSION

### 4.1 $RFE_{total}$ index and thin-section analyses

Figure 1 illustrates the probability of freeze-thaw damage initiation as a function of  $RFE_{total}$  index with different surface types. The same trendlines for each surface type, along with the actual data points, are also presented separately in Figure 3. The reliability of the calculations can be evaluated with the coefficient of determination  $R^2$ , as shown in Table 5. Even at its lowest value (clinker tile cladding,  $R^2 = 0.87$ ), the coefficients indicate a very strong fit.

Table 5 – Obtained coefficients of determination  $R^2$

Facade surface type	Coefficient of determination $R^2$	Number of samples
All combined	0.96	713
Clinker tile cladding	0.87	91
Painted plain concrete	0.98	116
Plain concrete	0.95	87
Brick tile cladding	0.95	179
Exposed aggregate concrete	0.92	242

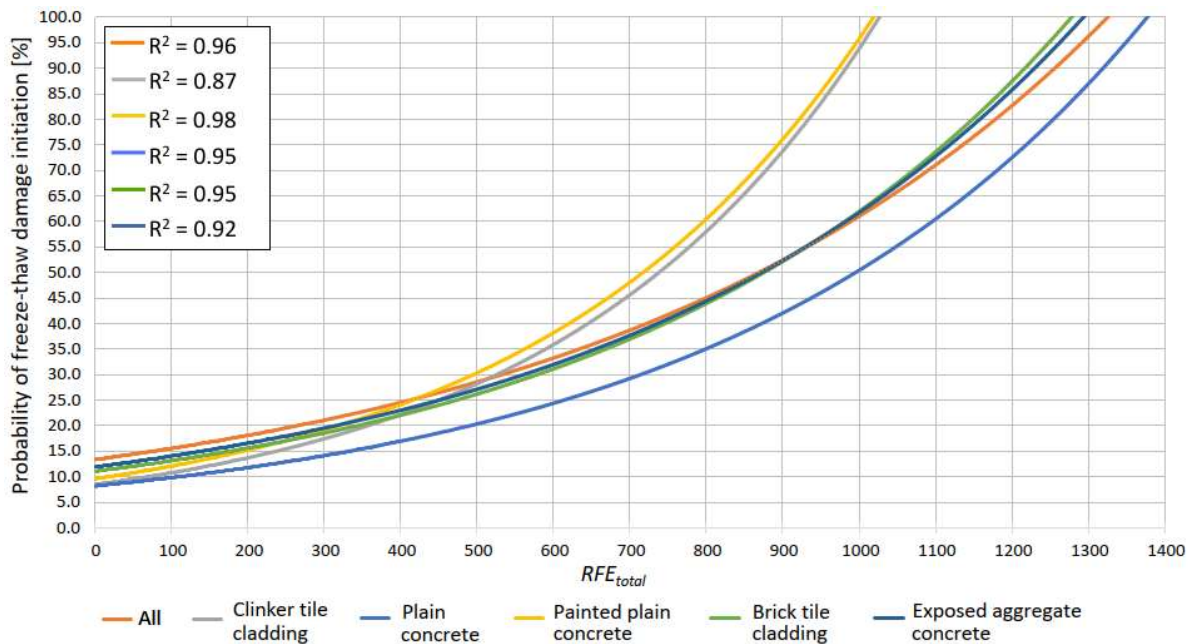


Figure 1 – The probability of freeze-thaw damage initiation with different surface types.

From the lines representing different facade surface types, it can be observed that plain concrete facades have the longest service life, while painted plain concrete facades have the shortest. This is due to the inadequate maintenance of painted concrete surfaces in Finland. The service life of coatings used on facades typically lasts around 15 years, after which recoating should be performed. If this maintenance is neglected, wind-driven rain can infiltrate beneath the coating through damaged spots and fail to dry properly. This significantly increases the moisture stress on the concrete compared to other surface types. A similar trend is observed with clinker tile facades: while wind-driven rain can enter through the seams of the tiles, the dense nature of the tiles prevents the concrete from drying as efficiently as in other surface types. It should be noted that the significantly shorter service life of these surface types is also influenced by the fact that, according to previous studies, their air entrainment has been found more unsuccessful than other surface types [3].

Calculation example (also shown in Figure 2): The object of the study is a facade with brick tile cladding located in southern Finland. The facade is 40 years old and faces southeast. Table 4 shows the RFE index of 20 for the facade, resulting in an  $RFE_{total}$  index of  $20 \cdot 40 = 800$ . From Figure 2, we locate 800 on the x-axis ( $RFE_{total}$ ), where the y-value of the brick tile cladding curve is approximately 44.5%. This indicates that freeze-thaw damage has initiated on 44.5% of the facade area. To project the situation 20 years from now, we add 20 years to the facade’s current age, resulting in an  $RFE_{total}$  index of 1200. In this case, freeze-thaw damage would have started in approximately 88% of the facade area.

In theory, the curves should start from zero, as freeze-thaw damage does not typically occur in newly manufactured facade elements, with very few exceptions. However, this article examines the averages from laboratory analyses of older facades (averaging  $\approx 24$  years in age), which explains this bias. As a result, the model performs less accurately for very young facades but offers a good level of reliability when applied to older facades. In the calculations, an attempt was made to force the curves to start from zero. While this did not alter the order of service life among different surface types, it significantly reduced the estimated service life for all surface types.

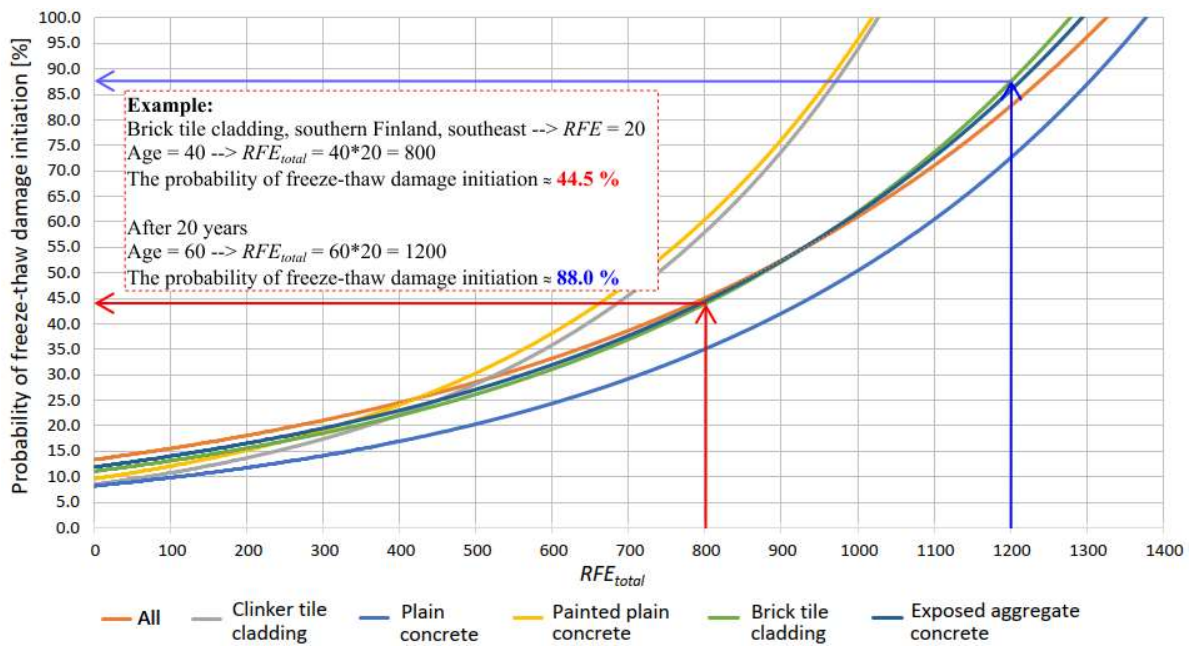
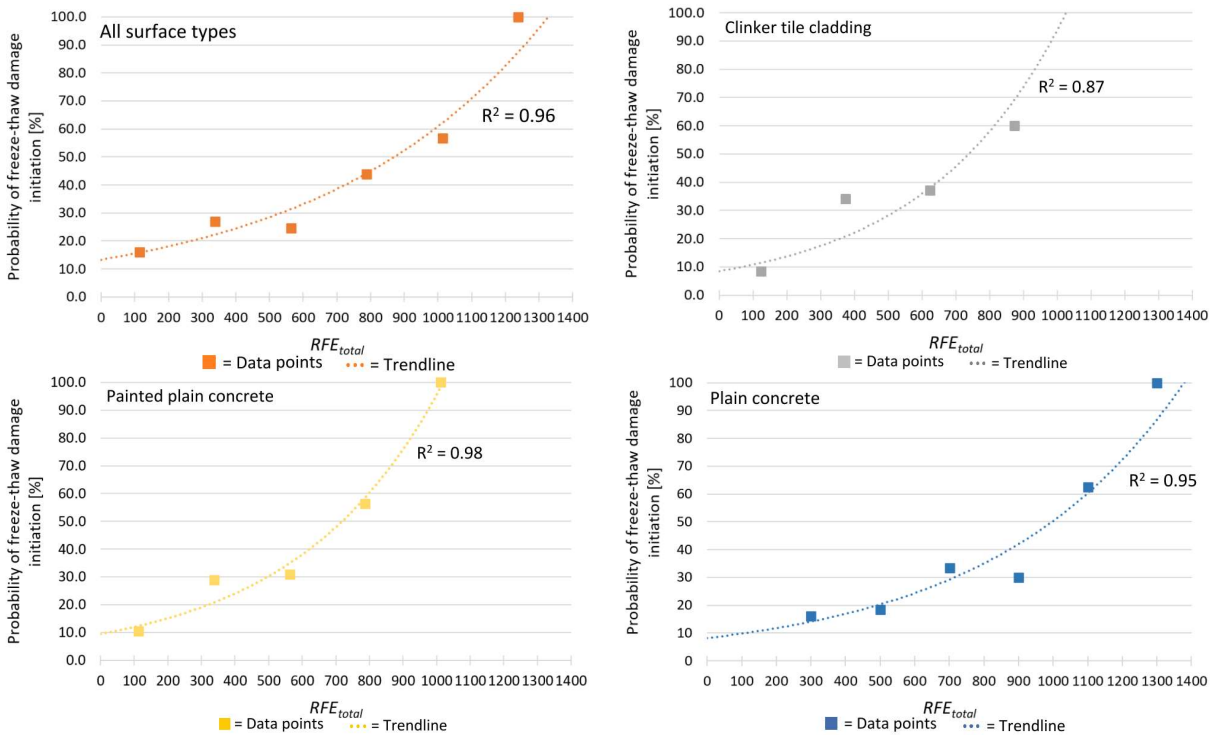


Figure 2 – Calculation example.



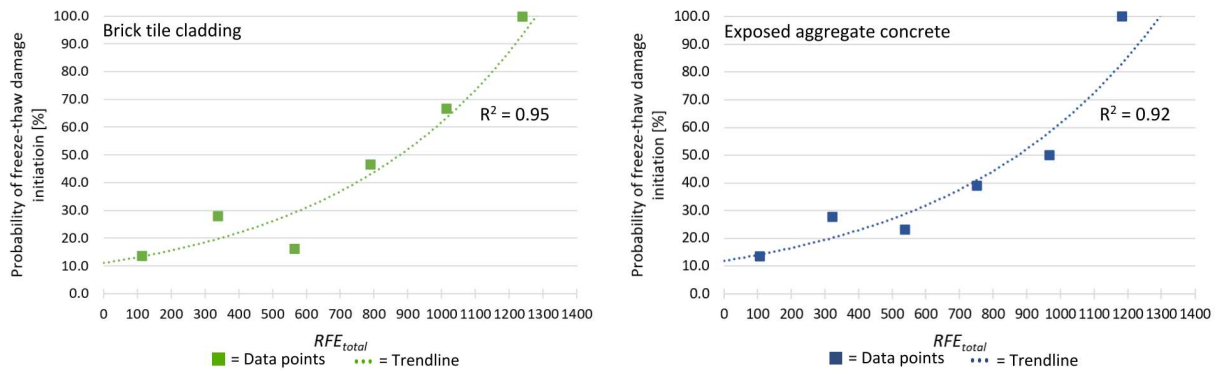


Figure 3 – The probability of freeze-thaw damage initiation and actual data points.

For practical illustration, Table 6 shows the development of freeze-thaw damage initiation in different geographical locations and facade directions. These values represent a combined curve that includes all facade surface types. On facades facing south in Finland’s coastal areas, freeze-thaw damage begins, on average, across the entire facade area at the age of 40 years. In contrast, Lapland’s west-facing facades experience total freeze-thaw damage initiation at the age of 190 years.

Table 6 – Probability of freeze-thaw damage initiation in different geographical locations and facade directions – all surface types, present climate

Location	Direction	RFE index	Age [years]																
			30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190
Coastal area	North	12	23	28	33	40	48	57	69	83	99	100							
	Northeast	17.5	30	39	50	66	86	100											
	East	23	38	54	77	100													
	Southeast	30.5	54	85	100														
	South	38	75	100															
	Southwest	28.5	49	75	100														
	West	19	32	42	57	75	100												
	Northwest	15.5	27	34	43	55	69	88	100										
Southern Finland	North	9	20	23	26	30	35	40	46	52	60	69	79	90	100				
	Northeast	13.5	25	30	37	46	56	69	84	100									
	East	18	30	40	52	69	90	100											
	Southeast	20	33	45	61	83	100												
	South	22	36	51	71	99	100												
	Southwest	17.5	30	39	50	66	86	100											
	West	13	24	29	36	44	53	65	79	96	100								
	Northwest	11	22	26	31	36	43	51	60	71	84	99	100						
Inland	North	9	20	23	26	30	35	40	46	52	60	69	79	90	100				
	Northeast	10.5	22	25	30	35	41	48	56	66	77	90	100						
	East	12	23	28	33	40	48	57	69	83	99	100							
	Southeast	13	24	29	36	44	53	65	79	96	100								
	South	14	25	31	39	48	59	73	90	100									
	Southwest	11.5	23	27	32	38	45	54	64	77	91	100							
	West	9	20	23	26	30	35	40	46	52	60	69	79	90	100				
	Northwest	9	20	23	26	30	35	40	46	52	60	69	79	90	100				
Lapland	North	10	21	25	29	33	39	45	52	61	71	83	96	100					
	Northeast	11	22	26	31	36	43	51	60	71	84	99	100						
	East	12	23	28	33	40	48	57	69	83	99	100							
	Southeast	12.5	24	29	35	42	50	61	74	89	100								
	South	13	24	29	36	44	53	65	79	96	100								
	Southwest	10	21	25	29	33	39	45	52	61	71	83	96	100					
	West	7	18	20	23	25	28	31	35	39	43	48	53	59	66	73	81	90	100
	Northwest	8.5	20	22	25	29	33	38	43	49	55	63	71	81	93	100			

Using the RFE index presented in Table 4, the calculations outlined in this chapter can also be applied to predicted future climates, making the model suitable for assessing the service life of existing concrete facades in future climate conditions. However, the model should not be applied to buildings constructed after the timeframe of the database used in this study, as the pore structure of newer buildings (from the 1990s onwards) differs from that of older building stock [27]. This has been influenced by the updates to the guidelines regarding durability and service life of concrete [28, 29]. If the database is updated to include condition investigation reports and laboratory analyses of newer buildings, the reliability and applicability of the service life model for the newer building stock will improve accordingly.

#### 4.2 RFE<sub>total</sub> index and tensile strength

Figure 4 shows the probability that tensile strength of concrete has decreased below 1.0 MPa and 0.5 MPa, respectively, as a function of RFE<sub>total</sub> index. Like in section 4.1, RFE<sub>total</sub> index can be translated into years when the geographical location, compass direction of the facade, and age of

the building are known. For both tensile strength thresholds, the coefficients of determination ( $<1.0 \text{ MPa } R^2 = 0.93$ ,  $<0.5 \text{ MPa } R^2 = 0.91$ ) indicate a strong fit, as shown in Table 7.

Table 7 – Obtained coefficients of determination  $R^2$

Threshold	Coefficient of determination $R^2$	Number of samples
Tensile strength $<1.0 \text{ MPa}$	0.93	1614
Tensile strength $<0.5 \text{ MPa}$	0.91	1601

Calculation example: Let’s consider the east-facing facade of a 50-year-old building in central Finland (Inland). Table 4 shows the RFE index of 12, resulting in  $RFE_{total}$  index =  $50 \cdot 12 = 600$ . According to Figure 3, the probability of that tensile strength has decreased below 1.0 MPa in that facade is approximately 27.5%, the same probability for tensile strength decreased below 0.5 MPa being about 10%. After 50 years, the corresponding probabilities for the same facade can be estimated to be approximately 73% ( $<1.0 \text{ MPa}$ ) and 52.5% ( $<0.5 \text{ MPa}$ ).

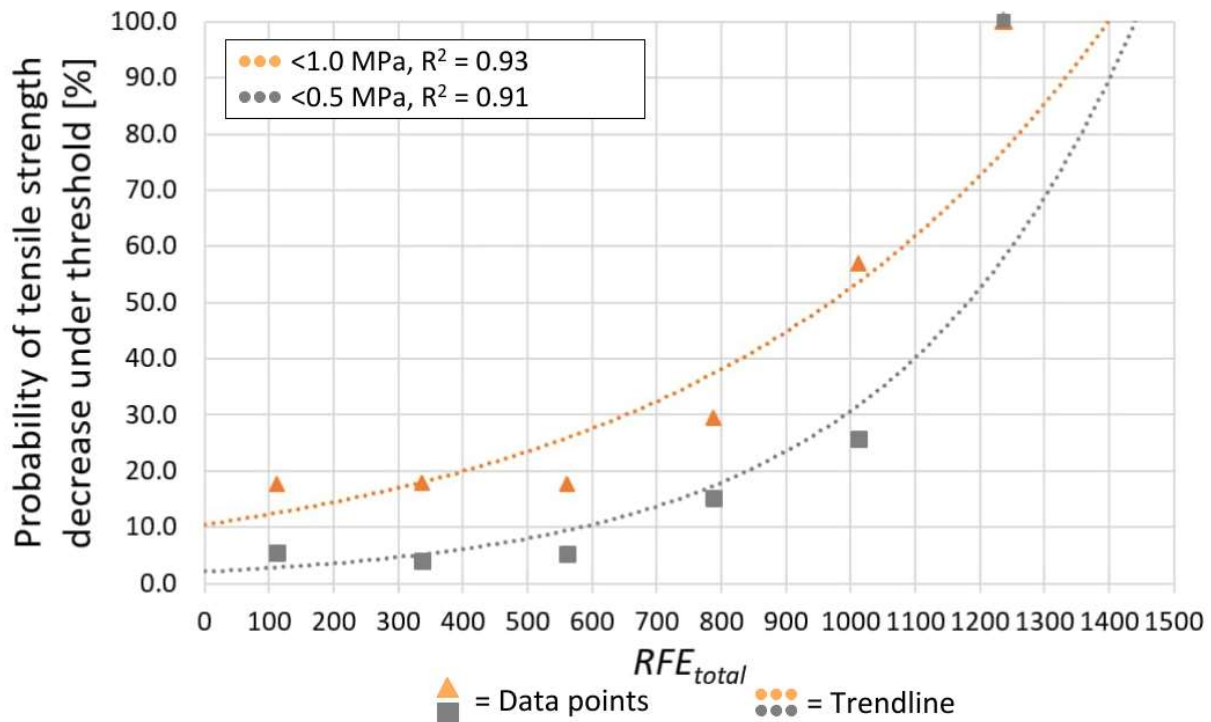


Figure 4 – The probability of tensile strength decreases as a function of  $RFE_{total}$  index.

When examining the development of tensile strengths, it is important to note that they differ significantly from the freeze-thaw damage rates obtained from thin-section analysis reports. The tensile strengths of facade elements can vary already at the manufacturing stage, depending on the guidelines and requirements in force during the design period. Additionally, tensile strength does not directly correlate with freeze-thaw damage; other factors (such as round-shape aggregates, alkali-silica reaction, corrosion of reinforcement, and drying shrinkage) contributing to deterioration may also affect the decrease in tensile strength. Therefore, tensile strength alone cannot be used to directly assess the progression of freeze-thaw damage on the facade although the correlation between them has been identified by comparing thin-section and tensile strength analyses taken from the same elements [3]. However, if the original design plans of the building are available during condition investigations, the service life model presented in this article can be utilised to evaluate the development of deterioration and the facade's reparability.

## 5. CONCLUSIONS

This article presents a novel service life model designed to estimate the probability and progression of freeze-thaw damage initiation in concrete facades in different geographical locations and facade directions. The model was developed based on an extensive database of condition investigation reports and Relative Freeze-Thaw Exposure index. Additionally, the model was employed to calculate the progression of deterioration in concrete facades by examining the reduction in tensile strength of concrete. The model was initially applied to current climate conditions, but it also allows to calculate freeze-thaw damage with future climate scenarios.

Moisture stress caused by wind-driven rain is a significant factor in reducing the service life of concrete facades, especially for painted and clinker-tiled surfaces, which were predicted to have the shortest service life. The results are due to the insufficient maintenance actions with painted facades since they should be recoated approximately every 15 years. According to the service life model, freeze-thaw damage occurs significantly later in unpainted plain concrete facades, since they have better opportunity to dry between rain events. In the case of clinker-tiled surfaces, WDR can enter through the seams, while dense tiles prevent the concrete dry efficiently. These findings emphasise the critical importance of regular facade maintenance and repair, as well as the careful planning and implementation of effective water drainage systems.

It is important to note that the assessment of the reduction in concrete tensile strength differs fundamentally from analyses based on thin-section analyses. The tensile strengths of concrete elements vary significantly already during the manufacturing phase, depending on the structural type and the guidelines and regulations in effect at the time of construction. Furthermore, a reduction in tensile strength does not always directly indicate freeze-thaw damage, as deterioration may result from other mechanisms. However, predicting the reduction in tensile strength can provide valuable insights into the rate of structural degradation and serve as a basis for planning timely and appropriately scaled repair actions.

The new service life model is best suited for examining old concrete facades and cannot reliably predict the damage state or progression in new structures. This limitation arises from the lack of data on the pore structure of new concretes in the database used to create the model. Therefore, if the database is updated in the future with condition investigation reports and laboratory analyses of new buildings, the model could be adapted for use with more recent building stock as well.

In summary, the service life model presented in this article is a reliable and practical tool for assessing the state and progression of freeze-thaw damage in concrete facades. The model provides property owners with cost-effective baseline information for scheduling facade repairs and planning the extent of necessary restoration work.

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