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Assessing Climate Change Effects on Freeze-Thaw Exposure of Concrete Structures

Toni Pakkala, D.Sc
University Lecturer
P.O. Box 600, FI-33014, Tampere University, Finland
toni.pakkala@tuni.fi

Niko Lindman, M.Sc
Doctoral Researcher
P.O. Box 600, FI-33014, Tampere University, Finland
niko.lindman@tuni.fi

Jukka Lahdensivu, D.Sc
Research Manager
P.O. Box 600, FI-33014, Tampere University, Finland
jukka.lahdensivu@tuni.fi

ABSTRACT

This study presents a novel method to assess the freeze-thaw exposure of concrete structures. The new Relative Freeze-Thaw Exposure index (RFE) is based on regression model that considers location-related actual freeze-thaw damage observations, number of freeze-thaw cycles and both annual and cycle-related amount of wind-driven rain (WDR) before cycles. The RFE index is then used to compare location-, direction- and climate-related freeze-thaw exposure levels.

It can be concluded that the amount of WDR before each cycle has the most significant effect on freeze-thaw damage. Freeze-thaw exposure level is highest in present climate and remains the highest in Finland's coastal area regardless of the used climate change scenario. In Finland's coastal area and southern Finland, the exposure level increases more from eastern and western directions than southern which indicates that the exposure level is getting more evenly distributed. However, the southern direction remains with the most severe exposure in almost every studied case in every location.

Freeze-thaw exposure for outdoor concrete structures is not getting less severe with the changing climate in Finland. The quality of concrete (e.g. success of air-entrainment) and protecting concrete from free water remain the main methods against the initiation of freeze-thaw damage.

Key words: concrete structure, freeze-thaw damage, wind driven rain, durability, climate change

1. INTRODUCTION

Freeze-thaw damage is one of the two major degradation mechanisms of climate exposed concrete structures in existing Finnish building stock, the other being carbonation induced corrosion [1]. In recent studies [2 - 4], it has been shown that the amount of wind-driven rain (WDR) before freeze-thaw cycles has a major effect on the rate of freeze-thaw damage. Based on a comprehensive condition investigation data [5], Lahdensivu [1] and Pakkala et al. [2] have presented that in Finland it has taken considerably fewer freeze-thaw cycles after rain or sleet events for incipient damage to occur in coastal area than in the inland. The numbers were 307 and 388 cycles, respectively, when the limit temperature was set to -5°C. In 1980 - 2009 climate conditions the numbers corresponded to 26 and 37 years, respectively, to incipient freeze-thaw damage to occur.

Pakkala et al. [3] presented that far-advanced freeze-thaw damage is strongly related to the amount of freeze-thaw cycles after rain or sleet events. In addition to location-related differences in far-advanced freeze-thaw damage, the observed damage is strongly related to the direction of WDR. Over 80% of far-advanced freeze-thaw damage observed in condition investigations has been concentrated on west to south-east directions, so is the share of WDR. The share of both the freeze-thaw damage and WDR is even more concentrated in mentioned directions in the coastal area than in the inland.

Freeze-thaw damage needs both the free water in the concrete pore system and freeze-thaw cycles to occur. Thus, the main stress factors are the number of cycles and the amount of water inside the concrete pores, mainly provided by WDR. Even though the relation between observed damage and the mentioned stress factors has been shown, the relevance of each component is yet somewhat unclear. There are no clear methods to estimate the severity of a freeze-thaw load. Lisø et al. [6] presented a combination of frost decay exposure index (FDEI) and freezing point crossings (FPC) to characterise the risk of freeze-thaw damage to a porous, mineral based materials in a given climate. In their studies, the freeze-thaw cycles were considered as temperature crossings over freezing point (0°C) and the number of cycles was defined as annual average number of days with freezing point crossings. The FDEI links FPC to the amount of liquid precipitation recorded from the day an FPC has occurred and the preceding two, three or four days. When the FDEI and FPC are shown in the same diagram, the risk of frost decay can be estimated by analysing their relation. However, Pakkala et al. [2] and Pakkala [4] presented a few problems with the studies: the actual freezing point temperature in concrete pore structure is lower, <-5°C depending on pore size [7], and freezing point crossings should be calculated after a rain event to assess the events when there is possible free water in the concrete pore system.

Based on measurements in Finland, Pakkala [4] has presented the number of freeze-thaw cycles with a limit temperature of -5°C, the average annual amount of the rain and sleet maximum of 72 hours before the cycles and the average amount of WDR maximum of 72 hours before a cycle. The calculations were made in 1980 - 2009 climate and projected to 2050 (2035 - 2064) and 2100 (2085 - 2114) climates, in four different locations and from different directions based on the wind direction during the rain event. The future climate projections were based on IPCC SRES A2 scenario [8]. The conclusion was that based on the used scenario, the number of freeze-thaw cycles is decreasing in all studied locations except the northernmost part of the country (Lapland). Based on the studied scenarios, the average annual amount of WDR before freeze-thaw cycles is decreasing in the coastal area and in southern Finland but increasing in other locations. The average amount of WDR before a cycle, considered as an intensity of the freeze-thaw load, is decreasing only mildly in the coastal area and increasing in every other location. In all the studied cases, the coastal area is the most loaded area. In future climate projections, the load level in inland locations is approaching the present level in coastal area.

Pakkala et al. [2, 9] and Pakkala [4] have assessed in former studies the effect of climate change on the freeze-thaw load on Finnish concrete facades and balconies. The studies were made based on IPCC 2007 [8] climate models and more precisely on a single scenario A2. Pakkala concluded [4] that one of the main needs for further research is to study both updated and other scenarios. The latter need is based on the assumption that if the projected CO_2 level is lower than in scenario A2, the number of freeze-thaw cycles might not decrease with such rate. In addition, it was concluded that more focus should be aimed to estimate the severity of the freeze-thaw load, i.e., to compare the number of freeze-thaw cycles after rain events, amount of annual WDR before freeze-thaw cycles and the amount of WDR before of a freeze-thaw cycle.

One third of the floor area of Finnish building stock is block of flats of which the major part is concrete buildings. A major part of it is now aged between 30 to 60 years. In addition, Lahdensivu [1] and Pakkala et al. [2] have shown that even though concrete buildings built according to current Concrete Codes are freeze-thaw durable, yet the actual quality of the concrete may not have reached the requirements. Thus, it is important to study the upcoming climate conditions for assessing the buildings' possible service life and as a groundwork for their maintenance programs and estimations of their possible repair costs in the future.

The research objective was to study how to assess the severity of freeze-thaw load in future climate in different locations in Finland. The results can be used also for other porous mineral-based materials with similar freeze-thaw damage mechanism such as bricks, mortars, and rendering. In this research, the climate change effect on freeze-thaw damage is studied by using updated climate change scenarios (Representative Concentration Pathways, RCPs) produced by Finnish Meteorological Institute (FMI) in a RASMI-project [10].

2. MATERIALS AND METHODS

2.1 Condition investigation database

The research material consists of the database collected by Tampere University and Ramboll Finland Oy, which includes condition investigation reports of concrete facades and thin-section analyses of concrete drill samples taken in connection with these investigations. The buildings in the utilised data were constructed between the years 1963 and 1995 and were on average 25 years old at the time of the condition investigation (min = 7 years, max = 49 years, standard deviation = 8 years). Facade condition investigation reports have been conducted in accordance with the Finnish condition investigation guideline [11]. The thin-section analyses have been performed in accordance with standard ASTM C856/C856M - 20 [12].

Since freeze-thaw damage observations in reports of the thin-section analyses have been expressed in verbal form, they have been converted into numerical values for the calculations. This conversion procedure is based on the system presented by Koskiahde [13], see Table 1. In this article, only those samples showing incipient to widespread freeze-thaw damage have been used (n = 325, damage class 2 - 4). In the initial data, concrete drill samples have been reported with precision for main and intermediate compass directions. In this article, the sampling directions have been adjusted to correspond only to the main compass directions in a way that samples taken from intermediate compass directions have been evenly distributed under adjacent main compass directions.

Table 1 – Classification of freeze-thaw damage indicating cracking observations [13]

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 <0.01mm in width and <10mm in length. No cracks exceeding 0.1mm in width and 25mm in length allowed.
3	Frequent freeze-thaw cracking. Crack pattern commonly parallel to the surface. Typical crack widths 0.01 - 0.1mm and lengths ≥10mm. Incidence <0.25 cracks/mm and <50% of paste-aggregate (coarse-grained aggregate) interfaces detached.
4	Severe freeze-thaw cracking. Several cracks >0.1mm in width and >25mm in length. Incidence ≥0.25 cracks/mm or ≥50% of paste-aggregate interfaces detached.

Finland is divided in four geographical areas based on both the climatic conditions and the population distribution: coastal area, southern Finland, inland and Lapland. The division and its fundaments are presented more precisely in Pakkala [4, pp. 17 - 18]. The database includes investigated buildings widely throughout Finland except for Lapland area. Only one investigated building located in Lapland, so the observations are included in the Inland data.

2.2 Estimating freeze-thaw load

The level of freeze-thaw load for vertical structures is estimated based on three different indices:

- Freezing Point Crossings (FPC): the number of freeze-thaw cycles with limit temperature -5°C and maximum of 72 hours after precipitation event.
- Annual Freeze-Thaw Exposure (AFTE): the average annual amount of WDR maximum of 72 hours before the FPC.
- Intensity of the Freeze-Thaw Exposure (IFTE): the average amount of WDR maximum of 72 hours before an FPC.

The precipitation event in all indices is considered to be precipitation in the form of rain or sleet. It is delimited from the climate data by considering precipitation only when temperature is ≥0°C. For modelling WDR, i.e., precipitation on vertical surface, a standardised airfield annual index I_A [14] is used. It gives an estimation of the amount of precipitation on vertical surfaces from different directions at a height of 10 m above ground level at an open place (in the middle of the airfield). The I_A [14] can be calculated with the following Equation 1:

$$I_A = \frac{2}{9} \frac{\sum v r^{\frac{8}{9}} \cos(D-\theta)}{N} \quad (1)$$

where, v is hourly mean wind speed [m/s], r is hourly total rainfall [mm], D is hourly mean wind direction from north [°], θ is wall orientation relative to north [°], N is the number of years for which data is available, and the summation is taken over all hours for which $\cos(D-\theta)$ is positive.

In AFTE index the airfield annual index is used as it is presented above but only for the cases where there is a FPC during following 72 hours. Thus, in I_A^{AFTE} the N in Equation 1 is 30 years. In IFTE index every FPC and the amount of WDR during preceding 72 hours is considered to be a unique case so that an average of every such case in the 30-year data is calculated. Thus, the Equation 1 is modified as follows:

$$I_A^{IFTE} = \frac{2}{9} \frac{\sum v r^{\frac{8}{9}} \cos(D-\theta)}{N_C} \quad (2)$$

where, N_C is total number of cases during the 30-year data.

2.3 Climate data

Finland is divided in four geographical areas based on both the climatic conditions and the population distribution. The division and its fundaments are presented more precisely in Pakkala [4, pp. 17 - 18]. 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 FMI [10] has produced climate data for those four locations in present and projected future climates for the time series 2050 and 2080. The time series representing future climate were compiled for three Representative Concentration Pathways (RCP):

- RCP2.6 representing small greenhouse-gas emissions.
- RCP4.5 representing medium greenhouse-gas emissions.
- RCP8.5 representing very large greenhouse-gas emissions.

The climate data of the weather stations representing present climate are collected every three hours between 1989 and 2018. The three-hour data linearly interpolated as an hourly data. The data used in this study consist of the following variables: temperature, relative humidity, wind speed and direction and precipitation. The hourly projections of the same variables are made for two future 30-year time periods: 2050 (2035 - 2064) and 2080 (2065 - 2094). The projections were made for all studied locations and scenarios.

The variables used in this study are presented in the data with the following accuracy:

- temperature: 0.01°C
- wind speed: 0.01 m/s
- wind direction: 0.1°
- precipitation: 0.01 mm.

Pakkala [15] has presented earlier the following numbers:

- The average annual number of FPC's with limit temperature -5°C and maximum of 72 hours after precipitation event in present and future climate projections.
- The average annual amount of WDR before freeze-thaw cycles, I_A^{AFTE}, in present and future climates and in different locations.
- The average amount of WDR before each freeze-thaw cycle, I_A^{IFTE}, in present and future climates and in different locations.

In Table 2, the numbers in present climate are converted as relative numerical values for the purpose of generating regression model presented in Section 2.4. As mentioned before, the observed freeze-thaw deterioration rate has been the greatest in southern facades in every studied location. Thus, to represent present climate, the relative number 100 is the number of FPC's after precipitation events and the amount of I_A^{AFTE}, and I_A^{IFTE} from southern directions. Lapland is excluded due to the lack of condition investigation data (see Section 2.1).

Table 2 – Created relative numerical values for each location and facing direction

Location	**Direction**	**Relative number of FPC's**	**Relative amount of I_A^{AFTE}**	**Relative amount of I_A^{IFTE}**
Vantaa	North	74	14	20
	East	59	25	43
	South	100	100	100
	West	105	49	47
Jokioinen	North	70	15	22
	East	50	26	53
	South	100	100	100
	West	109	60	55
Jyväskylä	North	80	36	45
	East	72	41	57
	South	100	100	100
	West	106	62	59

For the purpose to compare regression model-based freeze-thaw load level in different locations and climates and variously oriented facades, Tables 3 - 5 represent the relative number of FPC's and relative amount of I_A^{AFTE}, and I_A^{IFTE}, respectively, related to the coastal area southern facade (relative reference level: 100). The employed unitless reference value of 100 has been chosen arbitrarily, but it serves as a practical value for comparing the varying degrees of freeze-thaw load across different locations and facade orientations.

Table 3 – The relative number of FPC's on different locations, facing directions and studied climates. Relative reference level 100 is set to represent southern facade conditions in coastal area in present climate.

		Used climate data						
			2050			2080		
Location	**Direction**	**Present**	**RCP2.6**	**RCP4.5**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP8.5**
Coastal area	North	74	79	78	77	77	75	58
	East	59	64	62	61	62	58	48
	South	100	93	85	77	90	74	46
	West	105	97	90	77	95	80	45
Southern Finland	North	84	96	92	83	96	79	100
	East	59	65	64	62	65	60	76
	South	119	111	105	94	112	92	95
	West	130	118	111	95	117	90	103
Inland	North	106	111	116	120	110	117	103
	East	95	92	93	94	93	90	76
	South	133	134	133	132	132	127	92
	West	140	143	142	141	142	137	107
Lapland	North	84	103	116	124	105	123	151
	East	84	103	113	120	104	120	140
	South	129	145	161	159	146	162	168
	West	133	155	170	171	157	170	181

Table 4 - The relative number of I_A^{AFTE} on different locations, facing directions and studied climates. Relative reference level 100 is set to represent southern facade conditions in coastal area in present climate.

		Used climate data						
			2050			2080		
Location	**Direction**	**Present**	**RCP2.6**	**RCP4.5**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP8.5**
Coastal area	North	14	21	20	21	21	20	21
	East	25	34	37	31	35	30	31
	South	100	93	92	72	91	67	31
	West	49	45	44	37	44	35	19
Southern Finland	North	11	14	16	17	14	16	21
	East	19	20	23	26	21	26	26
	South	72	64	60	55	64	53	43
	West	44	41	42	36	41	35	30
Inland	North	19	18	23	24	18	24	28
	East	21	26	31	31	26	30	29
	South	52	54	59	57	55	56	49
	West	33	32	35	35	32	34	33
Lapland	North	13	15	19	21	16	21	29
	East	18	23	26	29	24	30	42
	South	43	51	59	64	52	65	71
	West	19	24	28	40	24	30	34

Table 5 - The relative number of I_A^{IFTE} *on different locations, facing directions and studied climates. Relative reference level 100 is set to represent southern facade conditions in coastal area in present climate.*

		Used climate data						
			2050			2080		
Location	**Direction**	**Present**	**RCP2.6**	**RCP4.5**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP8.5**
Coastal area	North	20	27	26	27	27	27	36
	East	43	53	60	51	56	52	65
	South	100	100	107	93	101	91	67
	West	47	46	48	44	46	44	43
Southern Finland	North	13	15	18	20	15	20	21
	East	32	32	37	42	32	43	34
	South	61	57	57	58	57	58	45
	West	34	35	38	38	35	39	29
Inland	North	18	16	19	20	16	20	27
	East	22	28	33	33	28	33	38
	South	39	41	44	43	42	44	53
	West	23	22	25	25	23	25	31
Lapland	North	16	15	16	17	15	17	19
	East	22	22	23	24	23	25	30
	South	34	35	37	40	35	40	42
	West	14	15	17	18	15	18	19

2.4 Multilinear regression model

As mentioned in Chapter 1, there is no comprehensive methods to combine all earlier mentioned factors of freeze-thaw exposure and thus, no methods to assess the severity of exposure so that every factor is considered. To formulate a relative method to combine the factors, a Relative Freeze-Thaw Exposure (RFE) index is created. To calculate RFE index, a multilinear regression was used utilising FPC, I_A^{AFTE}, and I_A^{IFTE} indices (see Section 2.2) and the collected far-advanced freeze-thaw damage data (see Section 2.1).

To create the multilinear regression model, location related relative FPC, I_A^{AFTE}, I_A^{IFTE}, and far-advanced freeze-thaw damage data were created, see Table 2 and Section 3.1. The relative reference level (100) is set individually in each of the locations because the share of the far-advanced freeze-thaw damage on different direction facing facades was location related. Each of the factor used to create the model were cross tabulated in regression calculations. The regression was calculated according to Equation 3.

$$RFE = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \tag{3}$$

where, β_0 is interception term, $\beta_1 x_1$ coefficient of independent variable 1 (FPC parameter), $\beta_2 x_2$ coefficient of independent variable 2 (I_A^{AFTE} parameter) and $\beta_3 x_3$ coefficient of independent variable 3 (I_A^{IFTE} parameter).

Finally, the model is used to compare freeze-thaw exposure in different locations and climate change scenarios. To compare the exposure level in different locations and climate change scenarios, relative FPC, I_A^{AFTE}, and I_A^{IFTE} indices presented in Tables 3 - 5 were used. In this case, the relative reference level was set to be 100 in southern direction in coastal area.

3. RESULTS AND DISCUSSION

3.1 Condition investigation data

Table 6 presents freeze-thaw damage observations according to geographical location and the sampling direction. In this study, the observations of freeze-thaw damage are analysed with the accuracy of main compass directions. Since the initial database encompasses both main and intermediate compass directions, the observations from intermediate compass directions are shared in half between the adjacent main compass directions.

Table 6 - Freeze-thaw damage observations according to geographical location and the sampling direction

Location	The number of freeze-thaw damage observations	Share [%]
Coastal area, total	199	100
North	22.5	11.3
East	48.5	24.4
South	74.5	37.4
West	53.5	26.9
Southern Finland, total	94	100
North	15	16.0
East	25	26.6
South	36.5	38.8
West	17.5	18.6
Inland + Lapland, total	32	100
North	4	12.5
East	9.5	29.7
South	12	37.5
West	6.5	20.3
All locations, total	325	100
North	41.5	12.8
East	83	25.5
South	123	37.8
West	77.5	23.8

Freeze-thaw damage observations seem to appear on the southern facades in all geographical locations, when the least number of damage observations was on the northern facades. In Finland, the geographical location has not been found to have significance on the properties of concretes pore structure, in addition to which various facade surface types have been used evenly across the country [1]. Therefore, the concentration of damage observations in certain directions can be logically explained by climate stress, even though samples are typically taken in relation to the most climate stressed facades during condition investigations.

3.2 Relative freeze-thaw exposure RFE

The used multi-linear regression model was judged by the coefficient of determination (R^2) of the model. The R^2 was 0.83 which can be seen as a relatively strong fit. Table 7 shows the parameters and regression coefficients that can be applied in the modelling of the freeze-thaw exposure level. Regression coefficients are used to quantify the relationship between each predictor and the dependent variable (freeze-thaw damage), indicating the direction and strength of their influence. The greater the distance of the regression coefficient from zero, the greater its effect on the dependent variable.

Table 7 – Regression model for RFE index in concrete facades

R^2	β_0 (intercept)	β_{FPC}	$\beta_{I_A^{AFTE}}$	$\beta_{I_A^{IFTE}}$
0.83	8.412	-0.045	-0.134	0.471

The coefficients indicate that the I_A^{IFTE}, i.e. the intensity of the freeze-thaw exposure, has the highest influence on RFE index and the number or FPC's the lowest.

The relative freeze-thaw exposure index, RFE, from different directions, i.e., on different direction facing vertical structures, is presented in Table 8.

Table 8 – RFE index in different geographical locations and facade directions

		Used climate data						
			2050			2080		
Location	**Direction**	**Present**	**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 is increasing in coastal area with every scenario and from every direction except 2080 RCP8.5 scenario from southern direction where the scenario decreases considerably. In addition, the RFE index remains the highest in coastal area compared to other studied locations. Only few numbers in other locations exceed the lowest numbers in coastal area, e.g. southern directions in southern Finland and in the inland with 2080 RCP8.5 versus northern direction in coastal area. In southern Finland the RFE index remains, in outline, at present level regardless of the used scenario. In the inland the RFE remains in present level except 2080 RCP4.5 and RCP8.5 scenarios where the increase is notable. Lapland is the only location where the RFE index decreases from every direction and with every scenario compared to present climate.

The inland is the only location where the direction related RFE index scatters compared to present climate, especially with 2080 RCP8.5 scenario. In other locations, the differences between RFE index from different directions remains at present level or even out. In most cases where the RFE index increases, the results indicate that the exposure level on north-facing structures will approach the present level on west-facing structures, level on west-facing structures the present level on east-facing structures and level on east-facing structures the present level on south-facing structures.

The average RFE index in different studied locations are presented in the Table 9 and Figure 1.

Table 9 – RFE index in different geographical locations

Location	Used climate data						
	Present	2050			2080		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Coastal area	23	25	27	25	25	25	28
Southern Finland	16	16	17	19	16	19	15
Inland	11	11	12	12	11	13	17
Lapland	11	9	9	8	9	9	8

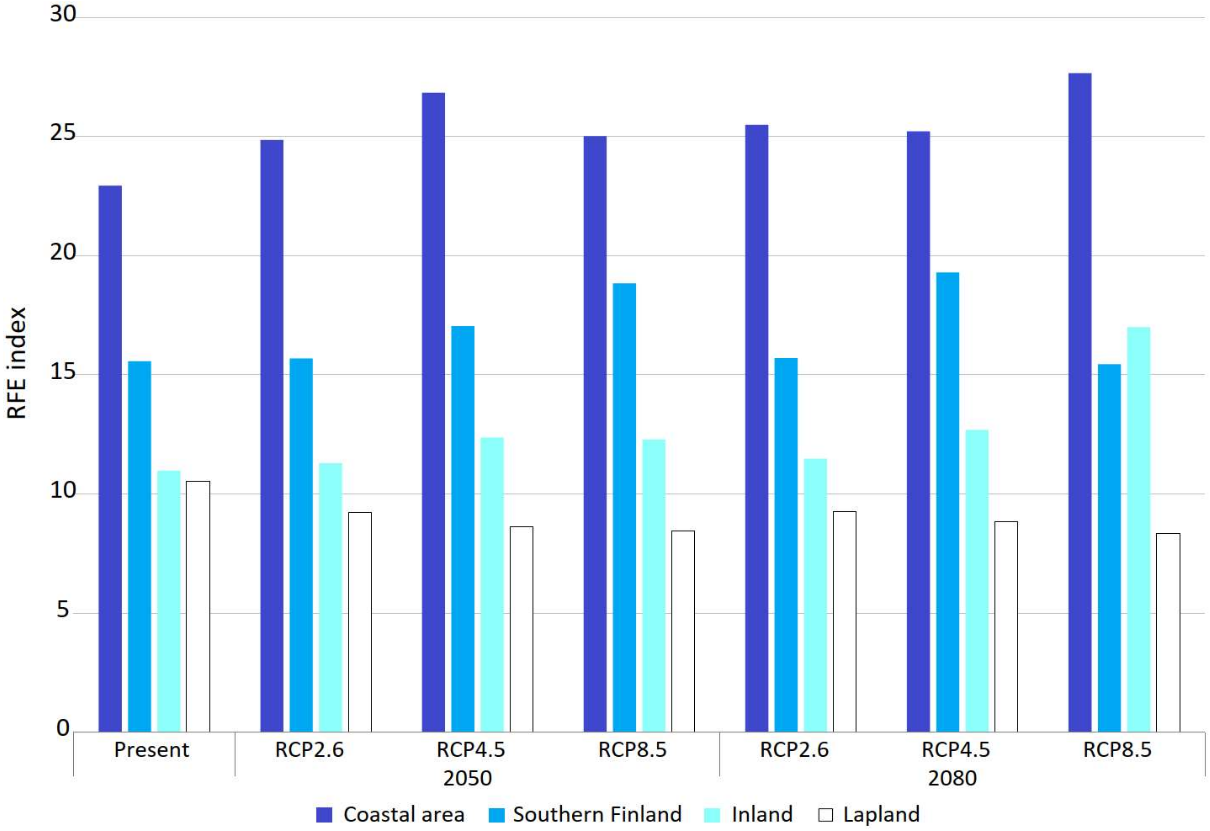

Figure 1 – Average RFE in different geographical locations and climates

Based on the RFE index, the severity of freeze-thaw exposure will be the highest in coastal area regardless of the used scenario. The highest index is with 2080 RCP8.5 scenario in coastal area and the lowest with 2050 and 2080 RCP8.5 scenarios in Lapland. The severity-based order of locations remains the same in every scenario except 2080 RCP8.5 where the inland overtakes southern Finland.

4. CONCLUSIONS

The study presents a novel method to assess the level of freeze-thaw exposure by relative freeze-thaw exposure index, RFE. RFE index is based on regression model that considers:

- Thin-section analyses based on freeze-thaw damage observations in extensive condition investigation database.
- Average annual number of freeze-thaw cycles with limit temperature -5°C.
- Average annual amount of wet precipitation before the freeze-thaw cycle.
- Average amount of wet precipitation prior to each freeze-thaw cycle.

Each factor is formed separately in four different geographical locations and in each location for four main directions. Finally, RFE index is used to estimate the freeze-thaw exposure between the different locations and directions and to assess the climate change effect to them.

Because the RFE index is based on actual freeze-thaw damage observations in present climate it is the highest in coastal area and from southern direction which have been in former studies shown to be predisposing for the most severe freeze-thaw damage. The results indicate that it will stay the highest regardless of the remarkable decrease in number of FPC's and amount of I_A^{AFTE} in coastal area with RCP8.5 2080 scenario. The results and calculated coefficients strongly indicate that the amount of I_A^{IFTE} has the highest significance on freeze-thaw exposure. It highlights the significance of the amount of free water in concrete pore structure prior to freeze-thaw cycle.

The lowest effect of used parameters appears to be the number of FPC's. It correlates with the interpretations made in former studies because the number of FPC's has been the highest in inland and northern Finland even though the freeze-thaw damage observations have been fewer.

Based on the results the following observations can be made:

- Freeze-thaw exposure level remains to be the highest in coastal area regardless of the used scenario and it is increasing with every scenario, in Lapland vice versa.
- In other studied locations, used scenario has more effect on the direction of the exposure level, yet principally remains quite the same level as in present climate.
- The amount of WDR before a freeze-thaw cycle, i.e., the intensity of freeze-thaw exposure, has the highest influence on the exposure level.
- In coastal area and southern Finland, the exposure level increases more from eastern and western directions than southern which indicates that the exposure level is getting more evenly distributed. However, the southern direction remains with the highest RFE in almost every studied case in every location.

As a conclusion it can be drawn that the freeze-thaw exposure for outdoor concrete structures is not getting less severe with the changing climate. Thus, the most important findings are that the quality of concrete (e.g. success of air-entrainment) and protecting concrete from free water remain the main methods against freeze-thaw damage.

The authors acknowledge many sources of error related to the study. E.g., there are far more sophisticated methods to calculate WDR amounts accurately on exact locations, buildings and areas on building facades. However, used method can be seen as an adequate method to compare WDR amounts on general level. In addition, the concrete core sampling is usually focused on the areas known to have the highest exposure level, such as upper parts of southern facades. Also, the surface type and coating of concrete have shown to have an influence on the freeze-thaw durability. However, the database is extensive, and the significance of the mentioned error sources can be seen quite minor when using the data in location and direction-related comparisons.

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