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A Dose-response Approach for Predicting Frost Damage with Hygrothermal Simulations

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Abstract. *Freeze-thaw degradation is one of the most prominent degradation risks of brick facades. Considering the difficulties of repairing freeze-thaw damage without replacing the materials, which may not always be an option due to heritage values, it is highly important to quantify the risk of frost damage in advance. Hygrothermal simulations have proven to be a valuable tool to assess the risk of deterioration of building facades. The performance criterion method generally applied today quantifies the number of critical freeze-thaw cycles (FTCcrit) as described by Mensinga et al (2010). This method is based on frost resistance tests that adopt high moisture contents and extremely low frost temperatures. However, building facades often experience milder frost temperatures and lower moisture contents rather than these extreme conditions. A journal article published by Feng et al. (2019) investigated the relationship of frost damage with temperature and moisture content, which enables a dose-response approach that goes beyond the existing threshold level criteria. The experimental study tested freezing temperatures from -2°C to -20°C and moisture saturation degrees from 0.1 to 1.0. This paper studies freeze-thaw risk using this advanced approach, and investigates whether the dose-response approach can lead to a clarification at what number of FTCcrit actual deterioration occurs and how this can be predicted by the use of hygrothermal simulations. Thereby, an attempt is made to derive a more representative performance criterion for frost damage.*

Keywords: *Frost Damage, Hygrothermal Simulations, Freeze-thaw Cycle, HAM.*

1 Introduction

Frost damage is known to be one of the main causes of brick decay. Specifically, after internal retrofitting an existing wall, the thermal and moisture balance of the masonry wall changes and the facade is subjected to more severe fluctuations. Hence, the masonry may be subjected to a higher number of freeze-thaw cycles (FTC), as was demonstrated for the Belgian climate (Vandemeulebroucke et al. 2021).

Typical freeze-thaw tests on bricks involve subjecting samples conditioned to a certain moisture content to alternating freeze-thaw cycles. The samples are generally subjected to very high moisture contents and very low freezing temperatures. The tests under such extreme conditions can be regarded as binary: if the sample shows no damage after such extreme conditions, it will most likely also perform well under milder conditions. If it fails the test under extreme conditions, it is considered unsuitable for actual exposure. Whether these tests are representative of the brick's behaviour under actual exposure is, of course, questionable.

Therefore, Feng et al. (2019) performed different freeze-thaw tests at lower moisture contents and milder temperatures to see how this influences the freeze-thaw damage.

In 2010, Mensinga et al. defined a critical freeze-thaw cycle when the ice mass volume over the pore volume surpasses 25%, based on the most freeze-thaw sensitive brick that was included in the study. In contrast, 91% may be considered as upper limit, assuming that every material with a saturation above this level will fail because of a lack of pore space for the ice to expand. The 25% criterion is often adopted for comparative studies, but the relevance of the threshold value, and to what extent the number of these critical freeze-thaw cycles result in actual damage, is unclear.

To assess the hygrothermal behaviour that may lead to freeze-thaw damage, HAM tools have proven to be valuable. In order to gain insights from hygrothermal simulations regarding frost decay, performing a sensitivity analysis has great potential (Calle et al. 2021). From these HAM studies, it becomes clear that rain intensity and the orientation have a big impact on the number of FTC, for Belgium the southwest orientation is the most critical (Janssens et al. 2023). Even a relatively modest change in the heat and moisture balance of a facade can lead to a prominent increase or decrease in the number of FTC. For some future climate projections, FTC are expected to decrease as the number of times the temperature fluctuates under 0°C decreases (Vandemeulebroucke et al. 2023).

2 Methodology

The study design consists of 41 472 HAM simulations performed in Delphin 6.1. An overview of the parameter variations for the HAM-simulations is provided in table 1. Each combination of parameters was simulated; 1D simulations were applied to reduce computational time. The setup proceeded as followed: first, a 1D cross-section of the wall was created and all boundary conditions were assigned. Subsequently, all simulation setups were varied and run with an R script on a high-performance computing infrastructure (HPC). Post-processing of the simulation results was performed after a convergence check.

Table 1. Parameter variations for the HAM-simulations

Parameter	Variations	Description
Climate	4	Historical climate (1972-2005), Climate projections RCP 2.6, RCP 4.5 and RCP 8.5 (2066-2099)
Orientation	8	N, N-E, E, S-E, S, S-W, W and N-W
Wall thickness	3	150 mm, 300 mm and 450 mm
Brick	4	ZH, ZG, ZB and ZK
Insulation type	3	None, vapour open and capillary active
Insulation thickness	3	50 mm, 100 mm and 150 mm
Rain exposure coefficient	4	0.5, 1.0, 1.5 and 2
Shortwave absorption coefficient	3	0.4, 0.6 and 0.8

Four different bricks were selected out of the material database of Delphin. The bricks ZG, ZB, ZK and ZH were selected after performing a clustering analysis with the bricks used in the experimental study of Feng et al. (2019) as shown in Figure 1. The clustering, based on the physical properties of the bricks, was performed with the Ward's method which shows to be most robust (Zhao J. 2012). Two different insulation systems were taken into account: a capillary active system, represented by calcium silicate without a vapour barrier, and a vapour open system with a vapour control layer with sd=2.3m. Three different insulation and wall thicknesses were adopted. Note that mortar joints have not been taken into account since the simulations are 1D.

The climate data consisted of two 30-year periods and were obtained from the ALARO-0 Regional Climate Model for the grid point of Brussels, Belgium (Giot et al. 2016). To take climate change into account, 3 different representative concentration pathways (RCPs) were considered, namely RCP 2.6, RCP 4.5 and RCP 8.5.

Eight different orientations were simulated. Further, three different shortwave absorption coefficients were used to represent different colours of the exterior facade. For the exterior boundary conditions regarding water vapour and heat transfer coefficients, EN ISO 6946 (2017) was followed. EN 15026 (2007) was used to determine the indoor climate conditions. Four different rain exposure coefficients were applied, namely 0.5, 1.0, 1.5 and 2.0.

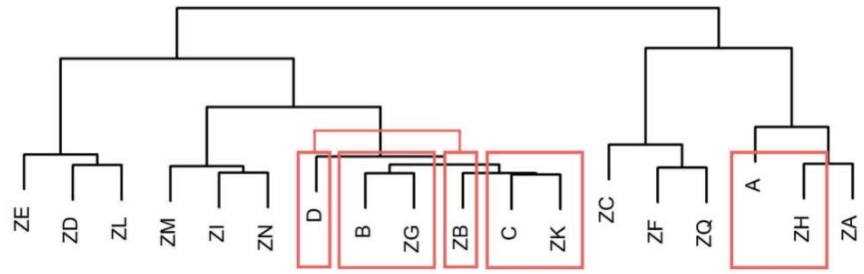

Figure 1. Clustering bricks A, B, C and D (Feng et al. 2019) with bricks from the Delphin database

In the study *Towards a more representative assessment of frost damage to porous building materials* of Feng et al. (2019), different freeze-thaw tests are carried out at milder moisture contents and temperatures, compared to the very high moisture contents and very low temperatures used in conservative freeze-thaw tests. Table 2 lists the selected freezing temperatures and saturation degrees. This table shows the test conditions applied for the different brick types A, B, C and D. The freeze-thaw tests were done for both 5 and 10 FTC. The reader can refer to the paper for the material characteristics of the bricks and further details on the test conditions.

Table 2. Test conditions for the different brick types (Feng C. et al. 2019)

Brick type	T= -2°C	-4°C	-6°C	-8°C	-14°C	-20°C
S= 0.10	-	-	-	-	-	A,B,C,D
0.25	B	B	B	B	B	A,B,C,D
0.40	B	B	B	B	B	A,B,C,D
0.55	A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D
0.70~0.75	A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D
0.85	A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D
1.0	A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D	A,B,C,D

After the tests the Young's modulus γ is obtained with the active acoustic emission method. Subsequently, the relative dynamic elasticity modulus P was calculated from γ and used to obtain Ω, as proposed by Løland (1980). A threshold for frost damage is described in EN 12371 (2010) as a relative change of the dynamic elasticity modulus by 30%, therefore Ω=0.3 is used as a damage criterion in this paper. When Ω = 0.3 is reached, the brick has already one or several cracks, holes or detachment of fragments larger than 0.1 mm width (cracks) or larger than 30mm² per fragment (detachment). Therefore, in this paper we presume Ω =0.05 as a threshold for risk of frost damage.

With the results of the hygrothermal simulations, several factors were quantified. First, the number of critical FTC (FTCcrit) was calculated as described by Mensinga et al. (2010). Next, the number of FTC for each of the applied frost temperatures listed in Table 2 was determined along with the corresponding average saturation degree. Note that the experimental dataset is rather limited and the impact of moisture and temperature is not identical for each brick. Subsequently, Ω was derived for each parameter variation with the obtained temperature and saturation degrees from the simulations to check whether the simplified approach of Mensinga et al. (2010) is still viable compared to the more detailed assessment using the experimental data of Feng et al. (2019) and for what number of FTCcrit actual deterioration occurs.

3 Results

3.1 Analysis

Figure 2 shows the spearman rank correlation for FTCcrit and Ω. It is essential to understand which parameters have a significant correlation with the performance criteria. The higher the Rho factor, the stronger the correlation. As already described in other research, the rain exposure and orientation have the most significant influence on the number of FTCcrit (Janssens et al. 2022). We can observe that besides FTCcrit, the rain exposure coefficient and orientation are also highly correlated with Ω. Although the number of FTCcrit is the factor with the highest Rho factor, it can be observed that the correlation is lower than 0.5, which is remarkable. One would assume that the number of FTCcrit correlates stronger with Ω, allowing to identify which number of FTCcrit leads to actual degradation.

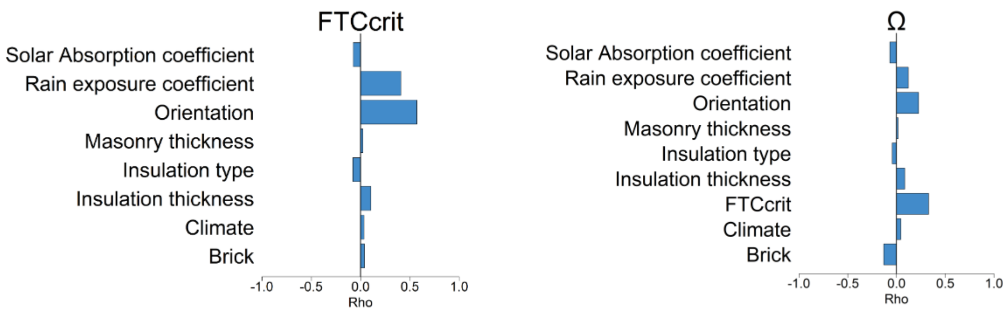

Figure 2. Spearman rank correlation for FTCcrit (Mensinga et al. 2010) and Ω.

In literature, a south-west (S-W) orientation is found to be most critical for frost damage in Belgium (Vandemeulebroucke et al. 2021). However, as shown in Figure 3.a, the overall Ω-value tends to be highest for a north-west (N-W) orientation. We can observe that this is because the Ω for FTC to -8°C and -4°C have a N-W critical orientation , compared to FTC to -2°C and -4°C that have a western critical orientation. As shown in Figure 3.b, for the FTCcrit as described by Mensinga et al. (2010) S-W orientation comes to front as most critical.

To explain why the critical orientation for Ω shifts to N-W compared to S-W for FTCcrit, the number of FTC up to a given freezing temperature and the corresponding saturation degrees are plotted in Figures 3.a and 3.b in relation to the orientation since Ω depends on the combination of the two. Given that the value of Ω increases significantly for higher saturation degrees in combination with colder FTC, the Ω caused by FTC down to -6°C and -8°C is more impactful for the total Ω, and their saturation degrees are highest for an N-W and N orientation. Moreover, at least 5 or 10 cycles are required to have a Ω-value above 0 based on the results of Feng et al. (2019).

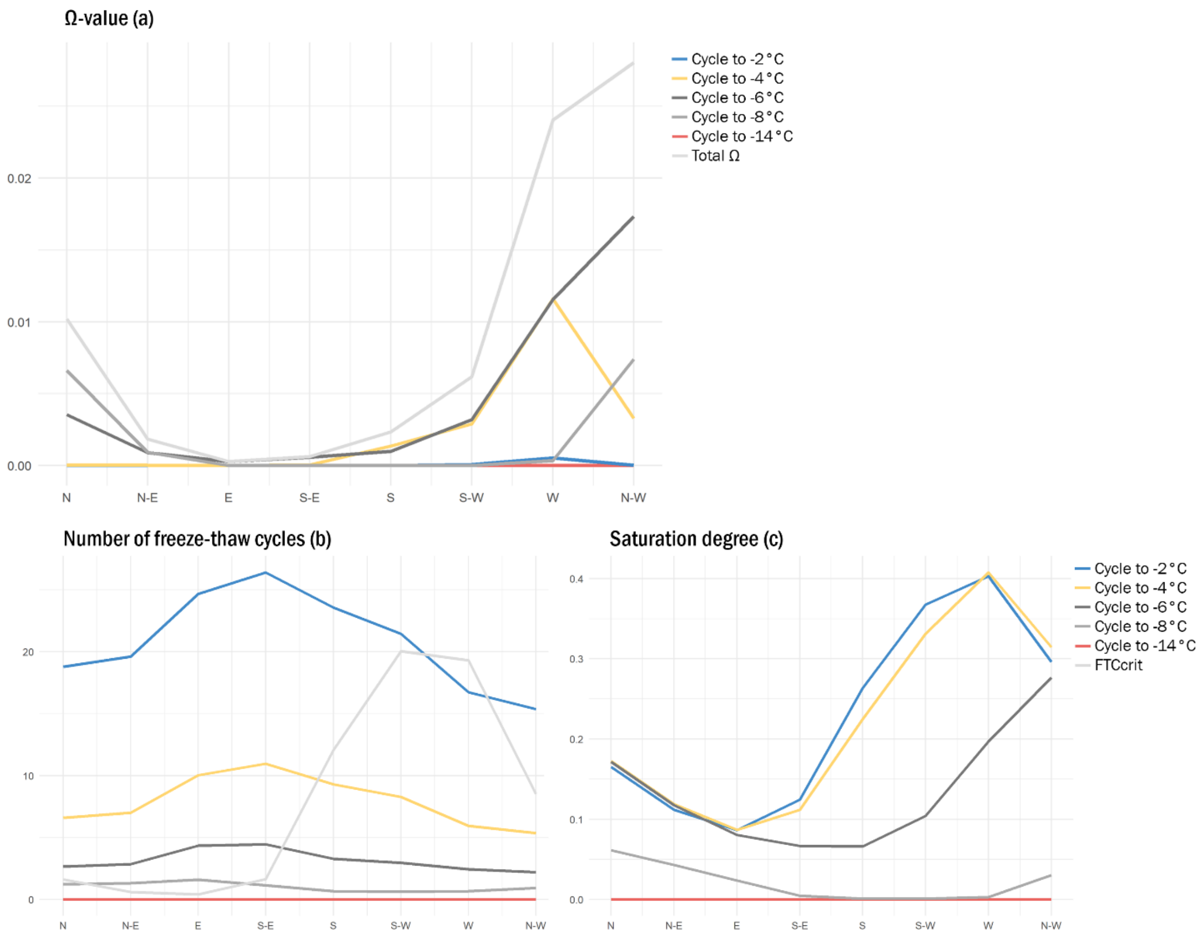

Figure 3. (a) Ω in relation to the orientation for the selected frost temperatures. **(b)** The number of freeze-thaw cycles in relation to the orientation for the selected frost temperatures. **(c)** The corresponding saturation degree when a freeze-thaw cycle occurs in relation to the orientation for the selected frost temperatures.

3.2 Towards a More Valid Freeze-thaw Criterion

Predicting the number of FTCcrit considering the availability of information known about a specific case has already been examined using decision trees by Janssens et al. (2023). However, it is currently unclear at which number of FTCcrit using the 25% criterion of Mensinga damage can be expected. Therefore, finding the relationship between FTCcrit and Ω (a quantitative way to determine the amount of damage) is of great importance.

Figure 4 shows a decision tree that predicts whether a case risks frost damage. At the bottom of the tree, the predicted answer is indicated along with the probability that the answer is correct. The risk criterion, $\Omega > 0.05$, is used for a 10-year period. The higher a parameter appears in the tree, the more influence it has on the final result. As can be seen, the first split is brick-dependent. Only then orientation and the number of FTCcrit appears. For ZB, ZH and ZK, there is no risk of frost damage when FTCcrit <37. For ZG, however, the threshold is at FTCcrit <5. Due to this large difference, we cannot establish a straightforward relationship between FTCcrit and Ω. Therefore, this relationship will have to involve the type of brick and orientation as well.

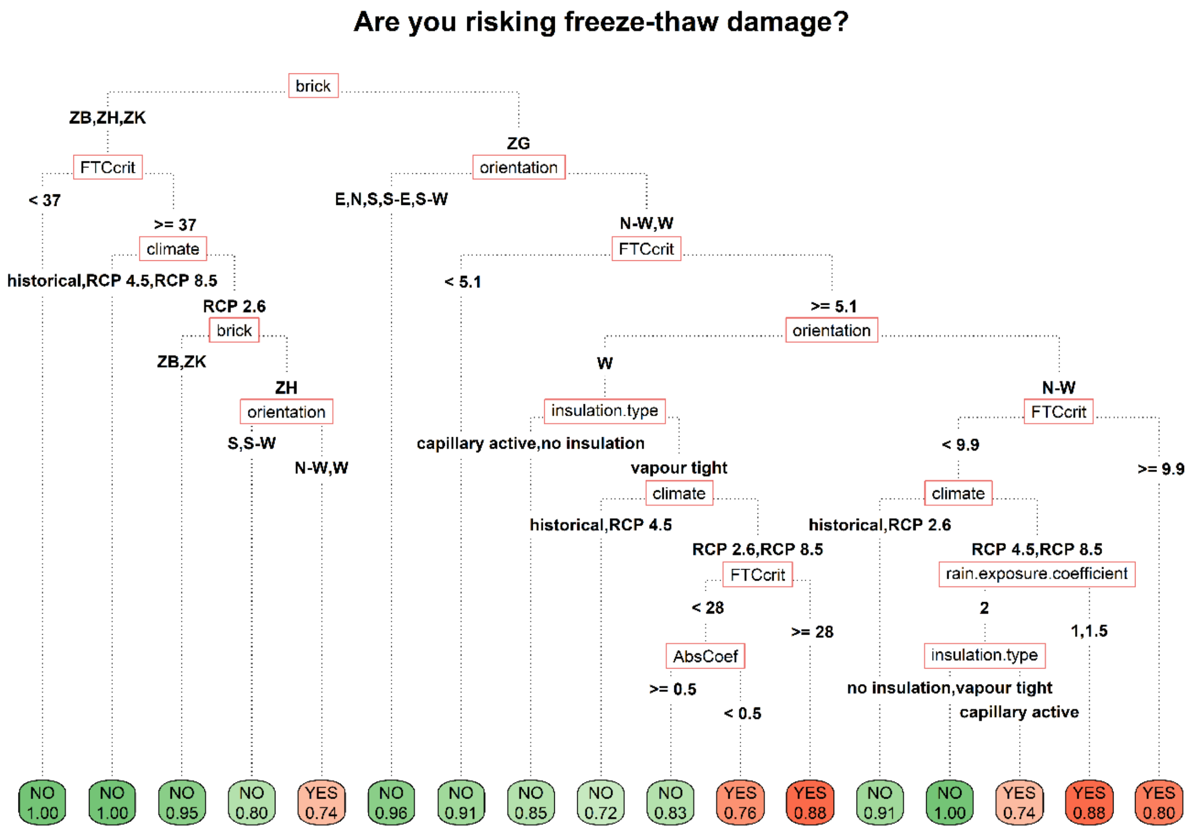

Figure 4. Classification tree for the risk of freeze-thaw damage ($\Omega > 0.05$)

In Figure 5, this relationship is expressed by means of contour plots. These are shown for each brick type and are function of orientation and the amount of FTCcrit. The contour lines depict the Ω-value. Note that the reported Ω-values are an average of all results involved, the results of outliers are therefore averaged out.

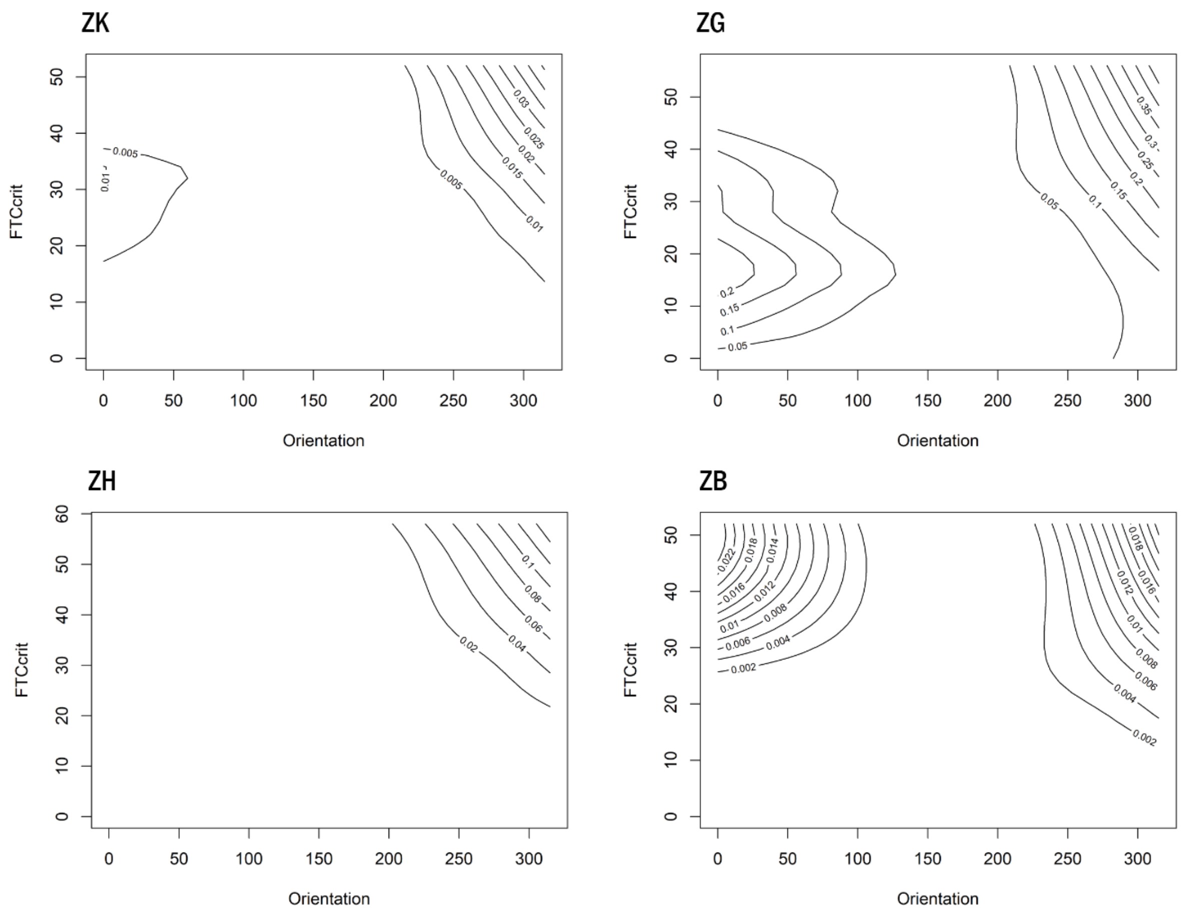

Figure 5. Ω for different bricks, based on orientation (degrees) and FTCcrit

We can observe that Ω is considerably higher for bricks that can be clustered under ZB. This clustering can be done by means of the clustering scheme of Vanderschelden et al. (2021) with known material characteristics of a brick. The graph confirms that for ZK, ZH and ZB the important increase in Ω starts around 25 FTCcrit. For ZG, a frost-sensitive brick, this starts already from 5 FTCcrit. For each type of brick the critical orientation is situated around N-W.

The contour plots in Figure 5 are simplified to some extent but already clarify the crux of the matter in a comprehensive way. Still, it would be better to use classification trees if more information on the facade is available.

4 Conclusion and Discussion

In this paper, the experimental results of Feng, C. et al. (2019) were combined with FTCcrit (Mensinga et al. 2010) by means of hygrothermal simulations. The experimental results include the Ω value, derived from Young's modulus, as a function of saturation and frost temperature. This Ω-value is a quantifiable factor used in EN 12371 (2010) as a threshold for frost degradation (Ω > 0,3).

The aim of this study was compare frost damage based on FTCcrit with the Ω value to see at which number of FTCcrit damage can be anticipated, in order to better predict frost damage with results from HAM simulations.

First, we can conclude that the number of FTCcrit shows the highest correlation with Ω, along with orientation and the rain exposure coefficient. However, the correlation is not as strong as one might expect. Therefore, it is not possible to find an unambiguous correlation function for FTCcrit and Ω. By using decision trees and contour plots, it becomes clear that the relationship between the two factors is mainly brick- and orientation-dependent. The best way to predict the risk of frost damage is to use decision trees, which include many different factors that all have a significant influence on the final result. It can be found that a threshold value for the number of FTCcrit is situated between 5 and 40 cycles (depending on the type of brick) to avoid the risk of frost damage ($\Omega > 0.05$). Remarkably, for the Ω-value the critical orientation shifts to N-W, whereas S-W is critical for the number of FTCcrit.

However, it should be noted that more research is needed to fully assess these results. Firstly, it would be interesting to conduct this study for different climates, particularly those with low freezing temperatures. Moreover, also the duration of the freeze-thaw cycle may have a significant impact. Subsequently, the experimental dataset should be extended towards different types of bricks and freezing conditions. Now, the Ω value has only been derived for 5 and 10 FTC, but given the non-linear relation between both more research is required to investigate the impact of repetitive cycling. Moreover, it should be noted that only a single sample of each type of brick is tested for the different frost temperatures and saturation degrees.

Acknowledgements

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