Durability Evaluation of External Thermal Insulation Composite Systems: Frequency Assessment of Thermal Shocks

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Abstract

The External Insulation Composite Systems (ETICS) are nowadays widely used to improve the energy efficiency of the building envelope. To assess the durability of ETICS we first performed a Failure Modes Analysis, studying effects and actions of the stressing agents, and we isolated the most relevant critical climate conditions that cycled many times lead to failure. Then, by means of Heat and Moisture Transport (HMT) numerical simulations, we evaluated the frequency of those events that are more critical for the durability of ETICS (such as thermal shocks or cyclic seasonal variations in surface temperatures) and the performance decay over time in several climatic contexts, especially Southern Europe.

The main results achieved with HMT simulations on a specific ETICS component, with different insulation types, showed that there is no relevant difference in intensity and frequency of thermal shocks, in terms of sudden surface variations, between expanded polystyrene (EPS) and mineral wool insulation (MW) systems. In fact, just a few more events occur for EPS than for MW systems. We also compared the performance of ETICS in Northern with Southern European climates, and we note that, also in summer, contrary to expectations, there is a large amount of events of thermal shocks in Northern Europe, up to 50% higher than Mediterranean cities, albeit with different intensity. Thanks to this analysis is possible to point out that also for Northern Europe is important to take into account summer conditions in procedures for accelerated ageing in the laboratory. This can represent an example of how the differences in terms of stressing agents and system reactions could affect the reference conditions which should be set for the ageing tests.

Keywords: Durability, ETICS, HMT simulations, EPS, Mineral Wool, Thermal Shocks

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1. Introduction

The Durability Research Group of Politecnico di Milano, within the framework of CIB W080 “Service Life Methodologies”, has developed an experimental programme for the evaluation of the durability of ETICS (External Thermal Insulation Composite Systems), which is a technological component widely used to improve the energy efficiency of the building envelope.

To evaluate the durability of building components it is important to study the failure modes that can occur over time. In the case of external insulation systems, failures occur mainly on the finishing layers, at interfaces between coating and insulation, or between insulation and substrate. The failures depend on the type and properties of coating and insulation. Some failures are particularly interesting considering ETICS: cracking, detachments, bulging and wrinkling, and biological growth. They are due to weathering, or design and laying errors, which often combine and enhance their influence. The classification of failures can be made considering their seriousness, their extension over the surface, or their probability.

We analyzed the agents, their actions, and effects resulting in the main failure modes, as shown in (Daniotti et al., 2012), with experimental studies we performed on that kind of systems (Daniotti et al., 2005), survey on existing buildings (Re Cecconi et al., 2008), literature review, and assessing failure cases provided by a manufacturer of mineral wool. The discussed failure modes are mainly related to ETICS with expanded polystyrene (EPS) - currently the most used - and mineral wool (MW) insulation. The reinforced base coat is usually cement-based with polymeric resins added, while the finishing coat may be an acrylic or mineral thick coating (only if the base coat has excellent planarity it may be a paint). In this analysis, we focused on degradation related to the natural ageing processes, thus excluding conception and construction errors (i.e. building pathologies). The main agents we considered are thermal shocks (actually a combination of agents), moisture, freeze-thaw, algae, mould, and other biotypes.

Thanks to the previous analysis, we saw that cyclic thermal shocks and water absorption are, in Southern Europe climates, often the most relevant mechanisms that cause degradation, loss in performances, and failures of ETICS. Whether the relevance of their effects on ETICS is known (ETAG 004, 2000), less studied, instead, are both the intensity of the shocks, which shall be reproduced in the laboratory, and their frequency in different climate areas. In fact, intensity and frequency are fundamental knowledge to study the durability of objects exposed to cyclic stress (Daniotti et al., 2008).

2. Hygrothermal Modelling

To evaluate the intensity and frequency of the most critical events, we performed heat and moisture transport simulations (HMT) with the software WUFI 5.1, a finite differences model, based on the numerical solution of the heat balance and the moisture balance equations (Kunzel, 1995). The main features of the WUFI model are the ability to simulate the thermal conductivity as a function of temperature and water content, the moisture transport in liquid phase by capillarity, beyond water vapour diffusion (with moisture transport coefficients as a function of water content itself), and latent heat exchanges, as well as heat and moisture sources/sinks. We used WUFI to compute the surface temperatures and assess their variations, in terms of thermal shocks, of an ETICS with a mineral wool compared to an EPS system in different climatic conditions. The insulation materials were modelled with the same thermal conductivity (λ = 0.04 W m^{-1} K^{-1}), so as to compare the results in terms of thermal shocks (materials properties are presented in Table 1). The simulations were performed in one-dimension, considering, thus, the main section.

Table 1: Properties of the layers of substrate and ETICS with MW or EPS

n°	Layer	t (m)	ρ (kg m^{-3})	$\lambda_{dry,10°C}$ ($Wm^{-1}K^{-1}$)	μ (-)	Porosity (-)
1	Silossanic finishing coat	0.0015	1340	0.70	150	0.40
2	Reinf. mineral base coat	0.004	1200	0.87	25	0.30
3 a/b*	Mineral wool	0.10	146	0.04	1.2	0.95
	EPS	0.10	30	0.04	50	0.95
4	Adhesive	0.005	1200	0.87	25	0.30
5	Cement lime plaster	0.015	1900	0.80	19	0.24
6	Aerated clay brick	0.200	650	0.13	15	0.74
7	Cement lime rendering	0.015	1900	0.80	19	0.24
* For layer two options were considered: a) MW, b) EPS.						

2.1 Reference conditions and input data

For the surface properties the solar absorbance α was set as a variable, ranging from 0.01 to 0.99 (extreme non-realistic cases useful just to show the influence of the incident solar radiation), with steps of 0.10 from 0.20 to 0.80; while the emissivity ε was kept constant and equal to 0.90. We considered the ETICS oriented in the four cardinal directions (herein we present the results just for the South exposure) and applied on a low rise building (height up to 10 m). The calculation period of simulations was set as three years. For the interior climate, we considered the conditions prescribed by the European standard EN 15026, with normal moisture load.

Weather data of some European cities selected as representative were selected from databases (Meteonorm) and include temperature, relative humidity, solar radiation, precipitation and wind speed. The following examples are related to two Italian cities (Milano and Palermo) representative for Southern Europe at two different latitudes, with respectively semi-continental and Mediterranean climate, and two cities in Middle and Northern Europe (Nantes and Espoo), with Atlantic and Baltic climate. The aim of this choice is to highlight the possible differences in terms of frequency and intensity of stressing conditions. A prospect of the weather data is shown in Figure 1, while Figure 2 shows the comparison in percentiles between the analyzed cities about the external air temperature (°C) and the solar radiation G_t (W m^{-2}) on a South facing surface, also distinguished into direct G_b and diffuse G_d component. In terms of solar radiation Milano and Nantes are very similar; Espoo, instead, has a G_t less than 100 W m^{-2} and Palermo less than 300 W m^{-2} for the 75% of hours. At the 95-th percentile the value of G_t is less than 500 W m^{-2} for all the considered contexts.

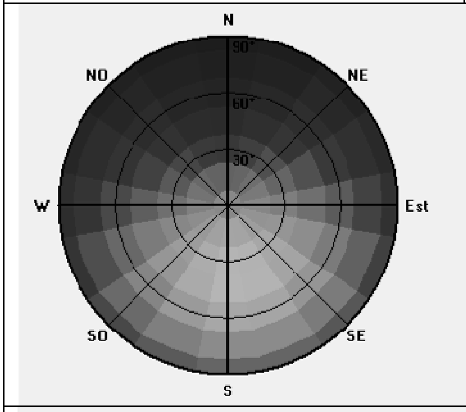
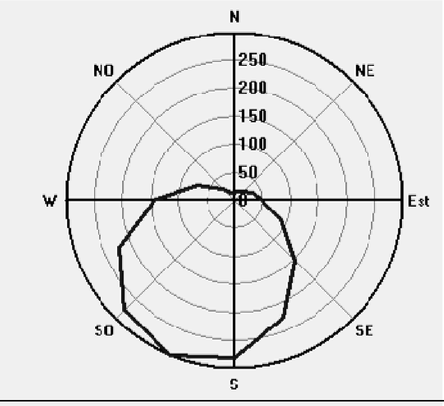
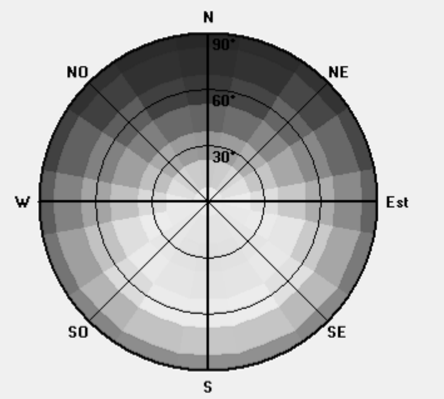
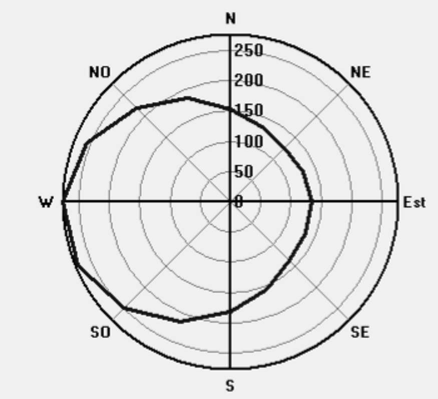
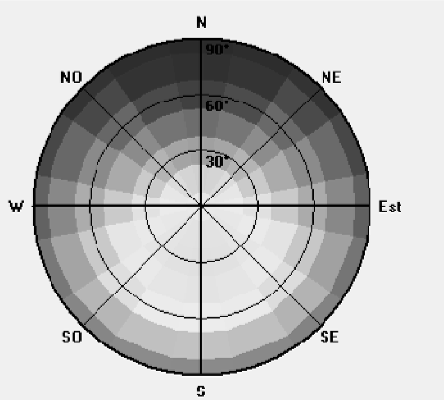
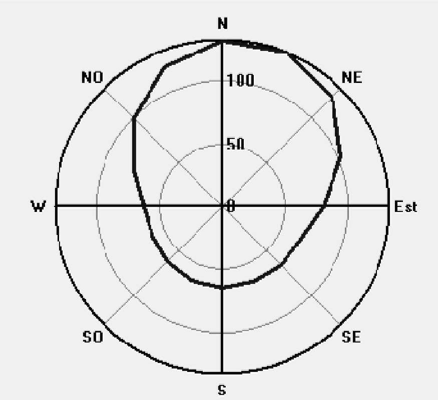
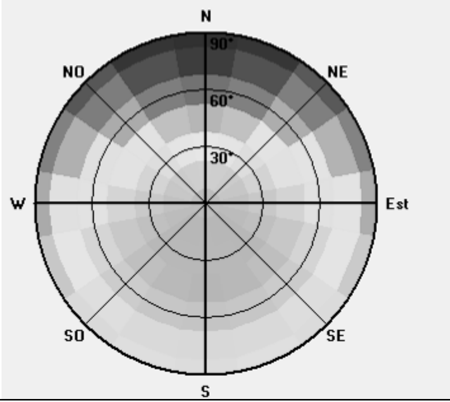
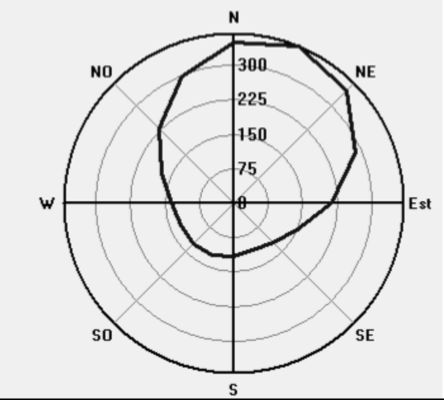
Total Solar Radiation (Kwh m^{-2} y^{-1})	Rain (mm y^{-1})	Cities	
		Espoo	
		T mean (°C)	5.5
		T max (°C)	28.4
		T min (°C)	-25.2
		RH mean (%)	79
		RH min (%)	22
		Rain (mm/y)	639
		Nantes	
		T mean (°C)	11.7
		T max (°C)	32.8
		T min (°C)	-5.4
		RH mean (%)	81
		RH min (%)	34
		Rain (mm/y)	786
		Milano	
		T mean (°C)	11.7
		T max (°C)	31.7
		T min (°C)	-6.9
		RH mean (%)	79
		RH min (%)	30
		Rain (mm/y)	950
		Palermo	
		T mean (°C)	18.0
		T max (°C)	34.9
		T min (°C)	4.0
		RH mean (%)	77
		RH min (%)	43
		Rain (mm/y)	599

Figure 1: Main climatic data for Espoo, Nantes, Milano and Palermo.

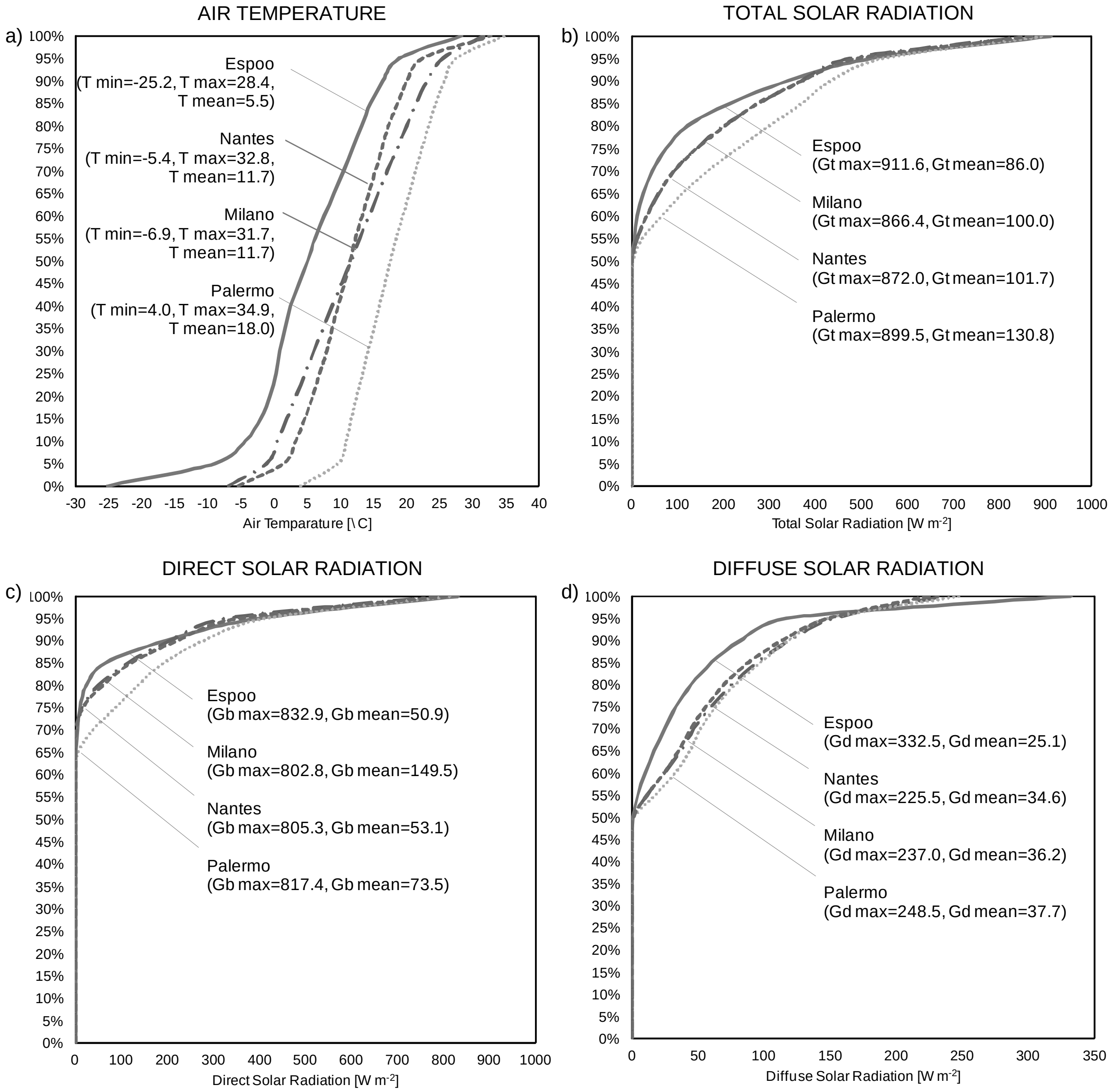


Figure 2: Air Temperature and Solar radiation for a South facing wall

2.2 Thermal shocks analysis

The analyses are based on hourly values of surface temperatures and are divided into different steps: partitioning in surface temperature classes, computation of surface temperature variations, with or without rain, just in summer conditions, and at the end considering the case with surface temperatures higher than or equal to 40°C. For this analysis (described more in detail in Daniotti et al., 2012) we considered as an example a South oriented wall in different weathering conditions.

2.2.1 Surface temperatures

The Figure 3 shows the surface temperatures divided into intervals of 5°C (ranging from -5°C to +70°C), and the hours per year in which can occur for each interval for the different cities. With this analysis we estimate the risk of failure due to stress-strain cycles produced by expansions and contractions.

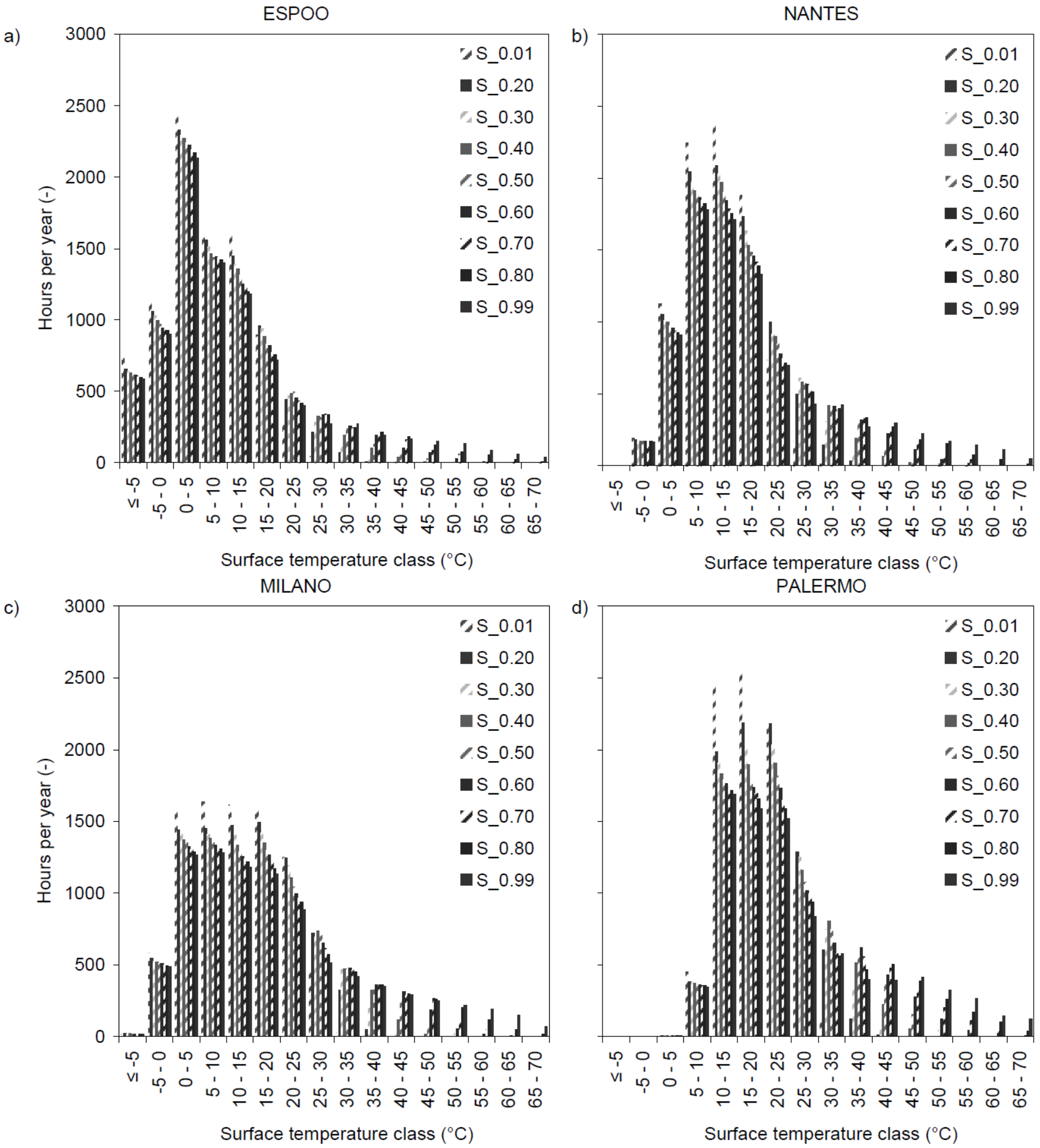


Figure 3: Surface temperature classes for different cities (EPS System)

In case of Espoo, in Finland, there is a high peak in the range 0 – 5 (°C), but the distribution type is similar to those for Nantes and Palermo, while for Milano we see a flatter distribution, with about 1000-1500 hours per year for several ranges from 0 to 25 (°C).

2.2.2 Surface temperature variations with driving rain

A thermal shock may be produced by several combinations of agents, such as: night-time surface cooling for exchange with a clear sky atmosphere and sunrise; rapid change in cloudiness; surface cooling by the action of a cool wind and subsequent heating when the surface is sunlit and heated; and the cycle of heating, cooling because of a summer storm, and subsequent heating when the storm is over.

Even though many thermal shocks occur during one year, the most critical events are those associated with rain, because water changes all properties of porous media: tensile and compression strength decrease, solar absorbance increases, thermal conductivity increases.

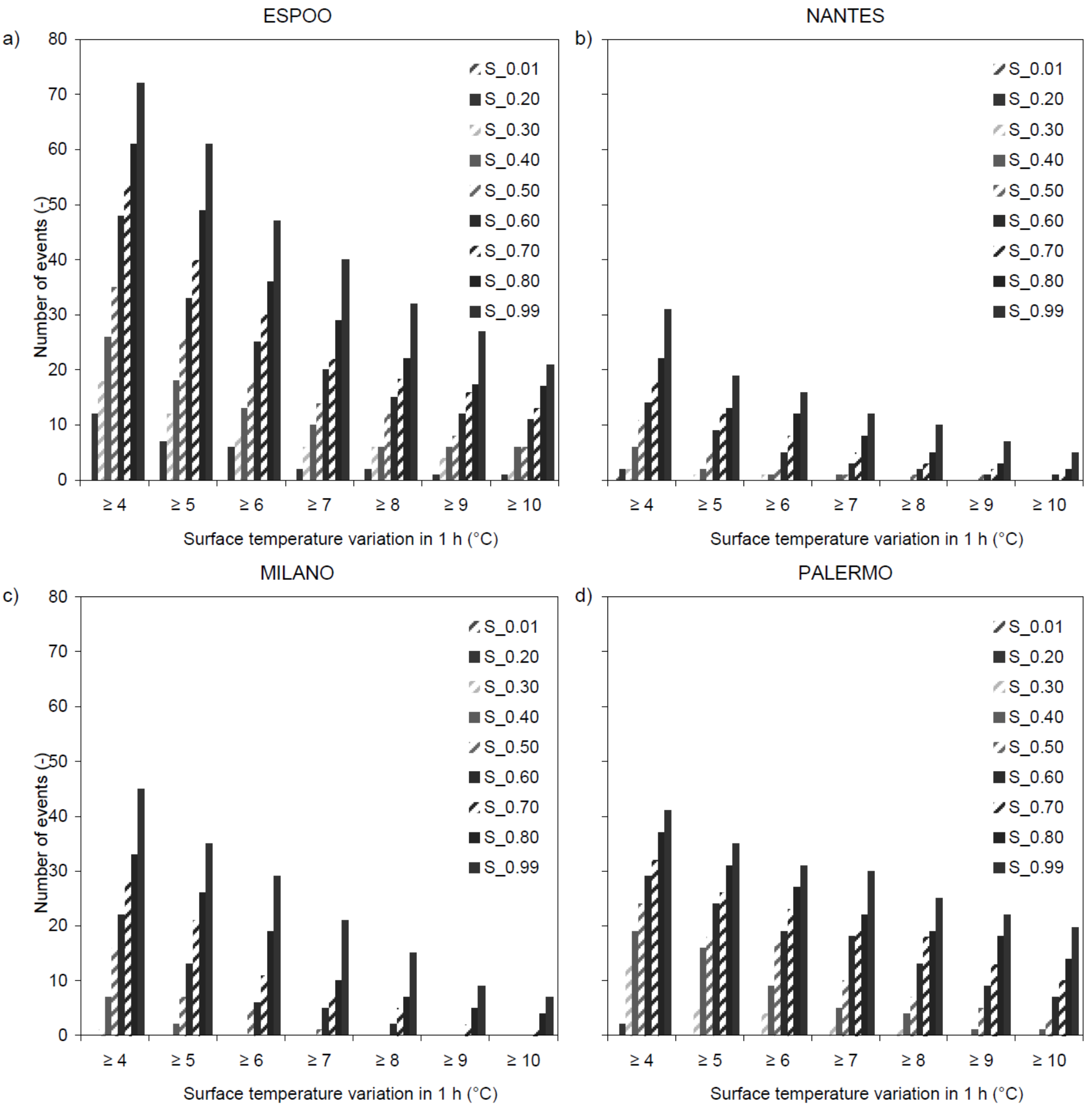


Figure 4: Surface temperature variations with rain for South facing of ETICS with EPS

As a consequence, when the reinforced base coat and top coat get wet, the surface temperature falls, and the rendering is subject to a rapid contraction right when its tensile strength is decreased because of the increased moisture content.

We counted how many times there was a sudden temperature variation and filtered the results counting only the events corresponding to a rapid change in surface temperature coupled with driving rain, considering the total number of events for the entire simulation period and computing a yearly average. In this case, the results of our analysis show (Figure 4) a higher number of events for Espoo, up to 60 with a temperature variation greater than or equal to 4 °C with solar absorbance equal to 0.8, which is the double compared to Nantes and even higher than for the cities of Southern Europe. Also considering just the spring and summer conditions, from April to September (Figure 5), the events of thermal shocks are more frequent for Espoo than for the other cities.

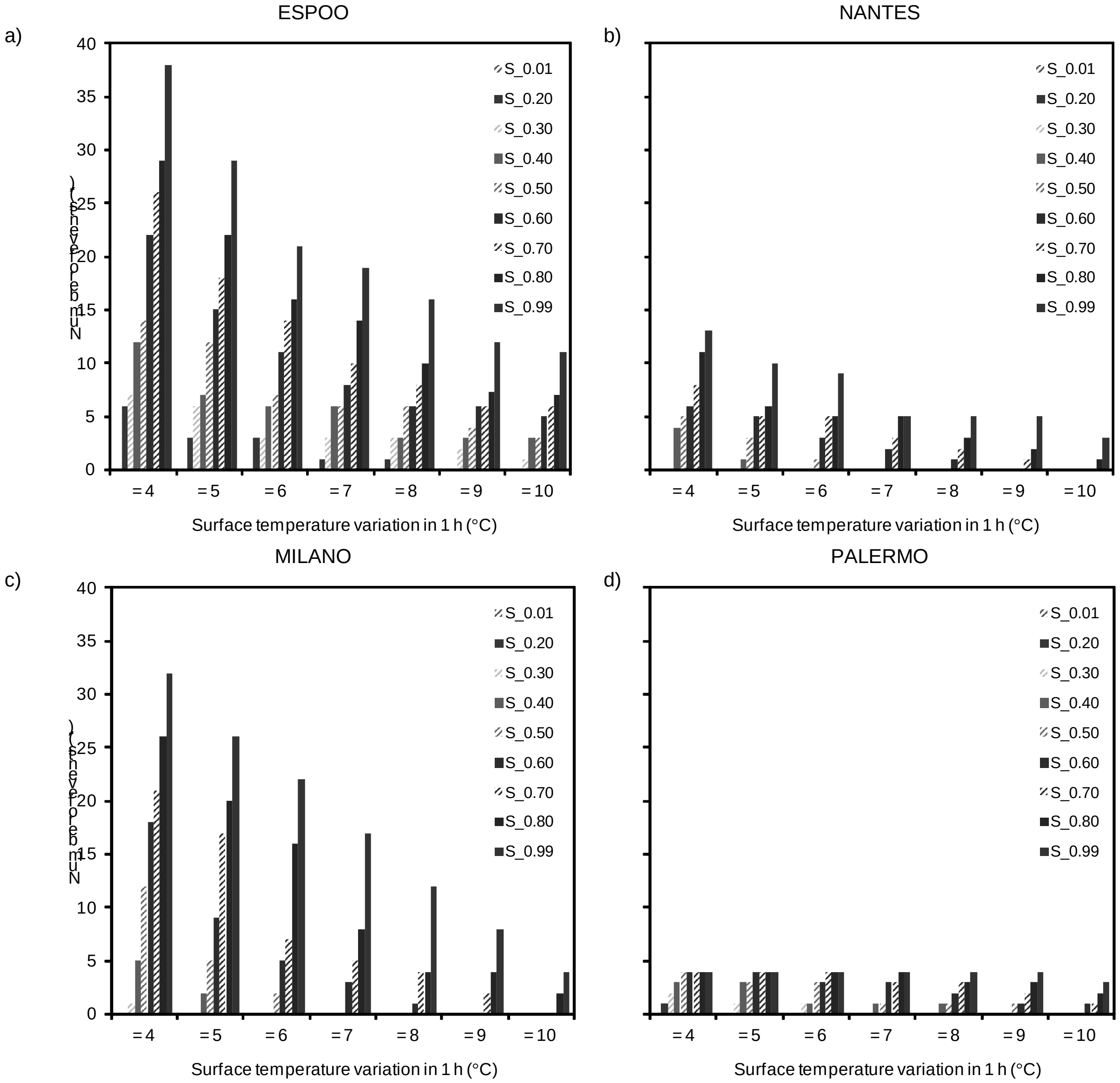


Figure 5: Surface temperature variations with rain in summer conditions.

2.2.3 Surface temperature variations with temperature ≥ 40°C

We considered just the events during which a sudden temperature change occurs combined with driving rain and the surface temperature of the initial or the final condition (the thermal shock may happen both with a sudden heating or a sudden cooling) is above 40°C. As shown in Figure 6, also the more extreme cases, in summer conditions, occur more frequently for Espoo respect to a Mediterranean city with an increase of number of events of about 50%.

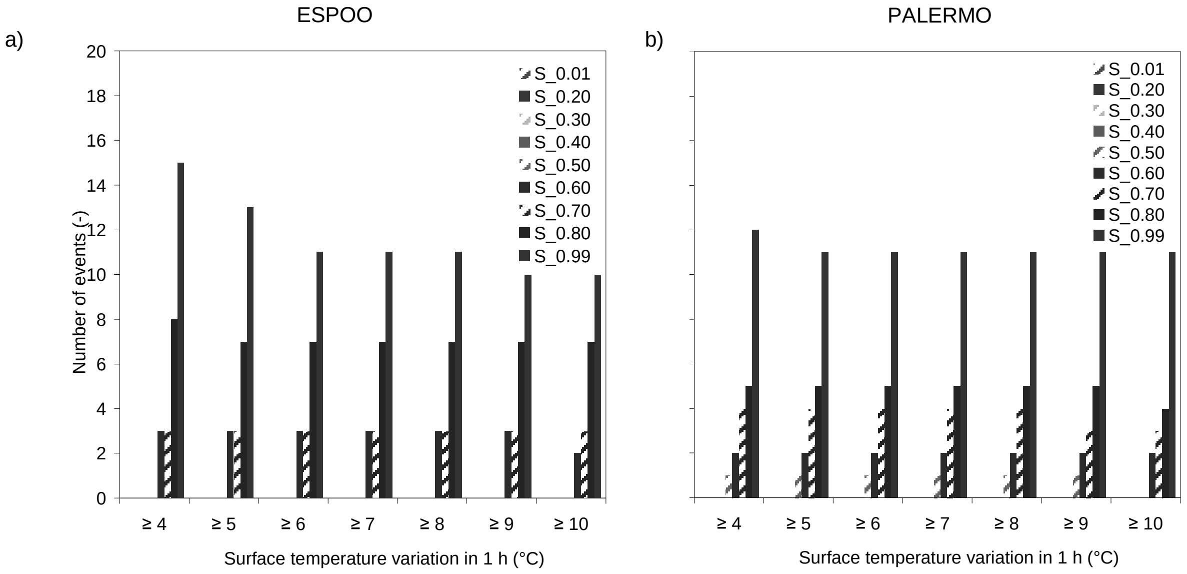


Figure 6: Surface temperature variations with high temperatures (≥40°C).

3. Results and discussions

3.1 Comparative analysis of Thermal shock for MW and EPS systems

The simulations carried out for the two systems, composed by the same rendering but with a different insulation panel, mineral wool or EPS, showed that there is no relevant difference in terms of intensity and frequency of thermal shocks, in other words for different surface temperatures.

Just for some values of solar absorbance (from 0.50 to 0.99) but for every weathering condition, it is possible to see a very light increase of number of events (about 10% more) of ETICS with EPS compared to ETICS with MW as shown in Table 2 for Milano, in which the grey cells represent the different values, from one to a maximum of three events.

Although there are small differences analyzing the surface temperatures, a different response in terms of thermo-mechanical behaviour should be expected due to the compression and tensile strain because of differential thermal expansion coefficient of materials.

Table 2: Surface temperature variations, comparison between ETICS with EPS or MW.

Milano_ΔT & Rain (ETICS - **EPS**)									
αs (-) ΔT(°C)	S_0.01	S_0.20	S_0.30	S_0.40	S_0.50	S_0.60	S_0.70	S_0.80	S_0.99
≥ 4	0	0	1	7	16	22	28	33	45
≥ 5	0	0	0	2	7	13	21	26	35
≥ 6	0	0	0	0	5	6	11	19	29
≥ 7	0	0	0	0	1	5	7	10	21
≥ 8	0	0	0	0	0	2	5	7	15
≥ 9	0	0	0	0	0	0	2	5	9
≥ 10	0	0	0	0	0	0	1	4	7
Milano_ΔT & Rain (ETICS - **MW**)									
αs (-) ΔT(°C)	S_0.01	S_0.20	S_0.30	S_0.40	S_0.50	S_0.60	S_0.70	S_0.80	S_0.99
≥ 4	0	0	1	7	14	22	27	32	44
≥ 5	0	0	0	2	6	11	21	25	32
≥ 6	0	0	0	0	2	6	8	18	28
≥ 7	0	0	0	0	0	4	6	9	20
≥ 8	0	0	0	0	0	1	5	5	14
≥ 9	0	0	0	0	0	0	2	5	9
≥ 10	0	0	0	0	0	0	0	2	5

A further analysis in water content (kg m^{-3}) is necessary, because we expected a different amount in the coating layers due to different capillary water absorption coefficient $A_{w,24}$ (Kg $m^{-2}s^{-0,5}$), even if it is very low, and the different water vapour diffusion resistance factor μ (-) of the insulation boards.

3.2 Comparative analysis in the Europe Climate

Contrary to results one might expect, there is a higher number of events of thermal shock in summer condition in the cities of Northern Europe than in the cities of Southern Europe, maybe due to the different direct solar radiation on the wall, Southern exposure in our case. In fact, as shown above, for Espoo there is an increase of the number of events up to 50% respect to the cities of Southern Europe. The differences could be generated also by the different amount of driving rain on the surface which changes the surface temperature.

In order to understand the reason, besides the water content analysis, further thermal shock studies are necessary just in winter conditions. Moreover, frequency and intensity of freeze-thaw cycles should be assessed. In addition, in order to point out the critical intensity for the thermal shocks the effect of temperature variation on the stress-strain curves should be evaluated.

4. Conclusion

We analysed the surface temperatures of ETICS, with mineral wool and EPS insulation having the same rendering and considering different values of solar absorbance. The assessment has been computed with Heat and Moisture Transfer (HMT) simulations for different climatic contexts, in order to highlight the differences in behaviour, making a comparison between Northern and Southern Europe.

The results, in terms of frequency and intensity of thermal shocks, have shown that there is no relevant difference between the two insulation systems, with mineral wool or EPS, for each weathering condition. The difference is just a light increase of events for EPS, respect to MW, in case of high solar absorbance. Of course, we have to expect a different response in terms of thermo-mechanical behaviour that we are going to analyze by Finite Element Methods. The critical reference ranges of values for thermal shocks should be defined knowing the effect of temperature on the stress – strain curves.

A higher number of thermal shocks, also in summer condition, occur in a city of Northern Europe, with a double amount respect to the Mediterranean cities, maybe due to the different direct solar radiation on the wall, but a deeply analysis should be carried out, with also a detailed survey about the climatic data. In fact, we know that there is a systematic error in the solar radiation modelling (diffuse and direct components) which determines an overestimation of the values. We are working on a new model based on actual data. Until now we have processed data for one year and we are going on with this analysis.

A further analysis of thermal shocks is also necessary just in winter condition, and the future work will be also analyzing the water content in each layer and the frequency and intensity of freeze-thaw cycles.

The first achieved result is that the analysis of frequency and intensity of critical events are fundamental for setting the right laboratory test parameters for the durability evaluation of ETICS in different stressing conditions. In fact we have seen, for example, that also for the Northern Europe is important to take into account the summer condition for the accelerated ageing test.

The analyses carried out for some climatic contexts should be repeated for more cases in order to achieve a complete scenario for Southern and Northern Europe, to have benchmarks, needed to evaluate the system behaviour and the best proprieties of materials to ensure the limit performance in different contexts.

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