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Effects of Ageing and Moisture on Dynamic Thermal Performance of ETICS Cladding

Bruno Daniotti [1]
Fulvio Re Cecconi [2]
Riccardo Paolini [3]

ABSTRACT

In this paper, we discuss the influence of ageing and increase of moisture content – achieved with accelerated laboratory exposure – on the thermal performances of External Thermal Insulation Composite Systems with rendering (ETICS).

We propose herein two types of dynamic test methods (non-standard methods), which were designed to assess time shift and decrement factor. With a first type of test, the exterior surface of the cladding, facing a climatic chamber, is exposed to a 24 h sinusoidal temperature forcing, while the conditions in the laboratory are stable. In a second test, the solicitation reproduces the sol-air temperature, to check the influence of temperature on time shift. Then, we discuss limits and improvements needed in the test method, and we present early results. Finally, we study the influence of uncertainty in values of material properties – namely thermal conductivity, density, and specific heat capacity – on time shift, decrement factor, and periodic thermal transmittance.

We note that, with ageing, the studied building component offered higher water absorption capability and, thus, the thermal resistance presented a decreasing trend, while an increasing trend was observed for heat capacity, and time shift. We conclude that a standard test procedure is necessary, including information about the duration of draining periods.

KEYWORDS

ETICS, Thermal admittance, Time shift, Decrement factor, Moisture.

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[1] Politecnico di Milano, Building Environment Science & Technology Dept., Milano, ITALIA, bruno.daniotti@polimi.it
[2] Politecnico di Milano, Building Environment Science & Technology Dept., Milano, ITALIA, fulvio.rececconi@polimi.it
[3] Politecnico di Milano, Building Environment Science & Technology Dept., Milano, ITALIA, ric.paolini@gmail.com

1 INTRODUCTION

Exterior insulation cladding systems are a very common building technology – since the 1960s – both in Continental Europe (where they are usually applied to a masonry substrate and are called ETICS), and in North America (where they are usually applied on a wood frame and are called EIFS). Despite differences in terminology, and more relevantly, different building materials, exterior insulation cladding systems offer similar durability issues. The most relevant reported degradation modes are: mould growth, cracking over joints of insulation boards and blistering due to summer thermal shock, water absorption [Künzel et al. 2006; Hens & Carmeliet, 2002; and Daniotti & Paolini, 2005], and air leakages combined with wind driven rain; the latter is true especially for EIFS [Sahal & Lacasse, 2005]. In synthesis, the most relevant problems occur in presence of water (by itself or in synergy with other agents). Furthermore, increase in moisture content in the insulator affects all hygro-thermal performances.

Given the importance of moisture influence on degradation and hygro-thermal performances, several Heat and Moisture Transport (HMT) numerical studies have been performed to assess the response to moisture of exterior insulation cladding systems [e.g. Beaulieu et al., 2002; Zirkelbach et al., 2005]. However, software models are normally not able to cope with some phenomena (e.g. gravity), or they adopt simplifications, such as assuming a coefficient describing the percentage of water hitting the façade that does not bounce away from the surface (for walls, often assumed equal to 0.7). Sometimes, constraints are given by the lack of input data, for instance driving rain, especially with a sampling time shorter than one hour, or properties of interfaces between layers – relevant in heat and moisture transfer [de Freitas et al., 1996] – or of singular points. Actually, building details are the main points of penetration of rain in EIFS [Bronski, 2005]. Especially for ETICS, the main moisture flow takes place, beyond connections with other building components (e.g. windows), through joints between insulation boards [Barreira & de Freitas, 2005; Daniotti & Paolini, 2008b].

In the laboratory, with accelerated ageing and testing, we assessed ETICS cladding durability [Daniotti & Paolini, 2008a,b], comprising the survey of both degradation of the finishing system and evolution of the thermal performances. Early results, namely loss in thermal resistance, are offered in Daniotti & Paolini [2008b]. We introduce herein two types of test methods for assessing time shift and decrement factor, we discuss limits and improvements needed in the testing procedure, and we present results. Finally, we discuss the influence of uncertainty in thermal conductivity, density, and specific heat capacity on time shift, decrement factor, and periodic thermal transmittance (according to ISO 13786), later identified, respectively as φ, f_a, and Y_{12}.

2 THERMAL PERFORMANCE EVOLUTION WITH ACCELERATED AGEING

We performed, in the laboratory, accelerated ageing exposure on a 1 m^2 sample (Tab. 1) of an ETICS over masonry wall, including UV, freeze-thaw, and summer thermal shock cycles, grouped in macro-cycles as detailed in Daniotti et al. [2008]. Before ageing, and at each macro-cycle, we monitored degradation, and evolution of performances: thermal resistance; time shift (sine temperature curve forcing); thermal constants (solicitation: +20°C, +70°C, +20°C, each for 24 h); and a moisture response cycle (RH: 20%, 50%, 80%, then, rain; each step for 2 h).

2.1 Measurement of Thermal Resistance and Derived Moisture Content in Layers

Thermal resistance was measured, by means of ISO 9869 method, of main section profile, for the entire specimen, for substrate, and for ETICS. Data in table 1 and 2 refer to the sample non-aged (T0), and after exposure to two macro-cycles (T1, and T2). Condition T2+ concerns ageing time T2 after a rain cycle (1 lt m^{-2} h^{-1} for 2 hours). With a correction to the mean heat flow rate (using the storage effect method described in ISO 9869), we took into account for each layer both the thermal capacity when dry (labelled as *dry*) and the total thermal capacity, including moisture contribution (labelled as *wet*). Then, we derived thermal resistance and water content of each layer from a numerical solution starting, from an estimate of moisture and thermal gradient in the sample.

Table 1. Estimated water content (w) and thermal conductivity (λ_{wet}) - derived considering water content - of the tested sample not aged (T0), after ageing (T1, T2, and T2+). In the calculation, we subdivide EPS in six layers of 1 cm.

n° Layer	*t* *[m]*	w_c *T0* *[kg m^{-3}]*	w_c *T1* *[kg m^{-3}]*	w_c *T2* *[kg m^{-3}]*	w_c *T2+* *[kg m^{-3}]*	$\lambda_{wet\ T0}$ *[W m^{-1} K^{-1}]*	$\lambda_{wet\ T1}$ *[W m^{-1} K^{-1}]*	$\lambda_{wet\ T2}$ *[W m^{-1} K^{-1}]*	$\lambda_{wet\ T2+}$ *[W m^{-1} K^{-1}]*
1 Gypsum	0.005	4.35	3.59	5.46	4.09	0.208	0.207	0.210	0.208
2 Plaster	0.015	33.53	29.92	39.28	29.96	0.913	0.901	0.932	0.901
3 Masonry	0.12	25.00	29.11	33.72	52.36	0.375	0.413	0.415	0.431
4 Plaster	0.015	49.38	61.56	54.72	66.3	0.966	1.007	0.984	1.023
5 Binder	0.003	62.52	61.56	54.72	66.35	1.010	1.007	0.984	1.023
6 EPS 1	0.01	5.00	5.00	5.00	5.00	0.0339	0.0335	0.0337	0.0337
7 EPS 2	0.01	7.50	10.00	15.00	20.00	0.0335	0.0334	0.0338	0.0339
8 EPS 3	0.01	10.00	15.00	20.00	37.50	0.0332	0.0365	0.0358	0.0382
9 EPS 4	0.01	12.50	17.50	25.00	40.00	0.0358	0.0371	0.0392	0.0435
10 EPS 5	0.01	15.00	20.00	27.50	42.50	0.0360	0.0374	0.0396	0.0435
11 EPS 6	0.01	23.59	22.36	29.83	43.04	0.0380	0.0378	0.0399	0.0436
12 Base coat	0.005	43.71	39.05	47.45	30.00	0.947	0.931	0.960	0.901
13 Top coat	0.0015	13.17	8.37	16.36	3.98	0.870	0.870	0.870	0.870

Table 2. Thermal performances of the tested sample not aged (T0), after ageing (T1, and T2), and at ageing time T2 after a rain cycle (T2+)

Thermal Performance		*T0* *dry*	*T0* *wet*	*T1* *dry*	*T1* *wet*	*T2* *dry*	*T2* *wet*	*T2+* *dry*	*T2+* *wet*	*unit*
Substrate resistance	$R_{cd,12}$	0.374	0.376	0.349	0.346	0.345	0.344	0.335	0.334	[m^2 K W^{-1}]
ETICS resistance	$R_{cd,23}$	1.716	1.725	1.699	1.684	1.642	1.640	1.556	1.553	[m^2 K W^{-1}]
Conductive resistance	$R_{cd,T}$	2.090	2.100	2.048	2.030	1.986	1.984	1.891	1.887	[m^2 K W^{-1}]
Conductance	Λ	0.479	0.476	0.488	0.493	0.503	0.504	0.529	0.530	[W m^{-2} K^{-1}]
Tot resistance	R_T	2.260	2.270	2.218	2.200	2.156	2.154	2.061	2.057	[m^2 K W^{-1}]
Transmittance	U	0.443	0.440	0.451	0.455	0.464	0.464	0.485	0.486	[W m^{-2} K^{-1}]
Substrate heat capacity	C_{12}	145.0	162.9	145.0	165.4	145.0	168.0	145.0	177.5	[kJ m^{-2} K^{-1}]
ETICS heat capacity	C_{23}	15.7	18.7	15.7	19.0	15.7	19.9	15.7	21.3	[kJ m^{-2} K^{-1}]
Tot heat capacity	C_T	160.6	181.6	160.6	184.5	160.6	187.8	160.6	198.8	[kJ m^{-2} K^{-1}]
Time shift SINa	ΔT	n.a.		10h 48’		6h 34’		n.a.		[h]
Time shift SINb	ΔT	n.a.		11h 07’		5h 54’		n.a.		[h]

2.2 Unsteady Thermal State Test Procedure

The sample was exposed (for two days to achieve harmonic periodic stabilised regime) to two types of tests to measure φ and f_a, namely:

- A sine wave reproducing the outdoor air temperature (SINa in fig. 1a) for Milano (Italy) the 21st July (peak yearly condition); and
- A curve reproducing the sol-air temperature with absorbance of the finishing coat set as 0.6 (SINb in fig. 1b).

Results for T0 (non-aged sample) are not available, since these tests were introduced only later. For high insulated samples, we acknowledge some issues in the measurement procedure, namely:

- With a low sinusoidal temperature wave (min 20°C, max 30°C) it is difficult to read φ, and f_a, since the very small thermal gradient between laboratory (20 ± 2°C) and climatic chamber;
- A non perfectly sinusoidal temperature wave representing the sol-air temperature has a higher maximum, but the same minimum value in solicitation, and the same problem in measuring f_a;
- Adopting higher values for the temperature waves, to enhance readability of the test, would alter the thermal properties of water, and the overall hygro-thermal response; and
- For well-insulated samples, it is difficult to measure f_a, since the error in estimation of results is of the same magnitude of the heat-flowmeter resolution. In our case, we could not read f_a.

Since these constraints, we adopted the selected testing solicitations, despite issues in readability of results. However, we stress upon the need of standardisation in terms of sensors resolution, laboratory conditions, curing time between tests, and complementary side tests to check the main measurement.

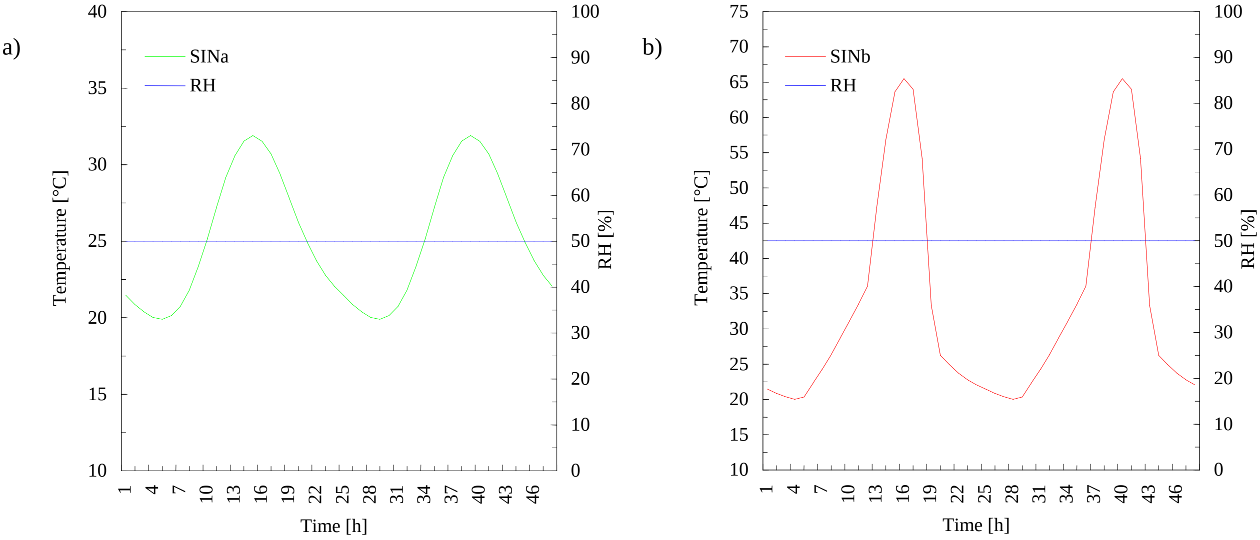

Figure 1. Test forcing for SINa (on the left) and SINb (on the right). Each sine solicitation is repeated for two days, so as to reach harmonic periodic stabilised regime

3 ERROR RISK ANALYSES

Given the risk of uncertainty in measurement results, and the risk of error in the calculation of dynamic performance due to uncertainty in input, we performed a risk analysis.

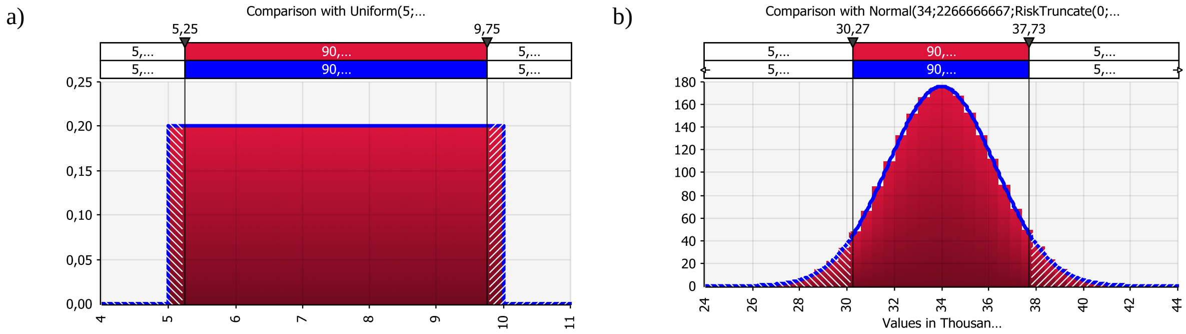

Figure 2. On the left, the probability distribution assigned to surface heat resistance. On the right, the normal probability distribution assumed for material properties (here for EPS thermal conductivity).

We assumed a probability distribution (Gauss) for thermal conductivity, density, and specific heat capacity of each layer. Then, for each parameter, we considered that a variability comprised between -20% and +20% (centred on a value selected as average or most probable) should represent the 99.7% of all the possible case (±3σ). Only for surface heat resistances (Fig. 2a), we assumed a flat probability distribution - any value has the same probability to be correct - since they are not the result of an industrial process, and may assume diverse values for the same building component. As centre value for surface heat resistances we assumed 0.17 m^2 K W^{-1} (estimated in the lab). For all other layers, instead, we assumed a normal probability distribution (Fig. 2b).

3.1 Risk analysis – Three Moisture Content Conditions

We computed Y_{12}(Fig. 3a), f_a (Fig. 3b), and φ (Fig. 4a) for three conditions of moisture content:

- Case A – all layers are dry;
- Case B – all layers present the typical moisture content for their class of material; and
- Case C – all layers present the moisture content in condition of free saturation.

Results are displayed versus cumulative distribution functions (by percentile), to assess the stochastic reliability of computed thermal performances.

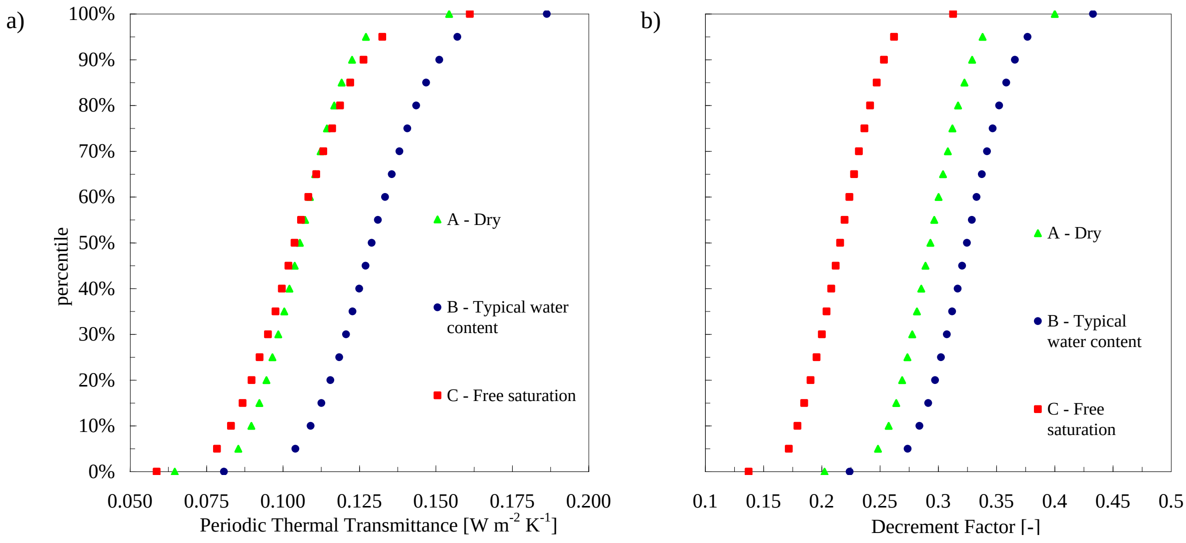

Figure 3. a) Periodic Thermal Transmittance; b) Decrement Factor.

For the materials employed for the aged sample, we did not measure the moisture storage function, the moisture diffusivity, and thermal conductivity depending on moisture content, but we assumed - as trial values for the stochastic risk analysis - the curves given in the literature [IEA, 1991; Künzel, 1995]. We adopted this approach since we note that, for many materials, properties may be highly influenced by laying conditions. For instance, a plaster may offer different properties when applied to a masonry substrate or by itself, manufacturing a small laboratory sample. We also note that, as yet, there is no test method to measure these properties depending also on temperature. In this work, we focus on dynamic parameters; other studies analyse on the influence of variability of hygro-thermal parameters values on moisture content, and they confirm the large influence that these parameters have on the result [Salonvaara et al., 2001].

3.2 Risk Analysis – Laboratory Testing and Stochastic Monte Carlo Simulation

We performed a second error risk analysis, with the same procedure, assuming as central values the thermal conductivities, specific heat capacities, and densities that we measured (and derived depending on the moisture content computed as discussed in § 2.1) for the ageing conditions T0 (non aged), T1, T2, and T2+ (i.e. T2 immediately after a rain cycle).

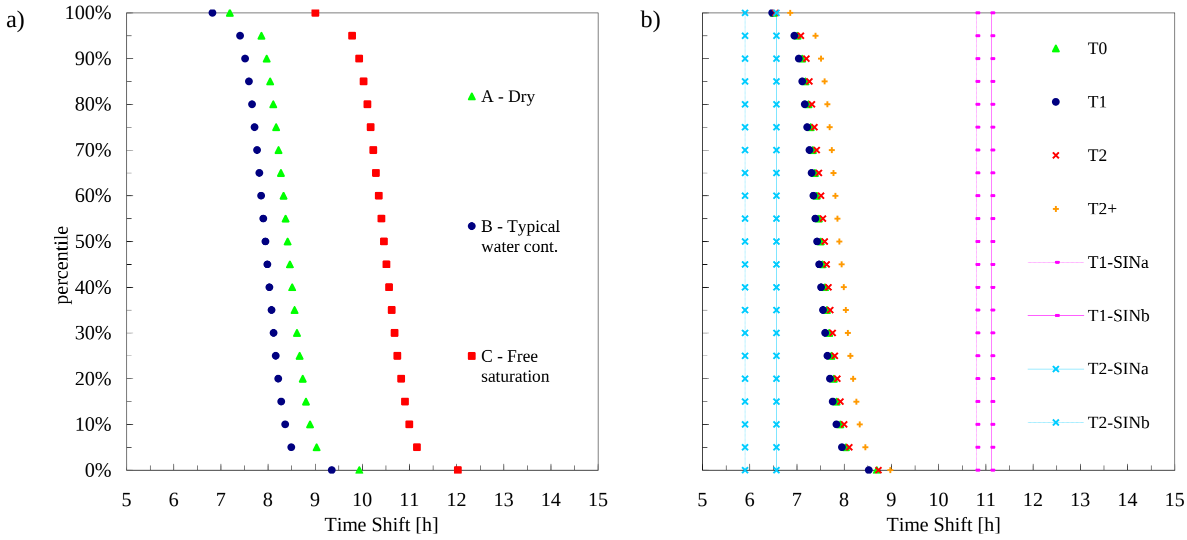

Figure 4. a) Time shift for conditions A - dry materials, B - with typical moisture content, and C - with maximum moisture content in free saturation (typical and maximum moisture content according to Künzel [1995]); b) Time shift for ageing times: measured (lines) and modelled (plots).

4 DISCUSSION

With reference to periodic solicitation, the dynamic thermal response (Y_{12}, φ, f_a) of building components – according to ISO 13786 – can be related to the periodic penetration depth δ (where $\delta = (\lambda T \pi^{-1} \rho^{-1} c_p^{-1})^{0.5}$, with T the period of solicitation in seconds), and hence to thermal conductivity, and the product of heat capacity and density. These quantities depend on water content (and temperature); thus, moisture has a dual effect: it decreases the thermal conductivity of a layer, and it increases the heat capacity and density of the layer. The risk analysis (Figs. 3, and 4a) highlights that with typical moisture content (case B), in comparison with the dry condition (case A), φ decreases (at 50%-ile from 8h 25’ in case A, to 7h 57’ in case B), while increase both Y_{12} (at 50%-ile from 0.106 W m^{-2} K^{-1} in case A, to 0.129 W m^{-2} K^{-1} in case B) and f_a (at 50%-ile from 0.29 in case A, to 0.32 in case B). Then, for high water contents (free saturation, case C) φ reaches the maximum (at 50%-ile 10h 28’), while Y_{12} and f_a show the minimum values (at the 50%-ile respectively 0.19 W m^{-2} K^{-1}, and 0.22).

In our experiment, we observed a loss in thermal resistance (Tab. 2), with increasing moisture content due to rain penetration occurred during ageing cycles, and decrease in time shift (from roughly 11 h at T1, to about 6 h at T2). We explain the decrease in time shift, considering that the increase in moisture content in the insulation board caused a reduction of the thermal resistance, more influent than the increase of the heat capacity for the same layer. Moreover, we did not observe a relevant increase in moisture content in the masonry substrate (except at T2+), meaning that the most of water penetrated and concentrated in the thermal insulator (Tab. 1).

Comparing measurement results with computer simulations, we observed that with laboratory testing we obtain a larger variation in time shift for the same moisture contents: with tests, φ is 10 h 48’ at T1, and 6 h 34’ at T2, while with calculations φ varies (at the 50%-ile) from 7 h 26’ (T1) to 7 h 35’ (T2). We explain this noting that the moisture content was derived for the main section, while the most relevant rain penetration occurs through the joint between insulation boards. In addition, we note that the time shift measured at T1 (10h 48’), corresponds, roughly, to that computed for free saturation condition (10h 28’, curve C – 50%-ile, Fig. 4a). Furthermore, water is subject also to draining forced by gravity, and we expect the largest moisture content to be at the base of the sample.

Moreover, we note a large influence on results of the surfaces heat resistances, which are difficult to characterise in the laboratory and may vary test by test (depending on the sample and the thermal gradient).

5 CONCLUDING REMARKS

We monitored the hygro-thermal performances of a sample of an ETICS over masonry wall subject to accelerated ageing. We observed decreasing thermal resistance – almost only for the ETICS – due to increase of water content caused by rain penetration. Then, performing dynamic tests with sinusoidal temperature solicitation, a decrease in time shift was observed. We also computed the time shift (together with decrement factor and periodic thermal transmittance) for the sample with moisture content derived at each ageing time. We observed large differences in values of computed and measured time shift. We impute these differences to the fact that we measured the moisture content for the main profile section, while we estimate (thanks to IR thermography) that most relevant water penetration occurs through the joint between insulation boards.

We conclude that ageing, and moisture, whose content within layers is increased by ageing, affect dynamic thermal performances. Moreover, we argue that considering the main section profile is not sufficient to capture hygro-thermal dynamic performances of ETICS. Moreover, we point out the need of standardisation of un-steady state thermal performance testing methods.

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