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Impact of natural and artificial ageing on the properties of multilayer external wall thermal insulation systems

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ABSTRACT

Multilayer external wall thermal insulation systems are widely used in new constructions and for the retrofitting of building façades. Despite the increasing use as constructive solution, significant anomalies have been frequently identified on these systems only few years after their application, raising questions on their long-term durability. This paper focuses on the effects of one-year natural ageing and artificial ageing through hygro-thermal cycles (heat/rain and heat/cold) on the water performance (capillary water absorption and drying kinetics), bio-susceptibility (mould development) and surface properties (colour, gloss, and roughness) of four multilayer external wall thermal insulation systems (three ETICS and a thermal rendering system). Results showed a significant loss of surface hydrophobicity after ageing. Considering the 24 h water absorption results, an increase up to 73% and 432% was obtained for the naturally and artificially aged systems, respectively, and when compared to the reference unaged systems. The drying kinetics was affected by ageing, with increases of the drying resistance ranging between 47% and 122% after artificial ageing. Traces of mould growth were observed on the artificially aged systems; however, no growth was detected on either the unaged or the one-year naturally aged systems. Substantial colour change for all systems after ageing was observed, confirming aesthetic alteration. Results contribute towards the development of implemented artificial ageing protocols, as well as for the delivery of multilayer thermal systems with enhanced performance and durability.

1. Introduction

The building sector is responsible for 40% of the energy consumption and 36% of greenhouse emissions in the European Union [1,2]. For this reason, several directives (e.g., [3,4]) have been approved over the past few years to support policies which aim at promoting building energy efficiency. The development of innovative materials and constructive solutions, which contribute to minimise the energy consumption and fulfil the comfort needs, has been thus considerably encouraged within the industrial and academic communities.

Different types of multilayer external wall thermal insulation systems have been extensively applied in new constructions and for the thermal retrofitting of building façades [5–7]. These systems guarantee an enhanced thermal performance of the building envelope, minimising the consumption and loss of energy [8,9].

External Thermal Insulation Composite Systems (ETICS) are multilayer external wall thermal insulation systems widely used in Europe [5,10]. These systems consist of a thermal insulation layer with high thermal resistance; a base coat with a reinforcement glass fiber mesh; and a finishing coat [11]. The application of ETICS on building façades can mitigate thermal bridges [8], reduce the risk of interior surface condensation on the wall and protect the masonry and the structural elements [6,12]. ETICS also have low implementation costs and their application is relatively easy [10,13]. However, extensive cases of anomalies were detected on ETICS and some of them shortly after the application of these systems [10,14,15]. Most of these anomalies are related or can be associated to the presence of water within the system, which can lead to physical–mechanical damages and trigger biological growth [16].

In order to develop an expert knowledge-based inspection for ETICS, Amaro et al. [14,59] visually analysed several buildings (146 ETICS façades), located in the north and centre of Portugal, with a service life up to 22 years. The most commonly detected anomalies in ETICS were biological colonisation (56%), other colour changes (49%) and runoff

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marks (43%). According to the authors, these anomalies can have not only a noticeable aesthetic impact, but also long-term effects on the thermal and mechanical performance of ETICS, if no periodic inspections (e.g., every 10 years [61]) and regular maintenance actions are carried out. Nonetheless, aesthetic deterioration only, as identified on most of ETICS façades within few years of use [62], has a key role in limiting a wider diffusion of ETICS technology.

In fact, numerous cases of biological growth have been described in multilayer external wall thermal insulation systems [17,18]. The bioreceptivity is influenced by the properties of the material, such as its hygroscopicity, porosity, pH, surface roughness, emissivity, among others [19,20]. Barreira and Freitas [17] concluded that the combined effect of wind-driven rain, drying process, surface condensation, and the rendering properties strongly influences the biological colonisation on ETICS. Additionally, the bioreceptivity of ETICS can be affected by both surface roughness and porosity [20], whereas the thermal conductivity of the systems significantly increases with their moisture content [21,22]. Hence, in order to avoid moisture-related anomalies, ETICS solutions should have suitable water repellent properties, i.e., enhanced water repellence, fast drying process, and adequate water vapour permeability throughout the system in-service conditions during the life cycle [11].

In recent years, alternative lightweight aggregates, such as cork [23,24], EPS [25,26], or even nanomaterials, such as silica aerogel [7,27], have been applied in the formulation of pre-mixed thermal insulating mortars. These mortars have enhanced thermal performance and are currently being used in different countries as thermal insulation in multilayer thermal wall systems [28]. The new mortar formulations potentiate a density reduction that usually imply a decrease of the thermal conductivity, but also a reduction of mechanical resistance [26]. Nevertheless, they present some advantages over ETICS, such as the possibility of levelling irregular surfaces, direct application over the substrate, and the possibility of being adopted for retrofitting external walls of historic buildings [7,29].

In Europe, the durability assessment of the thermal insulating mortars is defined by the standard EN 998–1 [30] following the test methods of EN 1015–2 [31]. However, those requirements apply only to the thermal insulating mortar, and not to the whole multilayer system. A more accurate assessment of the overall performance and durability of multilayer thermal wall systems with a thermal mortar as insulation layer – thermal rendering system (TRS) – can be achieved combining EAD 040083–00-0404 [32] and EN 998–1 [30]. Nevertheless, the EAD guideline only considers the hygrothermal and freeze–thaw behaviour for the durability assessment of ETICS and further deterioration agents (e.g., bio-susceptibility assessment) are not envisaged.

This paper intends to evaluate and compare the performance of different multilayer external wall thermal insulation systems (three ETICS and one TRS) after one-year of natural ageing and after artificial ageing through hygrothermal cycles (heat/rain and heat/cold). The water performance (capillary water absorption and drying kinetics), bio-susceptibility (mould growth), and surface properties (colour, gloss, and roughness) of unaged, naturally, and artificially aged systems were experimentally assessed. In accordance with the methodology defined in ISO 15686–1 [60], artificial and natural ageing exposure tests should be carried out and the relative results and degradation types critically analysed. Hence, a model for the service life prediction of the systems can be developed and validated, contributing towards the development of multilayer thermal wall systems with enhanced performance and durability in natural exposure conditions, as well as for the development of adjusted artificial ageing protocols.

2. Materials and methods

2.1. Multilayer external wall thermal insulation systems

Four commercially available multilayer external wall thermal insulation systems (MEWTIS) were tested (three ETICS and one TRS) (Fig. 1). The ETICS and the thermal mortar (Table 1) have European Technical Approval (ETA) and CE marking, respectively. The selected MEWTIS have also similar rendering system (base coat + finishing coat) (Table 1); however, different thermal insulation (EPS, ICB, MW, or TM). The identification and composition of the four systems are described in Table 1, according to either their ETA, CE marking or technical data sheet. The MEWTIS were supplied by the same manufacturer.

Table 2 presents values for some of the most relevant physical properties of the systems. These results were obtained either from previous work by the authors [11,26] or from the ETA and CE marking documents of the systems.

Specimens of each system were cut in different dimensions according to the tests performed (Table 3 and Section 2.3). The water performance (capillary absorption and drying) and the surface properties (colour, gloss and roughness) were assessed for the unaged systems, after artificial ageing (hygrothermal cycles) and after one-year of natural ageing. The biological suspceptibility to moulds was assessed with a laboratory test method for the unaged systems and after artificial ageing, and visually observed directly on the exposed test specimens every three months till one-year of natural exposure. Fig. 2 shows a schematic representation of the experimental programme.

2.2. Ageing tests

Artificial ageing (Fig. 3a) was carried out using hygrothermal cycles performed in accordance with EAD 040083–00-0404 guideline [32] (Table 4). Two specimens of each system with dimensions of 150 mm × 150 mm × thickness (Table 3) were first placed on a vertical rack at a 50 cm distance from both the sprinklers (total water flux of 1 L/(m^2.min)) and the thermal IR lamps (8 × 250 W). Then, hygrothermal cycles were conducted in a FitoClima 700EDTU climatic chamber and consisted of the following steps: 80 repetitions of heat/rain cycles; specimens were left to drain for 2 h; specimens were conditioned for 48 h (15 °C $\leq$ T $\leq$ 25 °C and RH $\geq$ 50%); 5 repetitions of heat/cold cycles (Table 4).

Two specimens of each multilayer system with dimensions of 150 mm × 150 mm × thickness (Table 3) were naturally exposed for twelve months (from October 2019 to October 2020) at an urban site in Lisbon, Portugal (38°45′31′′N; 9°8′29′′W; Altitude – 95 m). The specimens were placed on a rack at an inclination of 45°and facing South (Fig. 3b). Table 5 presents the meteorological conditions at the natural ageing test location for the exposure period, according to the data provided by the Portuguese Institute for Sea and Atmosphere (IPMA) for Lisbon (Portugal).

2.3. Analysis of properties

In the evaluation of the MEWTIS durability, water resistance was the main criterion selected for the characterisation of the systems, i.e., considering the capillary water absorption and the drying kinetics. In fact, most of the anomalies detected on MEWTIS can be linked to the presence of water [59]. Additional characteristics of the systems were also evaluated, such as the mould growth susceptibility and the surface colour, gloss, and roughness.

The capillarity water absorption test was performed in a conditioned room (T = 23 ± 2 °C; RH = 65 ± 5%) according to EAD 040083–00-0404 [32]. Specimens were sealed on the sides using a waterproof scotch tape to avoid direct contact between the water and the thermal insulation. Capillary water absorption was thus analysed through the capillary water absorption coefficient, representing the initial rate of liquid water absorption of the systems (Equation (1)), and the absorption curves.

$$C_c = \frac{M_2 - M_1}{A \times \sqrt{3}} \quad (1)$$

In the above equation, C_c is the capillary water absorption coefficient (kg/(m^2.min$^{0.5}$)), M_1 is the specimen's mass at the beginning of the test

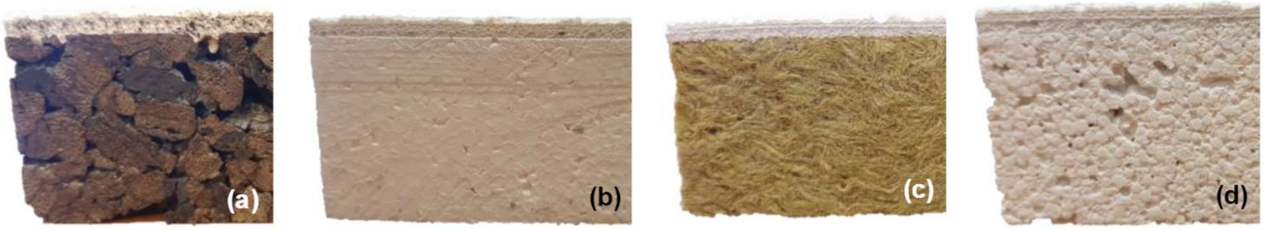

Fig. 1. Photographs of the MEWTIS: (a) $A_{(icb)}$; (b) $B_{(eps)}$; (c) $C_{(mw)}$; and (d) $D_{(tm)}$.

Table 1
Identification and composition of the MEWTIS.

System		$A_{(icb)}$	$B_{(eps)}$	$C_{(mw)}$	$D_{(tm)}$
Thermal insulation (TI)		ICB	EPS	MW	TM
Rendering system (RS)	Base coat (BC)*	Natural hydraulic lime, mixed binders and cork aggregates	Cement, natural hydraulic lime and mineral aggregates		
	Finishing coat (FC)	Key-coat: acrylic resin and mineral aggregate Finishing: acrylic paint, siloxane resin and marble powder**			
Average thickness [mm]	Total	41.91	43.30	44.77	43.13
	TI	37.52	38.51	39.93	38.29
	RS	4.39	4.79	4.84	4.84

ICB – expanded cork agglomerate; EPS – molded expanded polystyrene; MW – mineral wool board; TM – pre-dosed thermal mortar composed by mixed binders and EPS granulated; *Includes a standard or reinforced glass fiber mesh; **Contains biocide (isothiazole and butyl carbamate).

Table 2
MEWTIS. Relevant physical properties according to previous studies [11,26], ETA and CE marking documents.

	$A_{(icb)}$	$B_{(eps)}$	$C_{(mw)}$	$D_{(tm)}$
RS equivalent air thickness (m)	0.76	0.59	0.99	0.78
Water vapour diffusion resistance coefficient of the TI (-)	14.1	39.8	2.7	8.1
Bond strength between the BC and the TI after hygrothermal ageing (MPa)	0.14	0.23	0.03	–
Bulk density of the TI (kg/m^3)	100	19	100	406
Thermal conductivity of the TI (W/(m.K))	0.048	0.037	0.042	0.078

RS – rendering system; TI – thermal insulation; BC – base coat.

Table 3
Tests performed, sampling and references.

Test	Reference	Specimens	Dimensions [mm]
Capillary water absorption and drying kinetics	EAD 040083–00-0404 [32]EN 16,322 [33]	2	150 × 150 × thickness
Mould susceptibility	ASTM D5590-17 [34]ASTM C1338-19 [35]	3	40 × 40 × thickness
Colour and gloss	ASTM D2244 [36] ASTM D6578 [37] ASTM D523-14 [38]	3 (6 and 9 values per specimen for colour and gloss, respectively)	150 × 150 × thickness
Surface roughness	–	3 (9 values per specimen)	150 × 150 × thickness

(kg), M_2 is the specimen's mass after 3 min testing (kg) and A represents the immersed base area (m^2).

EAD 040083–00-0404 [32] defines, for ETICS, a water absorption threshold of 1 kg/m^2 at 1 h and refers that there is no need of further assessment through freeze/thaw cycles if this value is lower than 0.5 kg/m^2 at 24 h.

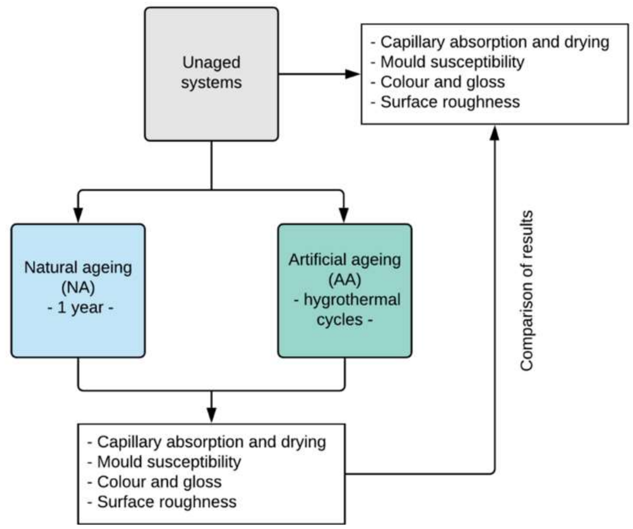

Fig. 2. Scheme of the experimental programme.

The drying test was carried out in a conditioned room (T = 23 ± 2 °C; RH = 65 ± 5%) immediately after the capillarity water absorption test and according to EN 16,322 [33]. The drying kinetics was analysed through the drying index (DI) and the drying curves over time. The drying index, obtained according to Equation (2), reflects the entire drying kinetics.

$$DI = \frac{\int_{t_0}^{t_f} f\left(\frac{M_x - M_1}{M_1}\right)dt}{\left(\frac{M_3 - M_1}{M_1}\right) \times t_f} \tag{2}$$

In the above equation, DI is the drying index (-), M_x is the specimen's mass registered throughout the drying process (g), M_1 is the specimen's mass in the dry state (g), M_3 (g) is the specimen's mass at the beginning of the test (t_0) and t_f is the ending time of the drying process (h).

Mould growth susceptibility of the unaged and artificially aged specimens was assessed using a method adapted from ASTM C1338-19 [35] and ASTM D5590-17 [34] and previously validated for ETICS by Parracha et al. [11]. The specimens were steam sterilized in an autoclave for 20 min and placed on test flasks containing culture media (4% malt, 2% agar). Afterwards, a mixed spore suspension of *Aspergillus niger* and *Penicillium funicullosum* was uniformly applied on specimens and surrounding culture media. The specimens were then placed for four weeks in a culturing chamber (T = 22 ± 1 °C and 70 ± 5% RH) and visually rated for mould growth each week using the scale (Table 6) of ASTM D5590-17 [34]. After four weeks of incubation, the specimens were carefully removed from the flasks and the final percentage of contaminated surface area was evaluated using a stereo microscope Olympus B061.

Three wood samples (*Pinus pinaster*) were used as controls, thus allowing to validate the test results [35]. For the naturally aged

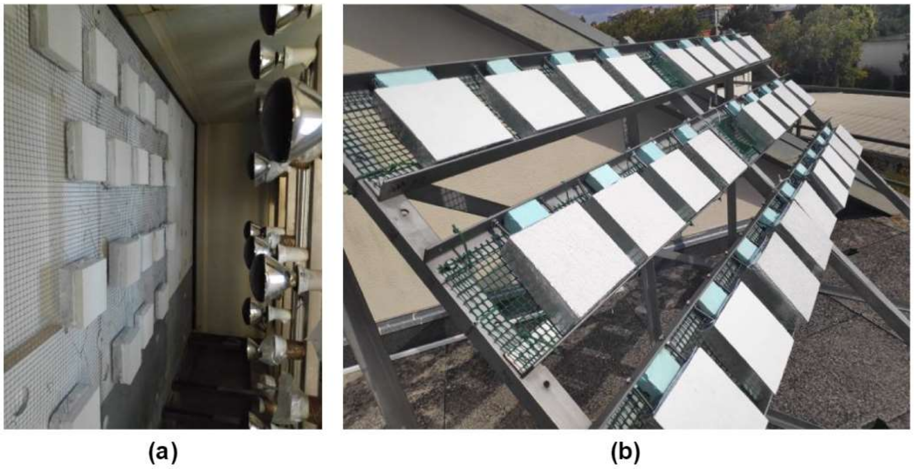

Fig. 3. Multilayer External Wall Thermal Insulation Systems (MEWTIS) during artificial ageing in a climatic chamber (a) and natural exposure (b).

Table 4
Artificial ageing protocol.

Method description		Number of cycles (total h)	Test conditions
Hygrothermal behaviour	Heat/rain cycles	80 (320)	3 h at 70 ± 5 °C (10–30% RH) 1h (1 L/(m^2.min) of sprayed water at 15 ± 5 °C)
	Room environment conditions	1 (2) 1 (48)	15 °C ≤ T ≤ 25 °C and RH ≥ 50%
	Heat/cold cycles	5 (120)	8 h at 50 ± 5 °C (≤30% RH) 16 h at −20 ± 5 °C

Table 5
Meteorological data for the natural ageing test location (Lisbon, Portugal) during the one-year exposure.

Period	Maximum average mean temperature [°C]	Minimum average mean temperature [°C]	Total annual rainfall [mm]	Mean solar radiation [kWh/m^2]
1 year	22.4	13.8	559.8	1700

Table 6
Scale for mould development assessment [34].

Rating	Contaminated area	Description
0	0%	None
1	<10%	Traces of growth
2	10–30%	Light growth
3	30–60%	Moderate growth
4	>60%	Heavy growth

specimens, mould growth was visually assessed on the exposed specimens every three months till one-year of natural exposure, using a stereo microscope Olympus B061 and the same scale presented in Table 6.

A Chroma Meter Minolta CR-410 was used for the colour characterisation by measuring the CIELAB coordinates (L^*, a^*, b^*), in which: L^* represents the lightness and varies from 0 (black) to 100 (white); a^* is the red/green coordinate, varying from $+a^*$ (red) to $-a^*$ (green); and b^* is the yellow/blue coordinate, varying from $+b^*$ (yellow) to $-b^*$ (blue). All measurements were performed in specular component included (SCI) mode, by adopting the illuminant D_{65} at an observer angle of 2° and 50 mm diameter area.

The global colour change is obtained using Equation (3) and considering the reference colour (unaged specimens) and the colour of the specimens after ageing (natural and artificial). The values of ΔL^*, Δa^*, and Δb^* were also considered.

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{3}$$

A specular gloss meter Rhopoint Novo-Gloss Lite was used for gloss determination using a measurement geometry of 60°. Specimens were analysed in 9 different points along the surface using a grid (Table 3). The average values and relative standard deviation were considered.

An Elcometer 223 surface profile gauge able to measure the peak-to-valley depth up to 2 mm (resolution of 0.001 mm) was used to determine surface roughness with a grid consisting of 9 different spots to analyse the specimens in different points along the surface. The average values and relative standard deviation were also considered.

3. Results and discussion

3.1. Visual and stereozoom observations

Visual and stereozoom observations were performed in order to detect possible anomalies on the surface of the specimens. Microphotographs confirmed that no surface anomalies are detectable in the unaged specimens, that were obtained from newly produced systems (Fig. 4).

When considering the artificially and the naturally aged systems, material loss and microcracks were observed, mostly in the case of the artificially aged specimens. Microcracking, which was the most common surface anomaly on the artificially aged systems, can be related not only to the water penetration within the systems during the hygrothermal ageing, but also with the dimensional variability of the material promoted by the heat/cold cycles (with a high temperature gradient within few hours in the range − 20 °C / 50 °C – Table 4). Additionally, water action during the hygrothermal cycles induced material loss, mostly of binder. Conversely, naturally aged systems presented dirt deposition, leading to a slightly darker tone of the aged surfaces (Fig. 4). In fact, the natural exposure urban site in Lisbon, Portugal, is about 2 km from the city airport and next to a highway, therefore, highly exposed to atmospheric pollutants (e.g. unburned hydrocarbons). Dirt deposition on the surface of the systems leads to aesthetic alteration and potentiates further degradation phenomena (e.g., biocolonisation) [39,57].

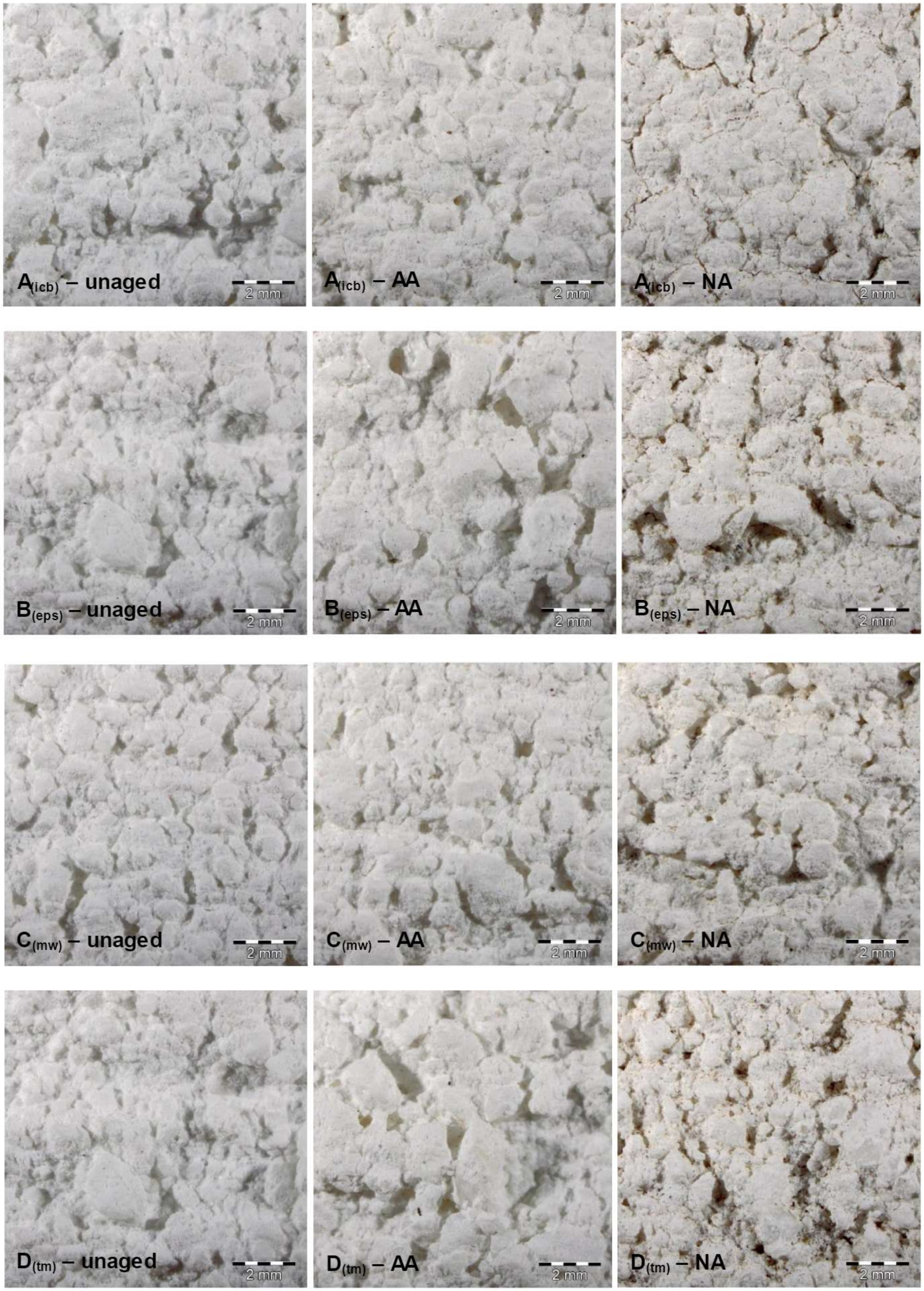

Fig. 4. Microphotographs of the unaged and aged surfaces (AA – artificially aged; NA – naturally aged).

3.2. Water absorption by capillarity and drying kinetics

Results show that the hygrothermal artificial ageing cycles strongly affected the water absorption of the specimens, with an increase of the initial water absorption (up to ~ 367% C_c increase), which is even higher after 24 h of testing (Figs. 5 and 6). Despite the results obtained, unaged and aged (naturally and artificially) specimens of ETICS ($A_{(icb)}$, $B_{(eps)}$ and $C_{(mw)}$) match the requirements of the EAD 040083–00-0404 guideline [32] (water absorption ≤ 1 kg/m^2 at 1 h testing). However, the values of absorbed water at 1 h for the artificially aged system $D_{(tm)}$ surpass the guideline threshold. Yet, system $D_{(tm)}$ is not considered an ETICS system and therefore the requirements and test methods of EAD 040083–00-0404 [32] may not be adequate for its assessment. The requirements of EN 998–1 [30] should be applied only for the evaluation of the thermal insulation mortar ($C_c \leq 0.40$ kg/(m^2.min$^{0.5}$) – class W1), and not to the whole multilayer system.

The water absorption results obtained for the one-year naturally aged specimens are similar to those obtained for the unaged specimens in the case of $B_{(eps)}$ (Fig. 5b). In fact, an increase of both C_c and water absorption at 24 h for the naturally aged systems $A_{(icb)}$ (ICB as TI), $C_{(mw)}$ (MW as TI) and $D_{(tm)}$ (thermal mortar as TI) was registered (Figs. 5 and 6). It is interesting to note, however, that a decrease of the C_c value (Fig. 5c) was obtained for the artificially aged system $C_{(mw)}$, which can be explained by a physical–chemical alteration of the polymeric matrix of the acrylic finishing coat leading to higher compactness and stiffness [40,41].

Despite the fact that all systems present a similar rendering system and only differ in the thermal insulation material (Table 1), it was observed different trends in the capillary water absorption of the four systems. When comparing the systems on their unaged state (Fig. 5), the highest values of water absorption at 24 h are obtained for $A_{(icb)}$ (ICB as TI), $C_{(mw)}$ (MW as TI) and $D_{(tm)}$ (thermal mortar as TI) and the lowest for $B_{(eps)}$ (EPS as TI). The results indicate that water might achieve the thermal insulation, since the ICB, MW and the thermal mortar have generally higher water absorption than EPS [15,42,43]. However, a different trend was observed after the natural and artificial ageing, with $D_{(tm)}$ obtaining the highest water absorption at 24 h. In fact, an increase of ~ 432% and ~ 73% was registered for the artificially and naturally aged $D_{(tm)}$, respectively and when compared to the unaged system. These results suggest that the rendering system of $D_{(tm)}$ was strongly affected by the artificial ageing procedure, with significant hydrophobicity loss, allowing water to achieve an also aged thermal insulation

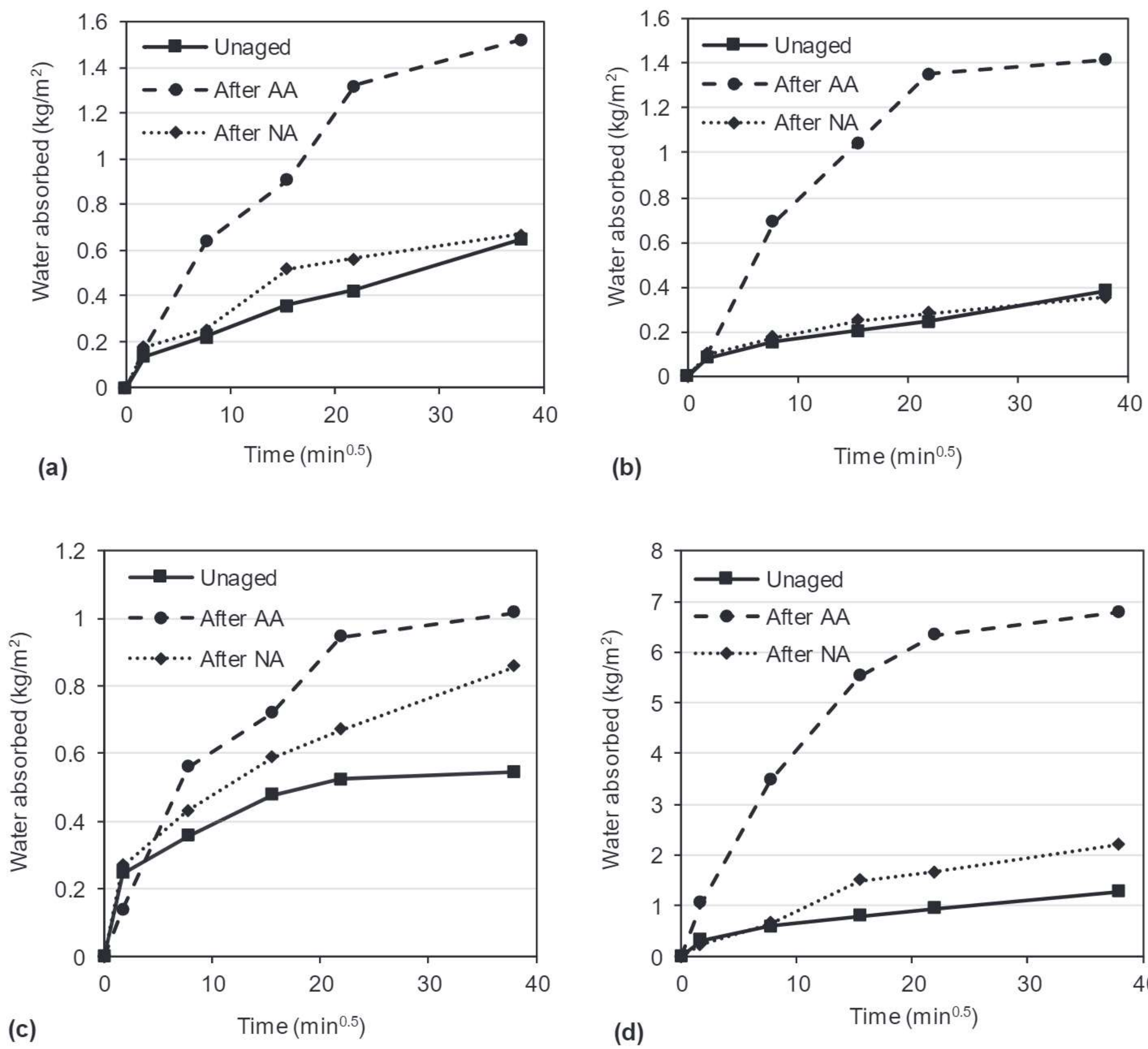

Fig. 5. Capillary water absorption curves for the unaged and aged systems $A_{(icb)}$ (a), $B_{(eps)}$ (b), $C_{(mw)}$ (c) and $D_{(tm)}$ (d). Note: absorbed water standard deviations < 5.8×10^{-2}.

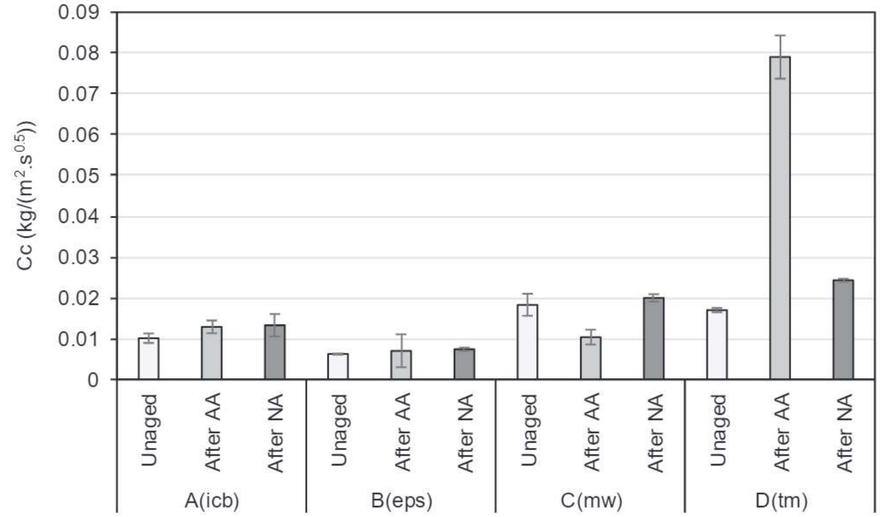

Fig. 6. Average values and relative standard deviation of the capillary water absorption coefficient.

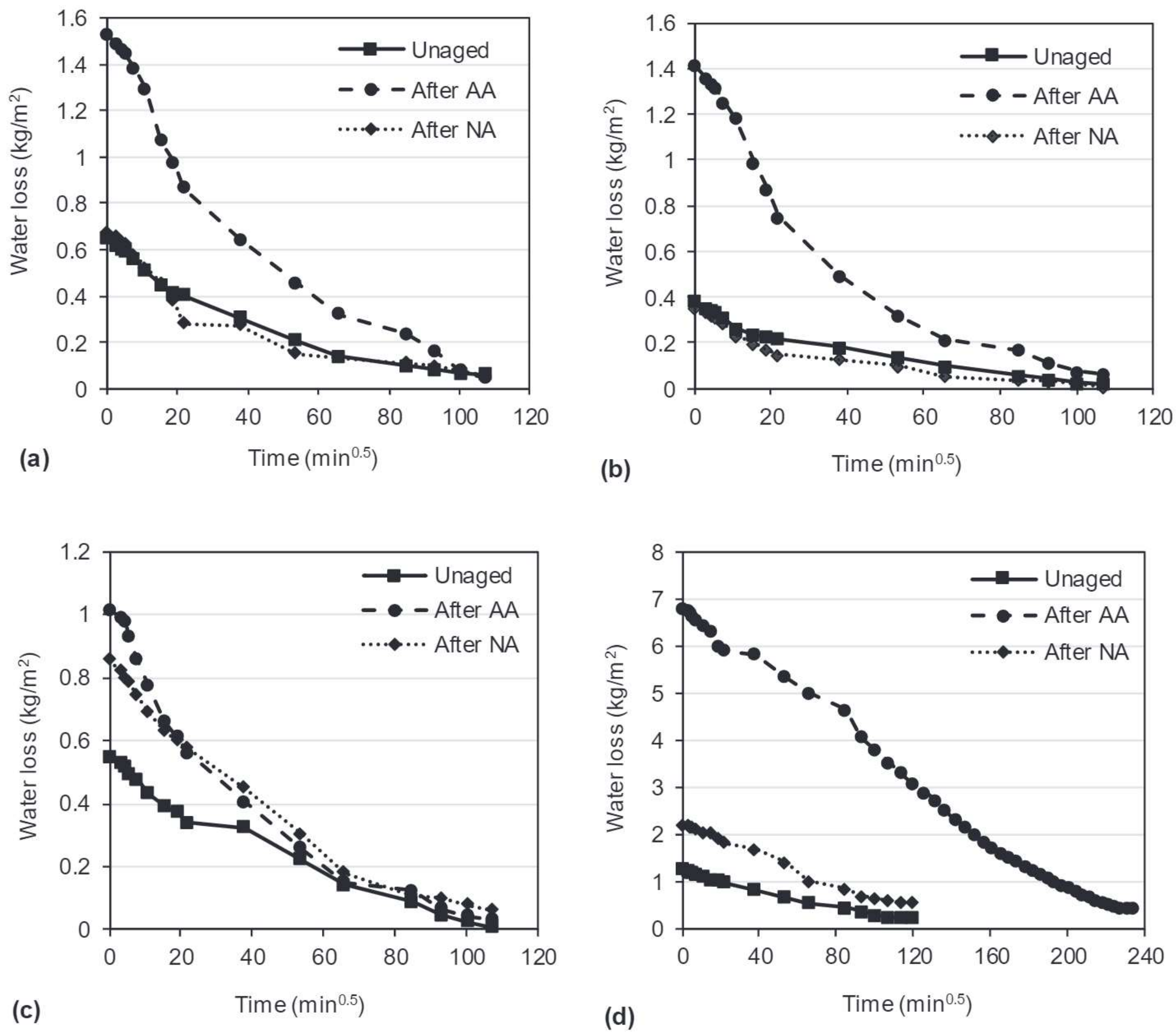

Fig. 7. Drying curves for the unaged and aged systems $A_{(icb)}$ (a), $B_{(eps)}$ (b), $C_{(mw)}$ (c) and $D_{(tm)}$ (d). Note: standard deviations of the water loss $< 5.8 \times 10^{-2}$.

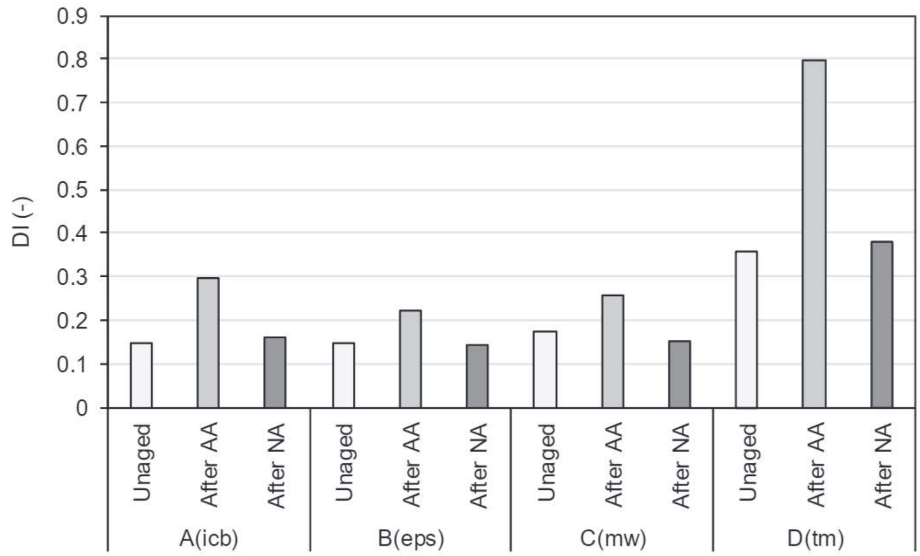

Fig. 8. Average values of the drying index.

(TM) [21,41,44].

Figs. 7 and 8 show the results of the drying kinetics for the unaged and aged ETICS. It was observed that both artificial and natural ageing influenced the drying kinetics, in accordance with the results of the capillary water absorption. In fact, a significant drying index increase for the artificially aged specimens $A_{(icb)}$ and $D_{(tm)}$ (101% and 122%, respectively) was obtained, which can be explained by an alteration of the pore size distribution of the rendering system, caused by the hygrothermal ageing cycles, that can possibly promote dissolution and recrystallization of some compounds or increase the hydration of cementitious materials. However, the ending time of the drying process of the unaged and artificially aged system $D_{(tm)}$ is not the same (mass stabilisation is achieved after 240 h and 912 h for the unaged and artificially aged $D_{(tm)}$, respectively – Fig. 7d). System $D_{(tm)}$ already presented the highest value of capillary water absorption at 24 h after artificial ageing (6.787 kg/m^2 – Fig. 5d), justifying a slower drying process. For the other tested systems, the ending time of the drying process till mass stabilisation was exactly the same (240 h) (Fig. 7a-c).

Previous studies [11,24] showed that unaltered unaged systems (ETICS and thermal mortars) that absorb more water tend to show better drying behaviour. In the present study, the hygrothermal artificial ageing of the multilayer systems caused not only a significant increase of water absorption, but also an increase of drying resistance, which is in accordance with the results obtained by Roncon et al. [41] for artificially aged ETICS finished with an acrylic-based paint. In contrast, the drying kinetics of the systems was almost unaffected after one-year of natural exposure, with a slight increase of the drying resistance for systems $A_{(icb)}$ and $D_{(tm)}$, and a DI decrease for systems $B_{(eps)}$ and $C_{(mw)}$.

3.3. Mould susceptibility

Table 7 shows the results of the average rate of mould growth obtained for laboratory evaluation of the unaged and aged ETICS and controls at the end of each week of incubation. In the unaged specimens, no biological growth was observed, which can be attributed to the presence of biocide in the finishing coat, preventing mould growth [11]. All three controls were rated 4 (heavy growth) after four weeks of incubation thus validating the test.

When analysing the results obtained for the artificially aged specimens, traces of mould development (<10% of contaminated surface) were firstly observed in the systems after the second week of exposure, except for system $A_{(icb)}$ (Table 7) where traces of mould were detected in two out of the three tested specimens earlier in the test. Though the differences in fungal development were small, the highest rate of mould growth (1.33) was obtained at the end of the test (week 4) for system $A_{(icb)}$, whereas the other systems were rated as 1. The increase of the bio-susceptibility for the artificially aged specimens can be explained by surface wear and microcracking detected on these systems (Section 3.1), possibly favouring moisture accumulation. Kvande et al. [10] also pointed out the possibility of biological growth beneath the ETICS or in the thermal insulation layer, which is particularly relevant when the substrate and/or the thermal insulation are organic-based materials (e.g., timber substrate, cork-based thermal insulation, etc.) [7,58].

Table 7
Mould growth for the unaged and artificially aged ETICS and controls after laboratory test (n = 3).

Systems	Mould development	Week 1	Week 2	Week 3	Week 4
Unaged	$A_{(icb)}$	0	0	0	0
	$B_{(eps)}$	0	0	0	0
	$C_{(mw)}$	0	0	0	0
	$D_{(tm)}$	0	0	0	0
After AA	$A_{(icb)}$	0.66 ± 0.58	1	1	1.33 ± 0.58
	$B_{(eps)}$	0	0.33 ± 0.58	1	1
	$C_{(mw)}$	0	0.66 ± 0.58	1	1
	$D_{(tm)}$	0	0.33 ± 0.58	1	1
Control (maritime pine wood)	3.33 ± 0.58	4	4	4	

Scale: 0 – no growth; 1 – traces of growth; 2 – light growth; 3 – moderate growth; 4 – heavy growth.

It is interesting to note that the artificially aged system $A_{(icb)}$ is composed of a cork-based thermal insulation (ICB) and has cork aggregates as additive in the composition of the base coat (Table 1). After the artificial ageing procedure, the surfaces of the systems have higher susceptibility to mould development, due to an alteration of the water absorption properties of the systems, as well as by microcracking occurred after ageing [10,46]. Microcracks can lead to moisture damage within the system and increase its bio-susceptibility, mainly in the case of renders with large amounts of organic additives, as in the case of $A_{(icb)}$ [10,47].

Conversely, no biological growth was yet observed for the one year naturally aged systems, confirming not only that the biocides have been so far effective in preventing biocolonisation, but also that surface anomalies (i.e., material loss and microcracks), in combination with the alteration of the water absorption properties of the systems due to natural exposure, had, so far, no clear influence on biocolonisation. Interesting to note that even though the amount of water for the artificial and natural ageing is quite similar, the moisture load happened under significantly different time spans, 80 h (~3.33 days) (Table 4) for the hygrothermal ageing and 365 days for the natural exposure (Table 5), leading to obviously different impacts on the systems.

3.4. Aesthetic properties

The results of the colorimetric coordinates for the unaged and aged systems are shown in Fig. 9. Table 8 presents the colour differences between unaged and aged systems, considering the CIELAB coordinates.

It can be observed that lightness (L*) is significantly affected after artificial ageing, with increases (ΔL*) up to 7 for systems $A_{(icb)}$ and $C_{(mw)}$ (Table 8). Results are in agreement with previous research of the authors [16] for artificially aged ETICS (ΔL* > 8 in some cases).

Natural ageing had a more significant impact on a* parameter if compared to artificial ageing. In fact, naturally aged systems become considerably more reddish (+a* values) when compared to the artificially aged specimens. Similar results were reported by Shirakawa et al. [49] for two-year naturally aged painted cement panels exposed in different Brazilian environments.

The chromatic coordinate b* was slightly more affected after natural ageing (Table 8) if compared to artificial ageing, with a tendency towards a yellowish colouration after one-year of natural exposure. Similar results were found by Paolini et al. [48] for a white siloxane finishing coat exposed in the urban environment of Milan (Italy), where a Δb* of ~ 3 was registered after one-year of ageing.

When considering the specular gloss results (Fig. 10), no significant differences were obtained after the artificial ageing, with a slight increase only for system $A_{(icb)}$ (+6.9%). However, a significant surface gloss decrease was obtained after natural ageing for all systems, ranging between –53.2% for $D_{(tm)}$ and –61.7% for $C_{(mw)}$. The loss of gloss for the naturally aged specimens can be attributed to dirt deposition detected on the surface of the systems (Section 3.1) as well as to the degradation of the acrylic finishing coat. Nevertheless, gloss differences lower than 2 units are not detectable by the naked eye [50]. Therefore, no macroscopically visible gloss alteration was observed after natural and artificial ageing of the systems.

3.5. Surface roughness

Fig. 11 presents the results of the surface roughness for the unaged and aged systems. No significant differences were obtained before and after natural and artificial ageing. However, a slight increase was observed for systems $A_{(icb)}$, $C_{(mw)}$, and $D_{(tm)}$ after ageing (natural and artificial). System $B_{(eps)}$ presented a slight decrease of surface roughness after natural and artificial ageing, when compared to the unaged system. Nevertheless, it is worth noting that considering the standard deviations, the surface roughness of the systems was not significantly affected by ageing.

3.6. Critical analysis of results

Table 9 provides a summary of the results obtained for the unaged and aged MEWTIS as well as the percentage change of each parameter considered in the table for the aged systems, when compared to the unaged specimens of each type. A colour-coding was also adopted in Table 9: red and green indicate a negative and positive outcome, respectively, while yellow indicates that no significant change of performance was observed.

The results obtained from the water absorption by capillarity test show a generally high-water absorption capacity of the aged systems when compared to the unaged ones. The increase of the water absorption after ageing is generally not beneficial, being water among the most harmful degradation agents [15]. With exception of $C_{(mw)}$, it can be observed that the capillary water absorption coefficient (C_c) increased between 13% and 367% after artificial ageing. The C_c values globally increased between 9% and 44% for the naturally aged systems (Table 9). It can thus be concluded that a loss of surface hydrophobicity is generally induced by ageing, particularly for the artificially aged systems, in agreement with the capillary water absorption results.

When considering the threshold value (0.5 kg/m^2) for the water absorption at 24 h testing defined by the EAD 040083–00-0404 [32] for ETICS to avoid the need of specific freeze–thaw resistance tests, only the unaged system $B_{(eps)}$ (EPS as TI) match this value (0.382 kg/m^2). Unaged systems $A_{(icb)}$ (0.649 kg/m^2) and $C_{(mw)}$ (0.545 kg/m^2) are slightly higher than this threshold. After ageing, a remarkable increase of the water absorption by capillarity was observed, mostly when considering the artificially aged systems. In fact, the results more than doubled the threshold of EAD 040083–00-0404 [32], especially for the artificially aged $D_{(tm)}$ (thermal mortar as TI). Additionally, the water absorption rate of most systems (unaged and aged) decreased over time (Fig. 5), however, no complete water saturation is achieved at 24 h. Similar results were obtained by Griciute et al. [51] and Parracha et al. [11], when testing unaged ETICS with different finishing coat (e.g., silicate, silicone, lime-based).

On the other hand, systems exposed to natural ageing presented a lower capillarity water absorption at 24 h when compared to the artificially aged systems, but higher than the results obtained for the unaged systems, with exception of $B_{(eps)}$ (Table 9). The results point out a loss of surface hydrophobicity over time, which can give rise to moisture damage and thus affect the long-term durability of the systems [10,15]. In fact, the hygrothermal cycles defined in the EAD 040083–00-0404 [32] and adopted in the present study for the artificial ageing were designed assuming a service life for the ETICS of at least 25 years under appropriate use and maintenance conditions.

The drying kinetics of the systems (Fig. 8) is represented by the drying index (DI). The increase of the drying index is generally considered a negative outcome, since it implies a higher drying resistance of the multilayer systems, which can hamper the dissipation of the absorbed water [11,24].

An increase of the DI (in the range between 47% and 122%) was observed after hygrothermal artificial ageing. Conversely, the drying kinetics of the naturally aged systems was almost unaffected, with a slight increase of the drying resistance for systems $A_{(icb)}$ and $D_{(tm)}$, and a DI decrease for systems $B_{(eps)}$ and $C_{(mw)}$. It is worth noting that the drying kinetics significantly differs when comparing ETICS ($A_{(icb)}$, $B_{(eps)}$, $C_{(mw)}$) and the multilayer system with a thermal mortar ($D_{(tm)}$). In fact, a faster drying occurs for the ETICS in the first step of the drying process, followed by a decrease of the drying rate in the second step till mass stabilization (Fig. 7). In contrast, the drying rate of system $D_{(tm)}$ (thermal mortar as TI) is almost linear (higher drying resistance), especially in the case of the artificially aged system.

The increase of the bio-susceptibility of the systems can lead to cladding defacement, formation of stains, discolouration, and further physical and mechanical damage [10,17]. However, the presence of biocides within the finishing coat composition of the MEWTIS seem to be enough to avoid mould growth both on the unaged systems and those assessed after one-year of natural exposure. Traces of mould growth were observed on the artificially aged systems, possibly due to the change of the water absorption properties of the systems after the hygrothermal cycles, but also due to some surface wear and cracks appearing after artificial ageing [45].

As previously stated, the hygrothermal ageing cycles [32] adopted in this study were designed assuming a service life for the ETICS of at least 25 years. Therefore, the loss of performance of the artificially aged systems, considering the water resistance and bio-susceptibility

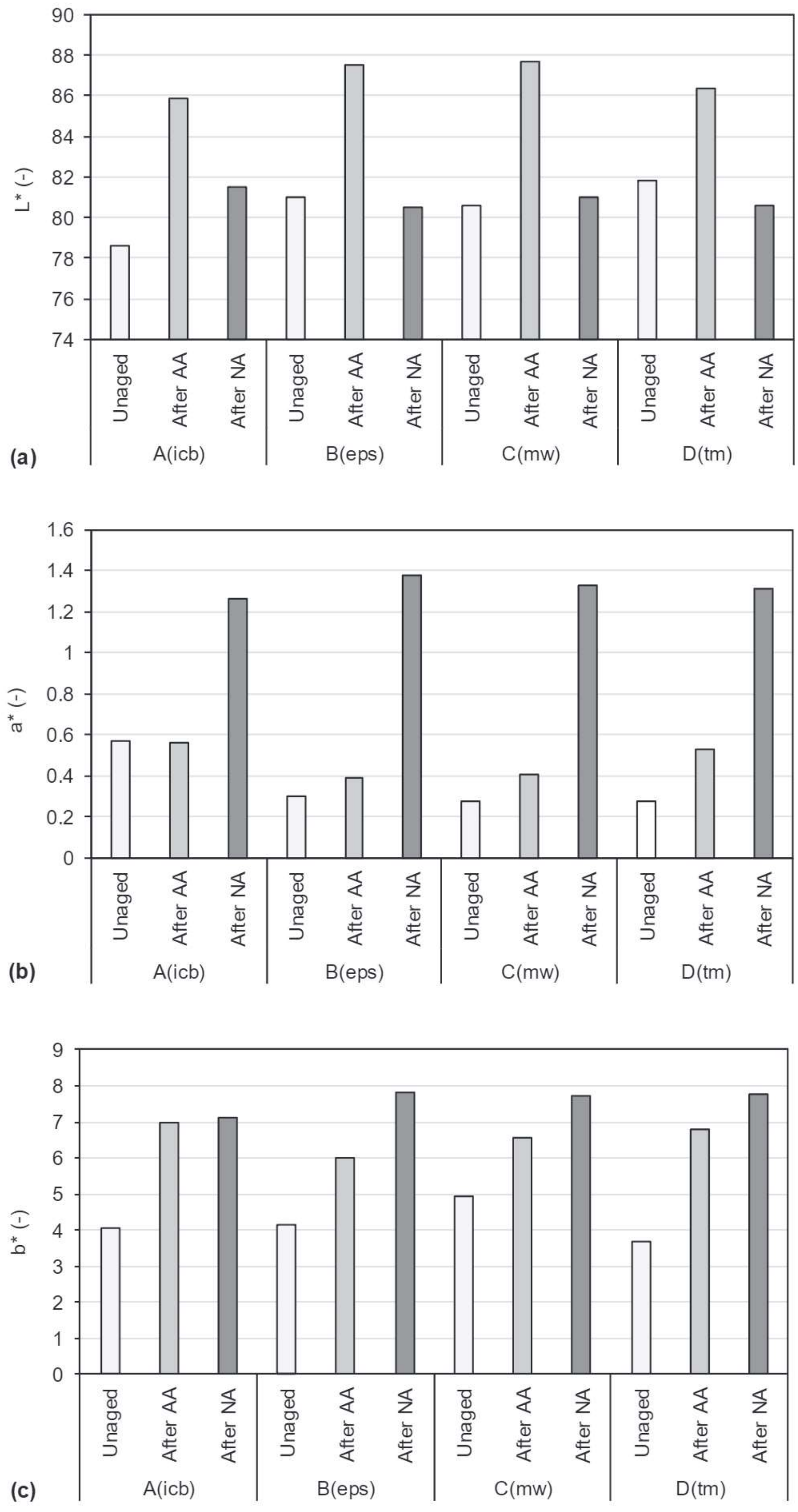

Fig. 9. Average results of the CIELAB parameters L* (a), a* (b) and b* (c) for the unaged and aged systems.

Table 8
Variation of the CIELAB parameters (L*, a*, b*) after ageing.

	ΔL*		Δa*		Δb*	
	After AA	After NA	After AA	After NA	After AA	After NA
$A_{(icb)}$	7.27	2.88	−0.01	0.69	2.95	3.08
$B_{(eps)}$	6.49	−0.56	0.09	1.08	1.84	3.65
$C_{(mw)}$	7.05	0.41	0.13	1.05	1.63	2.76
$D_{(tm)}$	4.54	−1.27	0.25	1.03	3.08	4.05

assessment, was expected to be higher than that of the one-year naturally aged systems. Nonetheless, a similar trend was observed for both artificially and naturally aged systems, namely a significant decrease of the water resistance. The results point out that, although presenting a similar trend, artificially aged systems have a significantly higher performance loss when compared to the naturally aged systems, meaning that the artificial ageing performed in this study correspond to more than one-year of natural ageing under the conditions described in Section 2.2.

An alteration of colour and gloss, as well as an increase of the surface roughness, can be considered as negative outcomes. In fact, discolouration and gloss reduction can often lead to coating degradation [52], whereas a high surface roughness can increase the risk of biological growth [20,53].

Artificial ageing had a higher impact on the colour alteration, if compared to natural ageing. In fact, stains, mostly associated with the use of ICB and MW as thermal insulation (which can release pigment), were observed on systems $A_{(icb)}$ and $C_{(mw)}$ after artificial ageing. Additionally, the colour change for both artificially and naturally aged systems was higher than 2 CIELAB units and therefore can be detected by an unexperienced observer [54].

An opposite trend was observed for specular gloss. In fact, no significant differences were obtained after artificial ageing, whereas a considerable gloss alteration (although not yet detectable by the naked eye) occurred for all systems after one-year of natural exposure [50].

The results indicate a slight increase of surface roughness for systems $A_{(icb)}$, $C_{(mw)}$, and $D_{(tm)}$ after ageing, in accordance with previous studies [55,56]. Water run-off and severe thermal shocks might have led to paint loss and embrittlement of the acrylic polymeric matrix, affecting the surface roughness. Conversely, a slight decrease of surface roughness was observed for system $B_{(eps)}$, which also had the highest surface

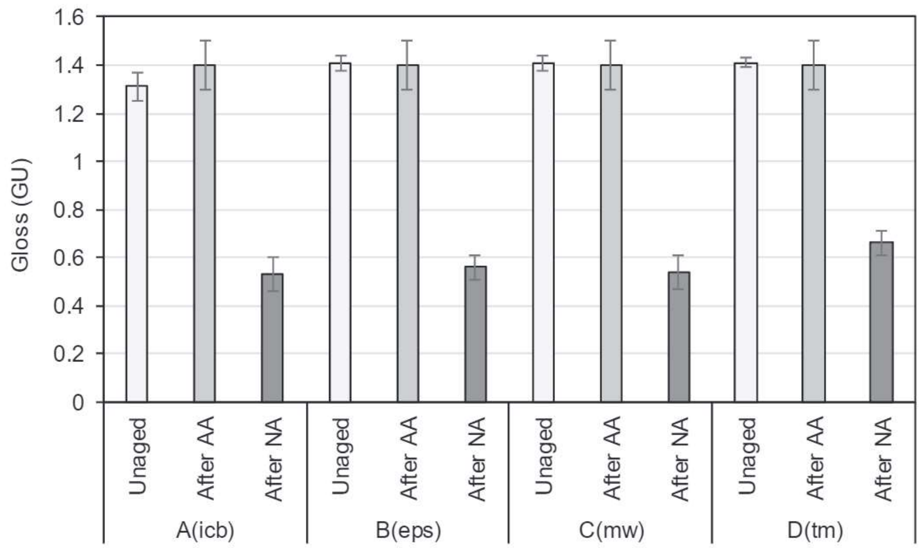

Fig. 10. Average results and relative standard deviation of the specular gloss for the unaged and aged systems.

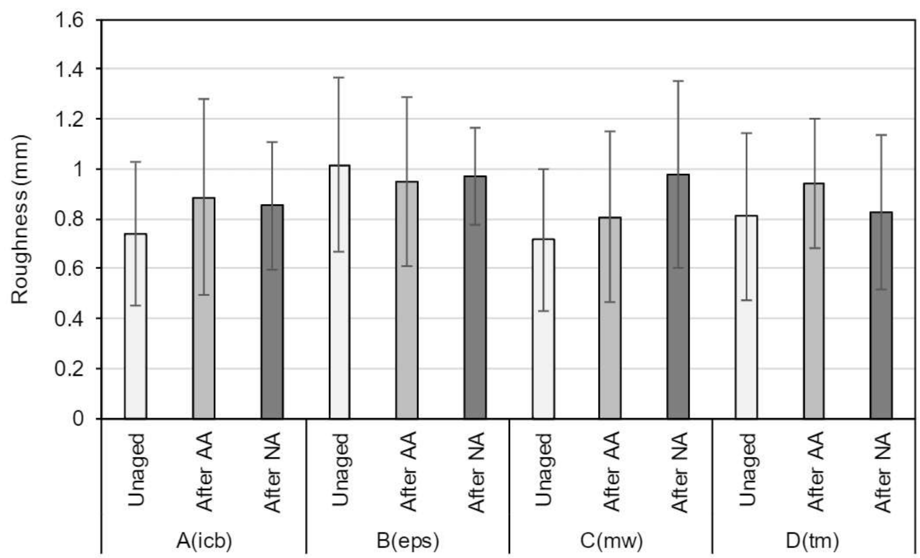

Fig. 11. Average results and relative standard deviation of the surface roughness for the unaged and aged systems.

Table 9
Summary of the results of the unaged and aged MEWTIS and percentage change of the studied parameters of the aged systems in comparison to the unaged specimens.

Systems			$A_{(icb)}$	$B_{(eps)}$	$C_{(mw)}$	$D_{(tm)}$
Water performance	Water absorption by capillarity (Cc)	AA	↑ (+ 28%)	↑ (+ 13%)	↓ (- 43%)	↑ (+ 367%)
		NA	↑ (+ 32%)	↑ (+ 19%)	↑ (+ 9%)	↑ (+ 44%)
	Water absorption by capillarity (24 h absorption)	AA	↑ (+ 134%)	↑ (+ 271%)	↑ (+ 86%)	↑ (+ 432%)
		NA	↑ (+ 3%)	↓ (- 7%)	↑ (+ 57%)	↑ (+ 73%)
	Drying index (DI)	AA	↑ (+ 101%)	↑ (+ 51%)	↑ (+ 47%)	↑ (+ 122%)
		NA	↑ (+ 9%)	↓ (- 9%)	↓ (- 13%)	↑ (+ 6%)
Bio-susceptibility	Average rate of mould growth	AA	↑ (1.33)	↑ (1)	↑ (1)	↑ (1)
		NA	→ (0)	→ (0)	→ (0)	→ (0)
Surface properties	Colour (ΔE^*_{ab})	AA	↑ (7.846)	↑ (6.746)	↑ (7.237)	↑ (5.492)
		NA	↑ (4.273)	↑ (3.847)	↑ (2.981)	↑ (4.368)
	Gloss	AA	↑ (+ 7%)	→ (- 0.7%)	→ (- 0.7%)	→ (- 0.7%)
		NA	↓ (- 60%)	↓ (- 60%)	↓ (- 62%)	↓ (- 53%)
	Roughness	AA	↑ (+ 20%)	↓ (- 7%)	↑ (+ 13%)	↑ (+ 16%)
		NA	↑ (+ 15%)	↓ (- 4%)	↑ (+ 37%)	↑ (+ 2%)

Notation: AA – artificially aged systems; NA – naturally aged systems; red – negative outcome after ageing; green – positive outcome after ageing; yellow – no significant change after ageing.

roughness in the unaged state (Table 9).

3.7. Performance indicators and criteria for durability

As specified in the previous sections, water is clearly one of the most harmful degradation agents affecting the long-term durability of the multilayer external wall thermal insulation systems (MEWTIS) [26,59]. Hence, water resistance was selected in this study as the main durability criterion for the systems characterisation, considering the capillary water absorption and the drying kinetics. The threshold value of 1 kg/m^2 of absorbed water after 1 h of testing, defined by the European guideline EAD 040083–00-0404 [32] for ETICS, is marked in Fig. 12 as a reference value.

Fig. 12 shows the variation of the water absorbed after 1 h and 24 h of testing for the unaged and the artificially and naturally aged specimens, as well as a range of performance indicators for each of those properties, which was defined for unaged ETICS in a previous study of the authors [11]. Regarding unaged and naturally aged systems, the range of absorbed water values at 1 h is below the reference value of 1 kg/m^2 and within the performance indicators range for ETICS defined by Parracha et al. [11] (Fig. 12a). If considering the results obtained for the artificially aged systems, the performance range overcomes the threshold defined for ETICS and assumed as a reference value, mostly due to the results obtained for the system with a thermal insulating mortar, which is clearly an outlier of the group. Thus, results confirmed that the hygrothermal artificial ageing test defined in the EAD 040083–00-0404 [32] for ETICS may not be suitable for the durability assessment of MEWTIS with a thermal mortar as insulation layer. Conversely, the results of the 1 h water absorption obtained for the ETICS are below the reference value, regardless of the thermal insulation material used (ICB, EPS or MW) and of the type of ageing considered (artificial or natural).

The results of the 24 h water absorption follow a trend similar to that found for the results after 1 h of testing, especially for the unaged and naturally aged specimens. Both of these performance groups are within the performance indicators range defined for ETICS, whereas the artificially aged systems obtained significantly higher values of 24 h water absorption. It is worth noting that the system with a thermal mortar is an outlier in all performance groups (unaged, after AA and after NA) (Fig. 12b). In fact, this system presents significantly higher values of absorbed water, when compared to the ETICS, possibly affecting its thermal and mechanical performances.

Concerning the drying tests, the systems showed no clear drying curve, according to the mechanism of first and second drying phase. Therefore, in accordance with the EN 16322 [33], the drying index was used to analyse the drying kinetics of the systems. However, performance indicators of the drying index were not inserted in Fig. 13 since these indicators were not previously defined by the authors [11].

The results of the drying index show a negligible variation after natural ageing. However, a significant increase of the drying resistance of the systems was obtained after the hygrothermal artificial ageing. Results showed that a more extensive natural exposure is necessary, in order to monitor the DI and to further clarify the correlation among artificial and natural ageing tests for the drying resistance indicator.

Finally, the systems with a thermal mortar are outliers in the three performance groups (Fig. 13), presenting significantly higher values of drying index in comparison with ETICS. Long-term natural exposure tests are also necessary in this case, especially if considering the significantly more reduced application and thus knowledge-based monitoring experience on multilayer systems with thermal mortars.

4. Conclusions

The aim of this paper is to evaluate the effects of natural ageing and artificial hygrothermal ageing on the water performance (capillary water absorption and drying kinetics), bio-susceptibility (mould development) and surface properties (colour, gloss, and roughness) of four multilayer external wall thermal insulation systems (three ETICS and

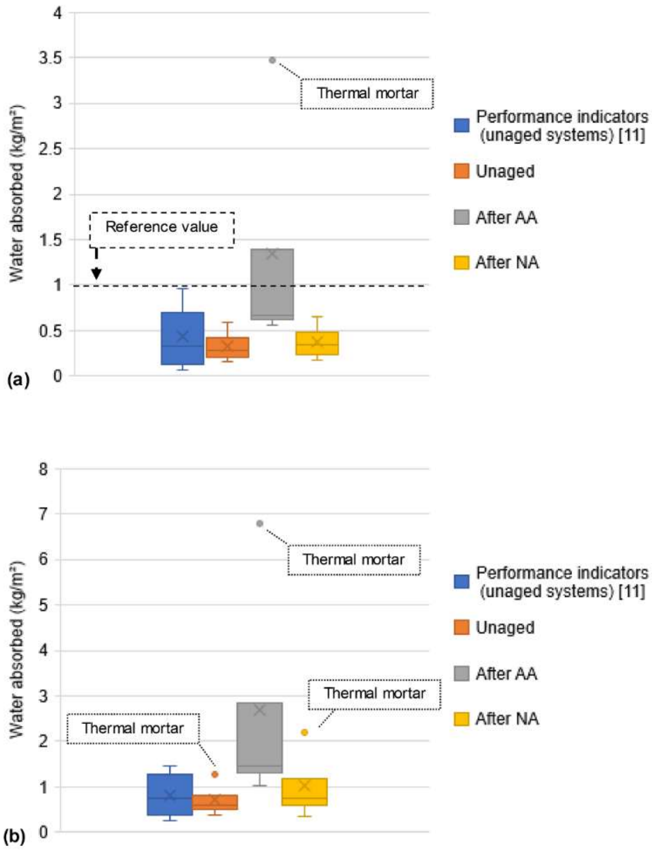

Fig. 12. Performance groups of unaged and aged systems considering the 1 h (a) and 24 h (b) capillary water absorption results. Reference performance indicators are based on previous works [11].

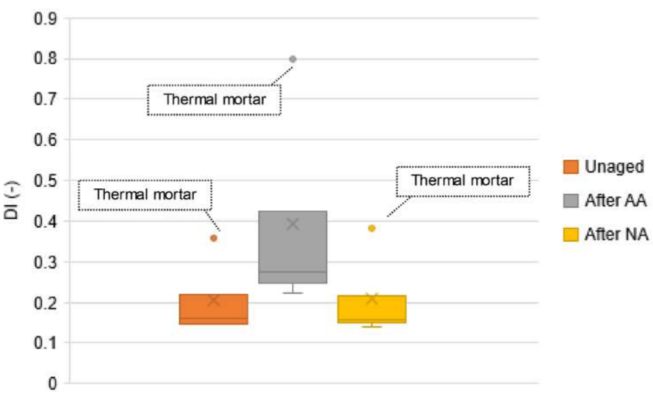

Fig. 13. Performance groups of unaged and aged systems considering the drying index (DI).

one thermal rendering system).

The water performance test results showed that a significant increase of capillary water absorption is registered after artificial ageing, especially for the multilayer system with a thermal mortar (+432% considering the 24 h water absorption). In fact, significant increases of capillary water absorption were observed for the artificially aged systems considering the results of the water absorption after 24 h rather than the capillary water absorption coefficient or the results after 1 h of water absorption. These findings clearly indicate that water achieved the thermal insulation, affecting the efficiency of the systems. Moreover, artificial ageing induced also a higher drying resistance of the systems (between + 47% and + 122%).

Traces of mould growth were observed on the artificially aged systems. However, no growth was detected on the unaged and naturally aged systems. The addition of biocide can control mould growth on these systems, whereas surface wear and microcracks caused by the hygrothermal cycles led to a slight biological growth on the artificially aged systems. These results highlight the need for appropriate and regular maintenance of the systems in order to avoid extensive mould growth during the service life of the systems.

Finally, substantial colour change was observed for all systems after ageing, confirming aesthetic alteration. No significant change of gloss was observed after artificial ageing, which could be expected as no dust nor pollution gases were used in the artificial ageing test at this phase, contrarily to what happens in the natural ageing; thus, a significant decrease up to 62% was registered for the naturally aged systems. Additionally, no significant differences of surface roughness were detected after ageing.

When considering the water resistance and bio-susceptibility assessment, it can be stressed that a similar trend was registered among naturally and artificially aged systems. However, the loss of performance was significantly higher after the hygrothermal artificial ageing. It can thus be concluded that the artificial ageing cycles considered in the present study correspond to more than one-year of natural ageing in a Mediterranean climate. On the other hand, additional degradation agents such as UV radiation or pollutants should be included in optimised artificial ageing protocols, since it was observed a generally higher aesthetic alteration of the naturally aged systems (e.g., a considerable decrease of surface gloss; dirt deposition detected through visual and stereozoom observations).

Future research is ongoing to evaluate the long-term durability of the systems to different artificial ageing cycles (e.g., UV radiation, pollutants) as well as to a more extensive natural exposure with the aim of correlating natural and artificial ageing, thus proposing and validating service life prediction models for multilayer external wall thermal insulation systems.

CRediT authorship contribution statement

João Luís Parracha: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Giovanni Borsoi:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Visualization, Writing – review & editing. **Inês Flores-Colen:** Conceptualization, Methodology, Validation, Resources, Project administration, Funding acquisition, Writing – review & editing. **Rosário Veiga:** Conceptualization, Methodology, Validation, Resources, Funding acquisition, Writing – review & editing. **Lina Nunes:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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