buildings

MDPI

Review

Toward the Sustainable and Efficient Use of External Thermal Insulation Composite Systems (ETICS): A Comprehensive Review of Anomalies, Performance Parameters, Requirements and Durability

João L. Parracha [1,2], Rosário Veiga [1], Inês Flores-Colen [2,*] and Lina Nunes [1,3]

[1] LNEC, National Laboratory for Civil Engineering, Av. do Brasil, 1700-066 Lisbon, Portugal; jparracha@lnec.pt (J.L.P.); rveiga@lnec.pt (R.V.); linanunes@lnec.pt (L.N.)
[2] CERIS, DECivil, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
[3] cE3c/Azorean Biodiversity Group/CHANGE—Global Change and Sustainability Institute, Faculty of Agrarian Sciences and Environment (FCAA), University of Azores, Rua Capitão João d' Àvila, Pico da Urze, 9700-042 Angra do Heroísmo, Portugal
* Correspondence: ines.flores.colen@tecnico.ulisboa.pt

Abstract: The identification of the main degradation agents and knowledge of the degradation mechanisms and long-term performance of ETICSs are of fundamental importance for the sustainable and efficient use of these systems. This review article presents the state of the art related to the durability of ETICSs, defining the required bases for their sustainable and efficient use. The aim is to identify the most common anomalies detected on ETICS façades and their causes, to overview the performance of ETICS, their performance parameters and requirements and to identify the most significant degradation mechanisms and the related failure modes. The results show that ETICS application is a key aspect in the performance and durability of the system, since most of the anomalies can be prevented with proper design, execution and appropriate assembly of the system components. The greatest drawbacks lie in dealing with enhancing the water resistance over time, which leads to extensive cases of anomalies, and improving the mechanical and thermal performance during the life cycle. Further research is needed to evaluate the synergistic effect of several degradation agents and mechanisms toward a development in optimized durability assessment methodologies for ETICSs.

Keywords: ETICS; EIFS; anomalies; causes; performance; durability

Citation: Parracha, J.L.; Veiga, R.; Flores-Colen, I.; Nunes, L. Toward the Sustainable and Efficient Use of External Thermal Insulation Composite Systems (ETICS): A Comprehensive Review of Anomalies, Performance Parameters, Requirements and Durability. *Buildings* **2023**, *13*, 1664. https://doi.org/10.3390/buildings13071664

Academic Editor: Florence Collet

Received: 29 May 2023
Revised: 23 June 2023
Accepted: 26 June 2023
Published: 29 June 2023

1. Introduction

It has been widely documented that the construction and maintenance of buildings contribute to more than 35% of global energy use, generating approximately 28% of energy-related CO_2 emissions [1]. The European building stock is responsible for more than 40% of energy consumption, and of which, approximately 27% is attributed to the residential sector [2,3]. Sustainable environmental policies aimed at decreasing the energy demand of existing buildings and improving the energy performance of new buildings have thus been introduced by the European Union (EU). For example, all new buildings should achieve near-zero energy consumption after 2020, and the EU directive 2018/844 [4] points out the energy retrofitting of buildings as one of its key targets to achieve climate-neutral building stock by 2050. As a result, several eco-efficient constructive solutions and energy-efficient systems have been designed and implemented to decrease the building environmental impact. The level of thermal insulation of the building envelope plays a fundamental role in a reduction in energy consumption, emphasizing the importance of the correct selection, design, performance and durability of the thermal insulation solution.

The external thermal insulation composite system (ETICS), also identified as the external insulation finishing system (EIFS), was developed in the 1950s and 1960s and first applied in Berlin, Germany, in 1957 [5]. These systems are technological multilayer solutions (Figure 1) which are applied to the building exterior walls, providing enhanced thermal performance to the building envelope [6]. ETICSs generally consist of three distinct layers (i.e., thermal insulation, base coat and finishing coat) whose properties are optimized to improve the performance of the complete system [7]. The following steps are considered during ETICS application: the thermal insulation is first fixed to the external wall using an adhesive product and/or mechanical anchors, the base coat incorporating at least one glass fiber mesh as reinforcement is then applied onto the thermal insulation and the finishing coat is finally applied and is generally formed using a key-coat and a paint or an organic or mineral render.

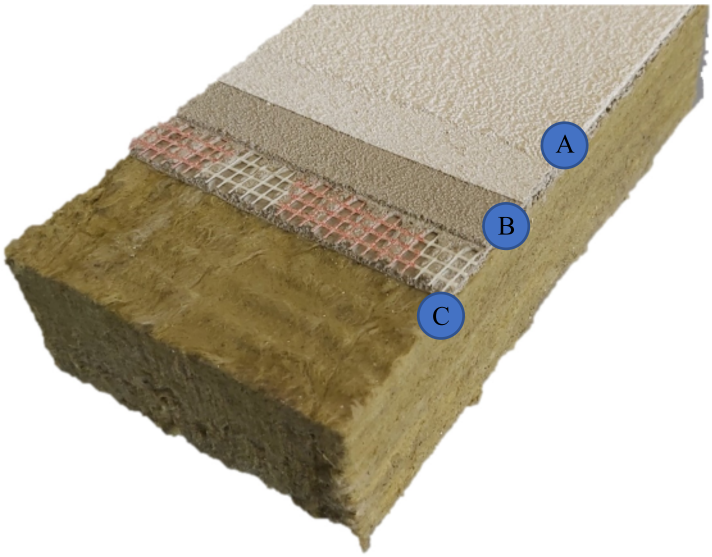

Figure 1. Example of an external thermal insulation composite system (ETICS), in which (**A**) is the finishing coat, (**B**) is the base coat with reinforcement mesh incorporated between the layers and (**C**) is the thermal insulation (in this case MW).

Different types of materials such as expanded polystyrene (EPS), extruded polystyrene (XPS), mineral wool (MW) and expanded cork agglomerate (ICB) have been used as thermal insulation in ETICSs, with EPS and MW being the most common in European applications, representing more than 90% of the market [8]. The base coat consists of a mortar usually applied via spray or with a trowel in two layers, with the reinforcement mesh placed between the layers. Additional mesh can also be used to improve the impact resistance of the ETICS [5]. There are several possible formulations for base coat mortar (e.g., hydraulic binder—cement, natural hydraulic lime or air lime; fillers; additives—mineral or organic) [7]; however, the compatibility between the mortar and the thermal insulation must be guaranteed [9]. The finishing coat cannot only provide a decorative finish to the ETICS, but can also act as a barrier against the main degradation agents [10]. This layer should assure enough protection to the multilayer system, confirming an increase in its service life, which is assumed to be at least 25 years under normal maintenance actions [11].

In Europe, the use of ETICSs in both new constructions and for the thermal retrofitting of building façades has significantly increased over the last few decades, which is mostly due to the system's enhanced thermal performance. A recent study by Varela Luján et al. [6] showed that using an ETICS for the thermal retrofitting of a building in Spain allowed for a significant reduction (~55%) in energy losses and gains. Indeed, ETICSs reduce the thermal bridge effect, increasing the thermal inertia while providing greater indoor thermal comfort [12]. These systems also have relatively low implementation costs, protect the masonry and structural elements, reduce the risk of internal condensation and are easy to apply, without disturbing the occupants of the buildings [13–15]. However, cases of anomalies have been detected with ETICS façades over the years, with some of them being shortly after ETICS application [5,16]. In fact, the constant exposure of ETICSs to weathering agents and anthropic factors can lead to physical–mechanical and aesthetic anomalies, thus affecting the long-term durability of the systems [10,17]. The most common anomalies reported in the literature are the following: material rupture (cracking, detachment of the finishing coat, loss in adherence between layers or material gap); aesthetic anomalies (color change, runoff marks or efflorescence); biological colonization and flatness anomalies (surface irregularities, visible joints between plates or swelling) [5,13,16]. According to Maia et al. [18] and Parracha et al. [19], most of the detected anomalies can be related to the presence of water. A review on the pathology of ETICSs including the identification of the most common anomalies and their causes is provided in Section 2 of the present study.

The Guideline for European Technical Approval of External Thermal Insulation Composite Systems (ETICS) with rendering (ETAG 004) [20] was published in 2000 by EOTA (European Organization for Technical Assessment) and reviewed in 2019 under the creation of a European Assessment Document (EAD 040083-00-0404) [11]. The EAD provides test methods, durability assessment and requirements for a correct evaluation of ETICS performance. If these requirements are fulfilled, the system can be assigned with a European Technical Assessment (ETA) document, which is allocated by an independent institute member of EOTA and dependent on the acceptance by the remaining EOTA members. The ETA document confirms that the system has adequate performance and suitable quality, considering the characteristics defined as being essential in the EAD [11]. According to Michalak [21], a significant number of 798 valid ETAs were available for ETICSs in Europe by the end of June 2021. However, some aspects that may have an influence on the long-term performance of ETICSs are not mentioned in the guideline. For example, ETICS durability is assessed considering only the hygrothermal performance (heat–rain and heat–cold cycles), and additional degradation agents, such as UV radiation, atmospheric pollutants and biological colonization, are not considered in the document. In this context, the identification of the main degradation agents and knowledge of the degradation mechanisms and long-term performance of ETICSs are fundamental for the sustainable and efficient use of these systems. Therefore, Sections 3 and 4 present an overview of the performance and durability of ETICSs, respectively.

1.1. Objectives of the Work

This review article presents the state of the art related to the durability of ETICSs, defining the required bases for their sustainable and efficient use. The aim is to identify the most common anomalies detected with ETICS façades and their causes (Section 2—Pathology), to overview the performance of ETICSs, their performance parameters and requirements (Section 3—Performance) and to identify the most significant degradation mechanisms and the related failure modes (Section 4—Durability). This paper ultimately aims to provide consistent knowledge on the durability of ETICSs to increase their sustainability and efficiency over time. In order to achieve the main goal of the study, some sub-objectives are defined as follows:

- Identify the most common anomalies with ETICS façades and analyze the most probable causes of these anomalies. Present a case study of a building complex with ETICS cladding, identifying, illustrating and analyzing the pathological phenomena.
- Review the performance, performance parameters and requirements of ETICSs, summarizing the most relevant data in this regard.
- Identity and analyze the main degradation mechanisms in ETICSs and the responsible agents for this degradation. Provide an extensive literature review on the durability assessment of ETICSs (e.g., laboratorial evaluation, numerical simulations and long-term performance).
- Highlight research needs and future challenges.

1.2. Method of Research

Considering the objectives of the work (Section 1.1), a preliminary background search was conducted to identify the pertinent keywords. These keywords (Table 1) were used to search for relevant studies using three databases (Scopus, Web of Science and Google Scholar). Both peer-reviewed articles and gray literature published in English were considered in the present study. The selected databases were chosen due to their wide variety of peer-reviewed articles (Scopus and Web of Science) and gray literature (Google Scholar). In this latter case, the "related articles" option was also used to help in the search for relevant studies.

Table 1. Keywords used for the identification of relevant studies.

No.	Keyword	No.	Keyword	No.	Keyword
1	"ETICS"	6	"performance"	11	"diagnosis"
2	"EIFS"	7	"durability"	12	"causes"
3	"thermal"	8	"anomalies"	13	"repair"
4	"insulation"	9	"defects"	14	"moisture"
5	"system"	10	"inspection"	15	"aging"

Note: Boolean operators (OR, AND) were used for combinations of keywords.

After the identification of the relevant studies, exclusion and inclusion criteria were applied to identify the studies that best answered the objectives of the work. Studies were further selected considering the following analysis sequence: removal of duplicates, review of title and abstract and full text review. Furthermore, only the literature published in English was considered. The search was limited to the period from 2000 onwards due to the significant improvement in ETICS technology in recent decades. All of the articles considered to be relevant to the study were selected for further analysis. A total of 76 published documents were considered for the dataset of this article.

2. Pathology

ETICSs were first applied in 1957 in Germany, following an important energetic crisis after the Second World War. Since then, the use of this technology in European buildings has increased considerably. Thus, with this increase, extensive cases of anomalies have been detected with ETICS façades and reported in several international papers and technical reports (e.g., [5,14,16,22–25]). This section first reviews the most common anomalies detected with ETICSs and the most probable causes of these anomalies. The deterioration phenomena are further illustrated with a case study of a building complex, located in Lisbon, Portugal, with ETICS cladding in fourteen façades.

2.1. Anomalies and Their Causes

In order to develop an expert-knowledge inspection and diagnosis system for an ETICS, Amaro et al. [13,16] visually inspected 14 buildings (146 ETICS façades) located in the north and center of Portugal, aged from 3 to 22 years. A total of 476 anomalies were detected, and 1098 causes were attributed to these anomalies. The most common anomalies seemed to be biological colonization in 56% of the ETICS façades, color change (49%) and runoff marks (43%). According to Amaro et al. [16], these anomalies can be considered to be aesthetic.

The Fraunhofer Institute for Building Physics IBP has conducted significant research in the field of ETICSs since the early 1970s. A study published in 2006 [23] presented the results of inspections conducted in 12 buildings in Germany with ETICS façades aged up to 35 years. The authors concluded that the damage or degradation of ETICS façades, as well as the costs and frequency of maintenance actions, are comparable to those found in conventional rendered masonry walls. Additionally, the service life of ETICS façades with a masonry wall substrate was assumed to be of at least 60 years. In 2015, the IBP report 42 [26] was published, summarizing the results of inspections of ETICS façades aged from 29 to 45 years. The results showed the inexistence of technical defects (e.g., cracking, blistering or render detachment) in façades that had not had any renovation of the coating in 14 to 29 years of service life. However, the authors observed significant gray discolorations caused by soling and a slightly higher susceptibility to biological growth in the case of ETICS façades.

In fact, biological growth has been identified in several ETICS façades and this issue has been the object of some studies [27–29]. Barreira and de Freitas [14] concluded that biological growth on ETICSs strongly depends on high levels of surface moisture content, resulting from the combined effect of wind-driven rain, the drying process, surface condensation and rendering formulation. According to Gonçalves et al. [30], ETICSs presenting greater insulation capacity (i.e., higher thermal resistance) and finished with a white-colored surface are usually more prone to biological growth in contrast to systems with lower insulation capacity and a darker finishing. This is explained by the lower values of external surface temperature for a longer time span, potentiating a higher risk of surface condensation. It is worth noting that surface condensation occurs whenever the external surface temperature drops below the dew point temperature of the air. Moreover, a slow drying process of the ETICS also contributes to an increased risk of biocolonization, because the surface moisture content remains high for long periods. Additionally, the use of renders with large amounts of organic additives, which provide ample nutrients to microorganisms, can also favor biological development [31,32]. In fact, some studies have highlighted the occurrence of biological growth beneath the ETICS caused by moisture accumulation in the building external wall. This phenomenon was particularly noticeable in the case of organic-based substrates (e.g., timber [33]) or organic-based thermal insulation materials [7,34].

Biological colonization alters the color of the cladding and occurs more frequently in areas of high moisture content (e.g., water runoff areas). Parracha et al. [17] evaluated the durability of commercially available ETICSs with different compositions after two years of outdoor natural exposure in both urban and maritime environments and observed higher levels of discoloration and surface gloss decrease in urban conditions, most probably due to the greater atmospheric pollution in the area. Additionally, Krueger et al. [35] analyzed the influence of several biocide mixtures in the biological colonization of ETICS specimens exposed in two locations in Germany and concluded that biological growth is significantly affected by the interaction between the biocide composition, the coating formulation and the atmospheric conditions. In fact, the incorporation of a biocide on the finishing render formulation substantially reduces the risk and the level of biological colonization [36].

Despite being considered in the literature as aesthetic anomalies, biocolonization, color change and water runoff marks can have a long-term impact on the performance of the complete ETICS without regular and adequate maintenance actions [37]. Nevertheless, according to Madureira et al. [38], 87% of the building façade defects with a priority intervention requiring short-term action within the next two years can be classified as aesthetic defects. Therefore, aesthetic deterioration has a major role in limiting a broader diffusion of ETICS technology.

Kvande et al. [5] analyzed the durability of ETICSs in Norway based on building inspections and accelerated aging tests. The authors identified 61 buildings with an ETICS presenting anomalies and attributed 150 causes to these anomalies. Out of these, 15 were identified as being the most prevalent: "defects associated with flashings against precipitation"; "incorrect reinforcement mesh"; "insufficient thickness of the render"; "faulty render mix or undesirable setting conditions"; "shrinkage and temperature movements in the render"; "incorrect end laps against adjoining structures"; "moisture from the ground (render down in the soil)"; "faulty anchorage of the system"; "microorganism growth in/on the render"; "variations in the render thickness over the insulation board"; "vibrations, movements in the structure, settling"; "incorrect choice of paint or incorrect cleaning prior to painting"; "insufficient impact resistance"; "leaching of pigment" and "mould growth behind ETICS". Most of the anomalies in ETICSs result from the combined effect of more than one degradation agent, with water action being the most important mechanism to be considered [39,40]. In fact, water penetration through the face of newly installed ETICSs is very unlikely due to the low capillary water absorption coefficient of the rendering system. However, it is almost impossible to avoid long-term cracking of the finishing coat due to a variety of factors (i.e., hygric stresses, embrittlement caused by aging, dimensional variations or incorrect design or execution of the system), potentiating water infiltration within the system and leading to further deterioration [41,42].

The omission or incorrect design/execution of tail-ends and protection elements as well as the overall incorrect application of the ETICS (e.g., deficient preparation of the substrate, incorrect alignment of the insulation or deficient flashing execution) have a primordial influence on the in-service performance of the system [13]. It is estimated that approximately 40% of the anomalies in ETICSs can be prevented with proper design, execution and appropriate assembly of the system components [16]. For example, ETICSs with "insufficient thickness of the render" can lead to an increase in the system water absorption [43], as well as to a greater tendency for the finishing coat to crack [5]. This, in turn, can potentiate not only further anomalies such as biocolonization [17] or water leakage [44], but also a decrease in the system efficiency. This latter aspect is particularly relevant if water penetrates the thermal insulation layer, since this can lead to a significant loss in ETICS thermal resistance [7].

Flatness (i.e., surface irregularities, visible joints between plates or swelling) and material rupture (i.e., cracking, detachment of the finishing coat, loss in adherence between layers, material gap) anomalies are also relatively common in ETICS façades. The rupture of materials in ETICSs can occur due to restrained movements of the different components, resulting in bending moments and possibly causing cracking and a loss in adherence between layers [45]. Oriented cracking (i.e., aligned with the joints of the insulation plates) can occur due to the stiffness and the linear thermal expansion coefficient of the thermal insulation, which is usually much higher than that of the rendering system. Therefore, the application of a thermal insulation material with lower stiffness can reduce the risk of oriented cracking. Furthermore, one of the main drawbacks of ETICSs is related to their low impact resistance [46,47]. In Switzerland, for example, hailstorms are becoming more frequent and intense, thus causing severe damage to ETICS façades [48]. In this respect, the design and execution of ETICSs with additional reinforcement mesh and higher thickness of the rendering system can help to reduce this anomaly. It is worth noting that impacts and perforation of the system cause aesthetic degradation and, most importantly, leads to further anomalies, which result from the combined action of several degradation agents (e.g., water intake; water-to-ice volume expansion inside the system; the thermal insulation potentially being exposed to UV radiation). Thus, material rupture anomalies strongly compromise the thermal and mechanical performance of the ETICS [23].

2.2. Case Study

In order to consolidate the knowledge of the most relevant anomalies in ETICSs and their causes, as reviewed in the previous section, a building complex located in Lisbon (Portugal) was studied (Figure 2). Three buildings (A, B, C) comprising 16 façades with ETICS cladding (F1, F2, . . . , Fx) were inspected. All ETICS façades contain expanded polystyrene (EPS) boards as thermal insulation, a cement-based base coat with mineral aggregates and an acrylic-based pinkish finishing coat. The building complex dates back to 1998; however, some maintenance actions have been performed over the years. A set of visits was conducted between September and November 2019 in order to inspect the ETICS façades, using visual criteria to identify the anomalies and their causes. No further auxiliary diagnosis methods were used. An inspection file was also adopted to register and map each anomaly detected.

A total of 144 anomalies were registered, and their most probable causes were identified. Six types of anomalies were considered as being the most relevant due to the high percentage of occurrence and considering the literature review of Section 2.1. Therefore, the most relevant anomalies, their causes and some recommendations to minimize their occurrence are summarized in Table 2. Figure 3 shows images of the anomalies reported in Table 2.

Figure 2. Representation of the inspected building complex identifying the 16 façades (credit: Google Earth).

Table 2. List of the most relevant anomalies identified in the case study, their causes and some recommendations to minimize the occurrence.

Anomaly: material rupture—perforation of the system in ground-level zones (Figure 3A). **Identified in the following:** façades F2 to F5, F7 and F8 (Figure 2). **Causes:** most of these anomalies are caused by human action, either negligent or willful (i.e., with a deliberate intention to cause damage). **Recommendations to minimize the occurrence:** Generally, the application of an ETICS is not recommended in areas very vulnerable to hard body impact, such as readily accessible areas (e.g., ground-level zones). The ETICS applied in these areas (i.e., impact resistance category I according to EAD [11]) should have additional reinforcement mesh and higher thickness of the rendering system.
Anomaly: cracking of the rendering system in corners and window openings (Figure 3B). **Identified in the following:** façades F1, F3, F5 and F7 (Figure 2). **Causes:** this anomaly is frequently caused by a lack of adequate design and/or execution of the corners and window openings (e.g., absence or inadequate application of reinforcement mesh in these areas). **Recommendations to minimize the occurrence:** Reinforcement mesh should be applied in areas of the system subjected to greater tensions, as in the case of window openings and corners. The mesh must be properly applied, in order to resist the tensile stresses.
Anomaly: biological colonization (Figure 3C). **Identified in the following:** north and northwest façades (i.e., F3, F7, F11 and F15) (Figure 2). **Causes:** This anomaly is quite frequent in ETICS façades in Portugal, especially in those facing north where the humidity is higher. Biocolonization is a complex phenomenon strongly influenced by surface properties (i.e., humidity, temperature, pH, roughness, composition) and climatic conditions, among others. **Recommendations to minimize the occurrence:** ETICS façades presenting biocolonization should be cleaned with water at a low pressure. Afterward, the application of a finishing coat containing biocide is recommended. Additionally, it is of fundamental importance that the architectonic and/or constructive solutions allow for a reduction in the water runoff over the building façades.
Anomaly: water runoff marks (Figure 3D). **Identified in the following:** façades F3, F5, F7 and F9 (Figure 2). **Causes:** this anomaly is due to the incorrect design and/or execution of projections to lead the downward flow of water (e.g., copings, sills, downpipes). **Recommendations to minimize the occurrence:** The proper design and execution of these elements is of fundamental importance to avoid not only this anomaly, but also further defects caused by moisture accumulation. It is worth noting that water is the most important degradation agent to be considered and that most of the failure modes in ETICSs occur when one or more degradation agent acts synergistically with water.

Table 2. *Cont.*

Anomaly: non-oriented cracking and detachment of the finishing coat (Figure 3E,F). **Identified in the following:** all façades. **Causes:** these anomalies may result from the combined effect of the application of a rendering system with insufficient thickness, lack of tensile strength of the mesh or inadequate application of the mesh and moisture accumulation within the system. **Recommendations to minimize the occurrence:** The rendering system should have enough thickness, which is specified in the ETA document of the ETICS. The system should have also adequate water vapor permeability (i.e., equivalent air thickness of the rendering system must be lower than 2 m or 1 m, in the case of a system with a cellular plastic insulation product (e.g., EPS) or mineral wool insulation, respectively [11]). Moreover, the tensile strength of the reinforcement mesh should be higher than 20 N/mm after aging [11], with this value also being specified in the ETA document of each system.
Anomaly: oriented cracking (Figure 3G). **Identified in the following:** F1 to F3, F5 to F7 and F10 and F13 (Figure 2). **Causes:** In this case, the cracking is oriented and aligned with the joints of the insulation plates. This anomaly normally occurs due to the stiffness and the linear thermal expansion coefficient of the thermal insulation (EPS). This coefficient is about five times higher than that of the rendering system. As a result, the insulation plates bend to the exterior due to thermal variation between their outer and inner surfaces. This phenomenon generates great tensions in the rendering system that can lead to cracking. **Recommendations to minimize the occurrence:** The application of a thermal insulation material with lower stiffness could be the solution. Therefore, the thermal insulation shall be chosen also considering the environmental conditions of exposure. Additionally, the compatibility between the rendering system and the thermal insulation material must be guaranteed.

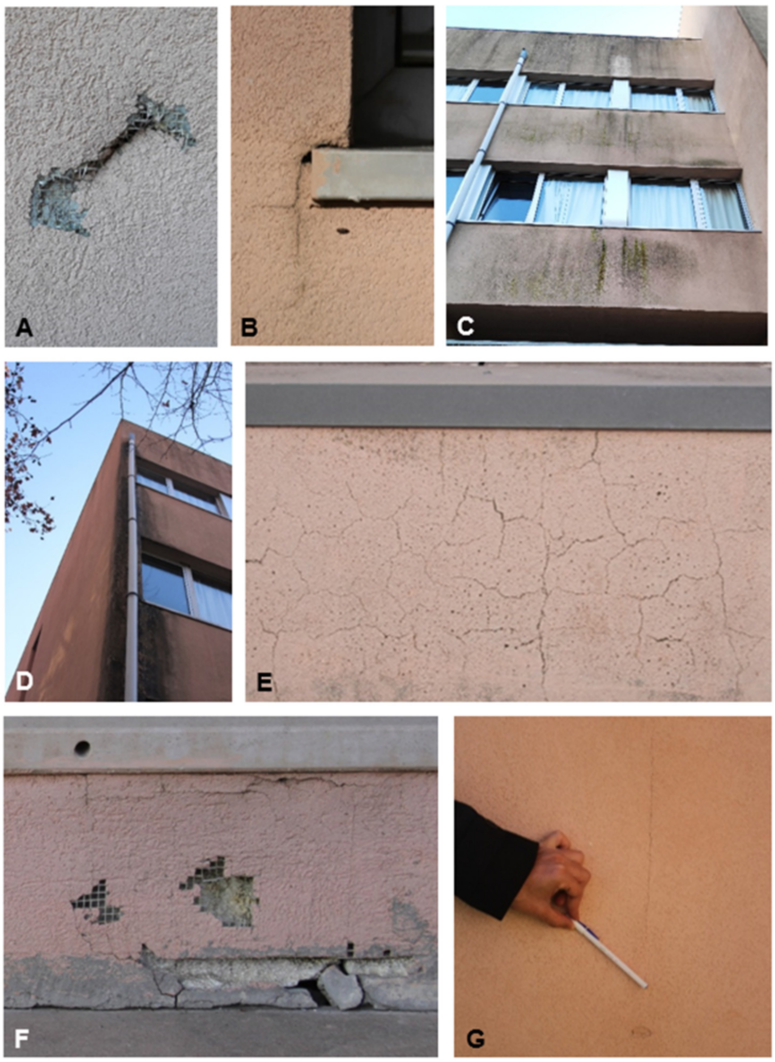

Figure 3. Relevant anomalies identified on the façades: (**A**)—perforation of the system; (**B**)—cracking of the rendering system in window openings; (**C**)—biological colonization; (**D**)—water runoff marks; (**E**)—non-oriented cracking; (**F**)—detachment of the finishing coat; (**G**)—oriented cracking.

3. Performance

In this section, the performance, performance parameters and requirements for ETICSs are reviewed, summarizing the most relevant aspects in this regard.

3.1. Fire Behavior

Fire safety is considered as a general prescription in the multi-objective optimization of building design, i.e., the performance is assessed based on the standard testing of materials and products and considering pass–fail criteria and a material classification [49]. This aspect raises some problems related to the fact that results from standard fire testing using different material scales are not fully representative of real fires and may not correspond to the most important failure modes in real life scenarios. According to the EAD [11], the fire behavior of an ETICS is evaluated considering the reaction to fire of the entire system (Table 3) and the relative thermal insulation (Table 4), but also, if requested by the manufacturer, the façade fire performance. The reaction to fire of the ETICS and thermal insulation material is determined using the classifications proposed in the EN 13501-1 [50] (i.e., Euroclasses). The Euroclass of the thermal insulation material determined considering the relevant test method [11] shall be presented in the ETA document. Additionally, the performance-based classification of EN 13501-1 [50] might not be sufficient for the use of an ETICS in some European countries, and some additional assessments following national provisions might be mandatory. Likewise, the façade fire performance shall be declared in the ETA document taking into account the legal regulations of each country (Table 3). National standards define thresholds considering the use of certain Euroclasses for specific uses.

Table 3. Summary of assessment methods for an ETICS.

Basic Work Requirement	ETICS Characteristic	Assessment Method
Safety in case of fire	Reaction to fire	EN 13501-1 [50]
	Façade fire performance	*
	Propensity to undergo continuous smoldering **	EN 16733 [51]
Hygiene, health and environment	Content, emission and/or release of leachable substances	EAD 040083-00-0404 [11]
	Water absorption (capillarity test)	EAD 040083-00-0404 [11]
	Watertightness: hygrothermal behavior	EAD 040083-00-0404 [11]
	Watertightness: freeze–thaw performance	EAD 040083-00-0404 [11]
	Impact resistance	ISO 7892 [52]
Safety and accessibility in use	Bond strength ***	EAD 040083-00-0404 [11]
	Wind load resistance	EAD 040083-00-0404 [11]
Protection against noise	Airborne sound insulation	ISO 10140-1 [53], ISO 10140-2 [54] and ISO 10140-5 [55]
Energy economy and heat retention	Thermal resistance	ISO 10456 [56]

* It should be tested considering the relevant assessment method in each country; ** only required in some EU member states for an ETICS with thermal insulation made using mineral wool, wood-based products, vegetable and/or animal fibers or cork; *** it should be evaluated before and after accelerated aging.

As previously discussed, expanded polystyrene (EPS) is one of the most commonly used thermal insulation materials in an ETICS [8]. This is a combustible material which is easily flammable, with a low limiting oxygen index (LOI) of about 18%, and which releases toxic gases when burned [57,58]. When EPS is exposed to heat it starts to melt and a serious fire can occur in upward and downward directions [59]. Some strategies have thus been adopted to decrease the fire impact and reduce the flame spread, such as the inclusion of fire barriers made of non-combustible materials around the window openings or separating the different floors [60,61], the increase in the rendering thickness [62] or the use of thermal insulation materials with fire-retardant combustion [63,64]. Niziurska et al. [61] evaluated the impact of adding MW partitions on an improvement in the fire performance of an ETICS with EPS thermal insulation and concluded that the performance of the façade was not significantly affected. The authors also obtained slight differences in the average temperatures and the dimension of the polystyrene melting area considering different configurations of insulation with MW partitions. The tested ETICS was classified as being a fire retardant according to BS 8414-1 [65], regardless of the applied MW partitions. Uygunoglu et al. [62] recommended the application of an ETICS with a rendering system of at least 4 mm thickness to improve the resistance to ignition. The same authors also recommended the use of fire-retardant insulation boards in ETICS applications. Finally, Hamdani-Devarennes et al. [64] investigated the performance of EPS with and without water-based fire retardants and achieved an upgrade in the Euroclass of EPS with a fire-retardant surface, from F to E.

Table 4. Summary of the assessment methods for validating ETICS components.

ETICS Component	Characteristic	Assessment Method
Thermal insulation	Length and width	EN 822 [66]
	Thickness	EN 823 [67]
	Squareness	EN 824 [68]
	Flatness	EN 825 [69]
	Density	EN 1602 [70]
	Reaction to fire	EN 13501-1 [50] *
	Water absorption (partial immersion)	EN 1609 [71]
	Water vapor permeability	EN 12086 [72]
	Tensile strength perpendicular to the faces **	EN 1607 [73]
	Shear strength and shear modulus of elasticity	EN 12090 [74]
	Compressive strength	EN 826 [75]
	Thermal resistance	EN 12667 [76] or EN 12664 [77]
	Dynamic stiffness	EN 29052-1 [78]
	Dimensional stability	EN 1604 [79]
Rendering system ***	Thickness	EN 823 [67]
	Water vapor permeability	ISO 7783 [80]
Base coat and mesh	Thickness	EN 823 [67]
	Render strip tensile test	EAD 040083-00-0404 [11]
Mesh (standard or reinforced)	Tensile strength and elongation ****	EAD 040083-00-0404 [11]
	Protection against corrosion *****	EAD 040083-00-0404 [11]
Anchors	Pull-through test of fixings	EAD 040083-00-0404 [11]
	Pull-out strength of anchors	EAD 330196-01-0604 [81]

* The reaction to fire of each insulation material shall be determined using the test method relevant for the corresponding Euroclass determined in the EN 13501-1 [50]; ** the test shall be performed in both dry and wet conditions; *** reinforced base coat and finishing coat; **** it should be evaluated before and after accelerated aging; ***** the minimum thickness of the zinc coat must be verified only for galvanized steel meshes.

3.2. Capillary Water Absorption and Water Vapor Permeability

Water resistance is one of the most important properties of an ETICS, since it strongly affects the system durability, possibly leading to extensive cases of anomalies (see Section 2). Following the guideline of the European Technical Approval of ETICS [11], water resistance is assessed through capillary absorption and vapor permeability tests and evaluating the hygrothermal behavior and freeze–thaw performance of the systems (Table 3). Considering the water absorption by capillarity test, the guideline indicates that water absorption after 1 h testing must be lower than 1 kg/m^2 for both the complete system (i.e., thermal insulation, reinforced base coat and rendering system) and the ETICS without rendering (i.e., thermal insulation and reinforced base coat). The capillary water absorption after 1 h and 24 h shall be presented in the ETA document of the ETICS. If the water absorption of the complete system after 24 h is lower than 0.5 kg/m^2, the system is considered to be freeze–thaw-resistant, without a need for further assessment in this regard. Additionally, the water absorption via partial immersion after 24 h testing of the thermal insulation board tested alone must be lower than 1 kg/m^2. The latter value shall also be declared in the ETA document.

Parracha et al. [7] evaluated the capillary water absorption of twelve commercially available ETICSs with different compositions and observed that all of the systems presented a capillary absorption lower than 1 kg/m^2 after 1 h, following the EAD [11] requirements. In fact, the ETICS obtained the greatest level of water absorption in the beginning of the test (i.e., in the first hour), followed by stabilization at the rate of absorbed water, which was not completely achieved after 24 h, as also observed by Griciute et al. [82] when testing ETICSs with different finishings (i.e., silicate, acrylic, mineral or silicone). In this regard, Dirkx and Grégoire [83] referred to the fact that the EAD guideline [11] not considering the full water saturation of the rendering system can be a disadvantage in evaluating the ETICS performance, especially considering the frost behavior. The same authors [84] also concluded that the finishing coat composition and the capillary water absorption of the rendering system are the main factors influencing algae growth on the surface of an ETICS (i.e., the likelihood decreases markedly when ETICSs have capillary absorption lower than 0.1 kg/m^2 after 24 h).

In the study of Parracha et al. [7], the lowest values of capillary water absorption after 1 h were obtained for systems with EPS thermal insulation, cement-based base coat and acrylic-based finishing coat, whereas the highest values were obtained for a system with ICB thermal insulation, cement–resin base coat and acrylic-based finishing coat and for a system with ICB thermal insulation and finished with a lime-based mortar. Both Parracha et al. [7] and Sadauskiene et al. [43] obtained a significant decrease in the initial capillary water absorption by increasing the thickness of the finishing coat.

The water vapor permeability of the ETICS is assessed in the EAD [11] by considering the equivalent air thickness (s_d) of the rendering system and the water vapor diffusion resistance coefficient (μ-value) of the thermal insulation (Table 4). According to the guideline, the s_d value should not be higher than 2 m in the case of an ETICS with cellular plastic thermal insulation materials (e.g., EPS and XPS) or any other thermal insulation product except mineral wool. In this latter case, a more conservative s_d threshold of 1 m should be considered, due to the considerably higher water vapor permeability of MW. Additionally, the μ-value of the thermal insulation material shall be declared in the ETA document.

In fact, the water vapor permeability of the complete ETICS is significantly affected by the type of thermal insulation material used [7,85]. In general, ETICSs with MW have significantly higher water vapor permeability, when compared to EPS systems. Therefore, when using thermal insulation materials with greater vapor permeability, the rendering system should have also high vapor permeability (i.e., low s_d value) [86,87]. This is of fundamental importance to facilitating moisture evaporation from the building envelope, decreasing the risk of internal water condensation and improving the long-term performance of ETICSs. Therefore, the μ-value of the entire ETICS shall thus be considered in the performance evaluation of an ETICS, as this value is important when comparing ETICSs with similar thermal insulation boards but different rendering systems.

3.3. Impact Resistance

According to the EAD [11], the impact resistance of ETICSs (Table 3) is determined using steel balls of 0.5 kg (fall height of 0.61 m) and 1 kg (fall height of 1.02 m), assuming a

90° impact angle (3 J and 10 J of impact energy). The surface damage is visually assessed, and the diameter of the notch caused by the impact is measured. The damage is then linked to an impact resistance category (Table 5). Both the notch diameter and the use categories shall be declared in the ETA document. Additionally, the presence of microcracking, cracking or penetration on the surface of an ETICS shall also be stated in the ETA.

Table 5. ETICS classification according to the impact resistance tests (3 J and 10 J) and use categories.

Test		Impact Resistance Category		
		I	**II**	**III**
Steel ball impact (90°)	3 J	NC *	NC *	NP **
	10 J	NC *	NP **	-

* No cracking. ** The system is considered to be "penetrated" if the thermal insulation can be observed in 3 out of 5 tests performed; otherwise, there is no penetration (NP) and there is deformation. **Use categories:** **I**—zones readily accessible at ground level to the public and vulnerable to hard body impacts but not subjected to abnormally rough use; **II**—zones liable to impacts from thrown or kicked objects, but in public locations where the height of the system will limit the size of the impact, or at lower levels where access to the building is primarily for those with some incentive to exercise care; **III**—zones not likely to be damaged by normal impacts caused by people or by thrown or kicked objects.

In Switzerland and Austria, a multistep classification scheme has been adopted to evaluate the impact resistance of façade products using ice balls of different diameters, with an impact angle of 45° and assuming different shot speeds. Steinbauer et al. [48] compared the Swiss and Austrian approach with the EAD methodology [11] using high-speed camera recordings to register the impact process and evaluate the degradation mechanism. They concluded that, using ice ball tests, a considerable increase in the fracture strengths is obtained and this test should therefore be considered for the assessment and validation of ETICSs regarding hail impact resistance. The authors also observed that all fractures are due to extensional strain, leading to elongation of the render. Therefore, the use of a rendering system with a high fracture strain (i.e., high flexibility), as well as the application of reinforcement meshes in the base coat, are highly recommended to improve the impact resistance of an ETICS.

3.4. Bond Strength between Layers

Table 6 presents the tests, conditions and requirements specified in the EAD [11] for the assessment of the bond strength between layers of an ETICS (Table 3).

Malanho and Veiga [9] evaluated the bond strength between the layers of fifteen ETICSs' solutions with different thermal insulation and base coat compositions, considering the assessment defined in the EAD [11] (Table 6). The results showed that the (cohesive) bond strength between the adhesive and the thermal insulation was mainly affected by the tensile strength of the thermal insulation material. Additionally, the cohesive rupture was mainly due to the lowest values of the tensile strength perpendicular to the faces and shear modulus of elasticity of the thermal insulation, especially in the case of MW and ICB. In fact, Norvaisiene et al. [88] evaluated the bond strength between the layers of an ETICS with fire barriers and concluded that the strength between the base coat and the joints comprising EPS and MW was significantly lower than that obtained between the base coat and only EPS. This is mainly due to the considerably lower cohesion of MW when compared to EPS, and thus the bond strength value will mainly depend on the ratio of the surface tested to the surface of EPS and MW. Therefore, the mechanical performance of the thermal insulation can be an indicator of the bond strength between the adhesive and the insulation. Furthermore, the authors [9] also observed that mortar flexural strength can be an important performance indicator considering the (cohesive) rupture in the adhesive between the substrate (concrete) and the adhesive. Likewise, the mortar flexural strength can also be used to provide an indication of the bond strength between the adhesive and the substrate.

Table 6. Assessment of bond strength between layers according to EAD [11].

Test	Conditions	Requirements
Bond strength between the base coat and the thermal insulation	Non-aged	The minimum and the mean value in kPa and the rupture type (adhesive or cohesive) shall be stated in the ETA. Both results must be higher than 80 kPa with cohesive or adhesive rupture. When the rupture occurs in the thermal insulation (cohesive rupture), the bond strength can be lower than 80 kPa.
	After hygrothermal cycles	
	After freeze–thaw cycles *	
Bond strength between the adhesive and the thermal insulation	Non-aged (dry state)	Adhesive rupture or cohesive rupture in the adhesive—bond strength must be higher than 80 kPa. Cohesive rupture in the thermal insulation—bond strength must be higher than 30 kPa.
	Non-aged (after water immersion)	Two hours after removing specimens from water—considering adhesive rupture or cohesive rupture in adhesive, the bond strength must be higher than 30 kPa; for the cohesive rupture in the insulation, there is no requirement. Seven days after removing specimens from water—considering adhesive rupture or cohesive rupture in adhesive, the bond strength must be higher than 80 kPa; for the cohesive rupture in the insulation, there is no requirement. The minimum bond strength values for each condition and the rupture type shall be stated in the ETA.
Bond strength between the adhesive and the substrate	Non-aged (dry state)	Bond strength must be higher than 250 kPa.
	Non-aged (after water immersion)	Two hours after removing specimens from water—bond strength must be higher than 80 kPa. Seven days after removing specimens from water—bond strength must be higher than 250 kPa.

* If necessary (see Section 3.2).

3.5. Thermal Resistance

According to the EAD [11], the thermal resistance of the complete ETICS solution (Table 3) must be lower than 1.0 (m^2.K)/W and shall be stated in the ETA document. This value is obtained considering the thermal resistance of the insulation material and that of the rendering system. Nevertheless, the thermal resistance of the insulation material (Table 4) should be representative of the complete system. Therefore, this latter value shall also be declared in the ETA.

Uygunoglu et al. [62] obtained energy savings between 76% and 79% for an ETICS with EPS, XPS and MW when compared to the uncoated wall. On the other hand, Varela Luján et al. [6] showed that using an ETICS for the thermal retrofitting of building façades can provide a reduction in energy losses and gains up to 55%. In fact, it is already known that one of the best ways of reducing the energy needs for the heating and cooling of buildings is an increase in the thermal insulation level of the building envelope. As a result, new solutions with extremely low thermal conductivity are being designed and included in the market. Mandilaras et al. [86] incorporated vacuum insulation panels (VIPs) in an ETICS to enhance the thermal behavior of the walls. The authors obtained thermal resistance 123% higher in the case of an ETICS with VIPs covered with MW on both sides when compared to a conventional ETICS wall with EPS thermal insulation. Indeed, one of the great advantages of using VIPs in an ETICS is the possibility of achieving higher thermal resistances with lower thicknesses [89]. However, the enhanced thermal performance of the system can also potentiate further anomalies, and the high cost of VIPs is still a barrier toward the wide-scale use of this technology. As an example, greater values of thermal resistance led to a decrease in surface temperature during the night, and therefore to a higher risk of surface condensation and biological colonization (see Section 2).

4. Durability

Durability is one of the most important criteria for the selection of building materials and construction products, since it affects the performance of these elements, possibly compromising the fulfilment of specific requirements during a building's service life [90]. Four different approaches can be considered for durability assessment: accelerated aging tests corresponding to benchmark tests; comparative tests, which allow one to calibrate methods, materials and equipment; environmental or stress tests and field tests, usually through natural aging and/or on-site monitoring [91]. This section aims at providing a literature review on the durability assessment of ETICSs considering a laboratorial evaluation (i.e., accelerated aging assessment), numerical simulation and long-term performance (i.e., outdoor natural exposure), identifying the most significant degradation agents and the related failure modes.

4.1. Laboratorial Conditions

The European guideline for the technical approval of ETICSs with rendering EAD 040083-00-0404 [11] defines a set of heat/rain, heat/cold and freeze/thaw cycles for the durability assessment of an ETICS, considering its hygrothermal and freeze/thaw behavior. Table 7 presents the accelerated aging procedure proposed by the European document, as well as the assessment that should be performed before and after aging. It is worth noting that some additional degradation agents such as environmental pollutants, UV radiation and biological colonization are not considered in the guideline, which aims only to evaluate the essential characteristics of the product. According to Michalak [21], this should not be a problem because the manufacturer performs a set of additional tests before putting the ETICS on the market, thus guaranteeing suitable quality and adequate performance. Nevertheless, cases of anomalies are still being detected with ETICS façades, reinforcing the importance of knowing the most relevant degradation agents and associated degradation mechanisms, which strongly depend on the climate as well as on the system composition and the correspondent resistance to climatic loads. Additionally, the accelerated aging procedure defined in the EAD [11] does not provide a service life prediction of ETICSs (i.e., the method is defined considering only the "suitability for use"). Therefore, considering the methodology proposed by ISO 15686-1 [92], short-term (accelerated aging) and long-term (natural aging) tests should be conducted and the type of degradation resulting from either one or the other test must be critically analyzed and compared. With these data, a model for the service life prediction of an ETICS can be developed and validated. It is important to note that there are still a lack of studies on this topic, despite the 25 years assumed to be a service life reference in the EAD [11].

Table 7. Accelerated aging procedure defined in the EAD 040083-00-0404 [11].

Test Conditions	No. of Cycles (Total h)	Accelerated Aging Cycles			Tests Performed before and after Aging
		Heat	Rain	Cold	
Heat/rain cycles	80 (320)	3 h at 70 ± 5 °C (10–30% RH)	1 h (1 L/(m^2.min)) of sprayed water at 15 ± 5 °C	-	Visual inspection, bond strength between layers
Heat/cold cycles	5 (120)	8 h at 50 ± 5 °C (≤30% RH)	-	16 h at −20 ± 5 °C	
Freeze/thaw cycles *	30 (720)	-	Immersion in water at 23 ± 2 °C for 8 h	16 h at −20 ± 2 °C	

* If the water absorption of the complete system (non-aged condition) after 24 h is lower than 0.5 kg/m^2, the system is considered to be freeze–thaw-resistant, without a need for further assessment in this regard.

Table 8 presents a list of scientific studies aiming to evaluate the durability of ETICSs using accelerated aging methods. Thirteen research studies were identified and most of them considered the hygrothermal behavior (i.e., temperature and moisture effects) and the UV performance (i.e., solar radiation) for the durability assessment of an ETICS. In some studies, accelerated aging tests are performed in small-scale specimens, and in some cases they are performed in the entire ETICS wall (i.e., on the rig). In fact, considering the method of the EAD guideline [11], the hygrothermal behavior (i.e., heat/rain and heat/cold cycles) should be evaluated in the entire ETICS wall (i.e., on the rig), whereas the freeze/thaw performance is assessed in small-scale specimens. As shown in Table 8, a new accelerated aging method for the durability assessment of ETICSs was designed in 6 out of 13 studies, considering the action of the relevant degradation agents (i.e., pollutants, UV radiation, biocolonization), degradation mechanisms and the climatic data of different countries. Landolfi and Nicolella [93] considered the EAD [11] procedure with minor variations to reproduce outdoor exposure, whereas Kvande et al. [5] used the NT Build 495 method [94], which is commonly used in Scandinavian countries for the durability assessment of ETICSs on walls. Additionally, Roncon et al. [95] used the accelerated aging method defined in EN 1015-21 [96] for the durability assessment of rendering mortars. Different trends and results were obtained considering the 13 research studies. In some cases, the accelerated aging tests significantly affected the water resistance, thermal performance and appearance of the ETICS. In some other studies, no significant performance decline or surface defects were detected after aging. Nevertheless, most studies identified the difficulty of reproducing the synergistic effect of several degradation agents on a lab scale and recommended further developments including long-term performance evaluation for the correlation of results obtained through accelerated and natural aging tests.

Table 8. Summary of research studies considering the durability assessment of ETICSs through accelerated aging tests.

Aim of the Study	Degradation Agents	Test Conditions	Main Results	Reference
Evaluation of the hygrothermal performance of ETICSs over time considering a newly designed accelerated aging procedure. The procedure was designed considering the degradation agents of ETICSs and corresponding degradation mechanisms, existing standards and climatic data from Milan, Italy.	UV exposure. Winter cycles (freeze/thaw behavior). Summer cycles (dry heat and rain).	1. UV exposure—25 cycles (25 h) of UV exposure at 35 °C (15 ± 2% RH) followed by 25 cycles (25 h) of sprayed water at 15 ± 2 °C and 100% RH. 2. Winter cycles—10 cycles (30 h) with −20 ± 2 °C followed by 10 cycles (10 h) at 30 ± 2 °C (50 ± 5% RH). 3. Summer cycles—25 cycles (25 h) at 70 ± 2 °C (15 ± 2% RH) followed by 25 cycles (25 h) of sprayed water at 20 ± 2 °C and 100% RH.	The thermal resistance of the ETICS significantly decreased with aging, most probably due to the significant increase in water absorption. A decrease in time shift was observed when evaluating the dynamic thermal performance of the system. Microphotographs have shown significant surface anomalies after aging (i.e., blistering, cracking), with an increase in the pores' dimension of the finishing coat.	Daniotti et al. [97]
Evaluation of the performance of ETICSs toward the definition of a new accelerated aging procedure considering the Lithuanian climate.	Hygrothermal behavior (heat/rain and heat/cold cycles) and freeze/thaw performance. UV exposure.	Sixteen cycles (672 h) of 7 h of sprayed water (1 L/(m^2.min)) at 20 °C; 7 h of freezing at −12 °C; 28 h of UV exposure (35–40 W/m^2) at 40 °C. According to the authors, 16 cycles correspond to ~1 year of natural aging in Lithuania.	An ETICS with silicate-based FC obtained higher capillary water absorption after aging in comparison with an ETICS finished with an acrylic-based paint. Capillary water absorption and bond strength between layers of ETICSs should be determined before and after aging. A visual inspection should also be conducted.	Griciute et al. [82]

Table 8. *Cont.*

Aim of the Study	Degradation Agents	Test Conditions	Main Results	Reference
Investigation into the durability of ETICSs in Norway. The performance of 19 ETICS solutions with different thermal insulation (i.e., EPS, MW and polyisocyanurate (PIR)) was assessed after aging.	Hygrothermal behavior (heat/rain and heat/cold cycles) and freeze/thaw performance. UV exposure.	A sequence of four different climatic zones according to the method NT BUILD 495 [92]: Hygrothermal cycles—1 h at 23 ± 5 °C (50 ± 10% RH); 1 h (15 ± 2 L/m^2) of sprayed water; 1 h at −20 ± 5 °C. UV exposure—1 h until reaching 35 ± 5 °C, 50 ± 5 °C or 75 ± 5 °C. The UV dose can be selected at different levels considering the UV tubes used. The ETICS performance is assessed after 4, 18 and 48 weeks of accelerated aging.	Failure modes occurring after aging were largely associated with incorrect design and/or execution of the system. The edges and corners of the ETICS were considered to be the most vulnerable areas. Therefore, the use of corner profiles and plinth flashings was recommended. Severe water exposure possibly leading to frost damage can be obtained with deficient flashing execution. Therefore, the use of plinth flashings in the case of an ETICS with MW to avoid the contact of water with the thermal insulation was recommended. Generally, an ETICS with EPS showed a better performance after aging when compared to an ETICS with MW.	Kvande et al. [5]
Evaluation of the impact of thermal insulation anomalies on the global performance of ETICSs.	Hygrothermal behavior (heat/rain and heat/cold cycles) and freeze/thaw performance. UV exposure.	Four hundred cycles (900 h) of the following: 1 h of heating at 50 °C (40 °C in the air) and UV radiation; 15 min of sprayed water (10 to 40 m^3/(m^2.h)); 1 h of freezing at −18 °C. According to the authors, 100 cycles correspond to 2–2.5 years of natural aging considering the climatic conditions of Upper Silesia.	The open porosity of the finishing coat increased after aging, and significant surface cracking was observed. The durability of the finishing coat affected the durability of the complete system.	Slusarek et al. [44]
Evaluation of the performance of ETICSs with fire barriers after accelerated aging. Estimate of the impact of using fire barriers with different insulation materials (e.g., EPS and MW) on the durability performance of ETICSs.	Hygrothermal behavior (heat/rain and heat/cold cycles).	Hygrothermal cycles were performed in accordance with EAD 040083-00-0404 guideline [11] (see Table 7).	No visible surface defects were detected in the systems after accelerated hygrothermal aging. The bond strength between layers of the ETICS after hygrothermal aging was significantly lower in the joints comprising EPS and MW (i.e., fire barriers), when compared to the zones only with EPS.	Norvaisiene et al. [89]
Durability assessment of six commercially available ETICSs after accelerated aging. Evaluation of physical and chemical–morphological properties of the ETICS prior and after each aging cycle, evaluating the loss in performance.	Hygrothermal behavior (heat/rain and heat/cold cycles). UV exposure. SO_2 exposure.	A sequence of the following aging cycles: Hygrothermal cycles—carried out according to EAD 040083-00-0404 [11] (see Table 7). UV radiation—125 cycles (1000 h) of 4 h of UV-A exposure at 60° followed by 4 h of condensation (T = 50 °C and 80% RH). SO_2 exposure—60 cycles (720 h) of 6 h of 25 ppm SO_2 (T = 40 °C and 30% RH) followed by 6 h of 25 ppm SO_2 (T = 15 °C and 85% RH).	Hygrothermal cycles significantly affected the surface properties of the ETICS (i.e., surface hardness decreased after the combined aging procedure, whereas the surface roughness increased). Surface gloss decreased after aging and a substantial color change was observed. An ETICS with acrylic and co-polymeric finishes presented low degradation after aging. Traces of mold growth (<10% of contaminated surface) were detected after the hygrothermal cycles. No further increase in biological growth was observed after exposure to UV or SO_2.	Parracha et al. [10]

Table 8. *Cont.*

Aim of the Study	Degradation Agents	Test Conditions	Main Results	Reference
Evaluation of the impact of using water-repellent products on the moisture transport properties and biocolonization of ETICSs before and after aging.	Hygrothermal behavior (heat/cold cycles) and freeze/thaw performance.	Accelerated aging cycles performed in accordance with EN 1015-21 [94]: Hygrothermal behavior—eight cycles of the following: 8 h ± 15 min of heating at 60 ± 2 °C; 30 min of stabilization at 20 ± 2 °C (65 ± 5% RH); 15 h ± 15 min of freezing at −15 ± 1 °C; stabilization at 20 ± 2 °C (65 ± 5% RH). Freeze/thaw performance—eight cycles of the following: 8 h ± 15 min of sprayed water at 20 ± 1 °C; 30 min of stabilization at 20 ± 2 °C (65 ± 5% RH); 15 h ± 15 min of freezing at −15 ± 1 °C; stabilization at 20 ± 2 °C (65 ± 5% RH).	After aging, the moisture transport properties of the systems were only slightly affected (i.e., lower water absorption, higher drying resistance and lower water vapor permeability compared to the unaged ETICS). Aged systems with water-repellent products showed better water performance than a newly produced ETICS without water-repellent products. No significant mold growth was detected before and after aging, showing the effectiveness of the biocide present in the formulation of the products.	Roncon et al. [95]
Durability assessment of six different ETICSs and corresponding thermal insulation materials in order to optimize maintenance actions. Evaluation of thermo-physical properties prior and after accelerated aging simulating outdoor conditions.	Hygrothermal behavior (heat/rain and heat/cold cycles) and freeze/thaw performance.	Hygrothermal cycles and freeze/thaw performance were evaluated in accordance with the method of EAD 040083-00-0404 [11] (see Table 7) with minor variations, as follows: Hygrothermal cycles—80 heat/rain cycles for 3 h at 80 ± 5 °C; 1 h (1.5 ± 0.5 L/m^2) of sprayed water at 15 ± 5 °C; 2 h of drainage at 20 ± 5 °C; 7 heat/cold cycles for 8 h at −10 ± 2 °C; 9 h at 70 ± 2 °C (≤30% RH); 7 h at −10 ± 2 °C. Freeze/thaw cycles—15 cycles of 8 h water immersion exposure at 23 ± 4 °C; 14 h of freezing at −20 ± 5 °C; 2 h at 50 °C.	An increase in water absorption was reported after aging both for the ETICS and for the thermal insulation boards tested alone. An ETICS with mineral wool, glass wool or wood fiberfill as thermal insulation showed higher short-term water absorption after aging. The thermal transmittance of the ETICS was only slightly affected after aging, thus suggesting that the thermal performance is not significantly affected during the service life. No significant performance decay was registered after accelerated aging.	Landolfi and Nicolella [93]
Evaluation of the performance of ETICSs after one year of natural outdoor exposure and hygrothermal artificial aging. The water performance, biological growth and surface properties were assessed for the systems in the pristine (non-aged), artificially and naturally aged conditions.	Hygrothermal behavior (heat/rain and heat/cold cycles) and natural outdoor exposure.	Hygrothermal cycles were performed in accordance with EAD 040083-00-0404 guideline [11] (see Table 7). Natural outdoor exposure was performed at an urban site in Lisbon, Portugal, in the period between October 2019 and October 2020. The specimens were placed tilted 45° and facing south.	Accelerated aging strongly influenced the capillary water absorption and the drying kinetics of the ETICS (i.e., an increase between 86% and 271% considering the 24 h capillary absorption and between 47% and 101% for the drying index). Traces of mold growth (<10% of contaminated surface) were only observed on the artificially aged systems. However, significant color change was registered in both naturally and artificially aged ETICSs. Gloss variation was almost undetected after artificial aging; a significant decrease up to 62% was obtained after one year of natural exposure.	Parracha et al. [98]

Table 8. *Cont.*

Aim of the Study	Degradation Agents	Test Conditions	Main Results	Reference
Assessment of the deformation effect of the finishing coat of ETICSs during accelerated artificial aging. Real-time observation of the deformation phenomena caused by aging.	Hygrothermal behavior (heat/rain and heat/cold cycles).	Hygrothermal cycles were performed in accordance with EAD 040083-00-0404 guideline [11] (see Table 7).	Deformation of the surface of ETICSs increases with increasing temperature. Then, the surface of the wall shrinks after being exposed to rain and cooling. Nevertheless, irreversible deformation was observed. In fact, the deformation on the ETICS surface became considerably larger with aging. After the occurrence of localized deformation, the surface cracks serve as a buffer area for wall expansion and shrinkage.	Yuan et al. [99]
Evaluation of the growth of two microalgal strains on ETICSs. Assessment of the impact of water absorption, porosity and surface roughness of ETICSs on biocolonization.	Water runoff test and a culture of Chlorella mirabilis ALCP 221B and Chroococcidiopsis fissurarum IPPAS B445Z8.	The accelerated growth test was carried out in a glass chamber placed in a dark room and equipped with two 39 W neon lamps (T ~ 5000 K) and two sprinkling rails connected to a 500 L/h water pump engulfed in broth culture. The accelerated aging test consisted of the following: 14 h of light with a sprinkled broth culture for 15 min followed by 10 h of dark for 60 consecutive days. The specimens' surface was also sprinkled with distilled water after 3, 6 and 9 weeks of aging to simulate a washing process. According to the authors, the aging procedure corresponds to ~ 2 years of natural exposure.	A correlation was found between microalgal growth and surface properties (i.e., water absorption, porosity and roughness). The higher the roughness, the greater the bioreceptivity. Moreover, the amount of available nutrients increases with water retention, thus leading to greater bioreceptivity. The same trend was observed considering the porosity, i.e., the higher the porosity, the greater the bioreceptivity.	D'Orazio et al. [28]
Evaluation of the aging impact in the microstructure of the rendering system of ETICSs.	Hygrothermal behavior (heat/rain and heat/cold cycles). UV exposure.	One hundred cycles (225 h) of the following: 1 h of heating at 50 °C (40 °C in the air) and UV radiation; 15 min of sprayed water (10 to 40 $m^3/(m^2.h)$); 1 h of freezing at −20 °C.	The open porosity of the external surface of the rendering system significantly increased after aging. On the other hand, a decrease in the total porosity of the internal zone of the aged rendering system was observed.	Bochen and Gil [100]
Evaluation of thermophysical and mechanical performance (i.e., temperature across several layers, water absorption, bond strength and impact resistance) of accelerated aged ETICSs.	Hygrothermal behavior (heat/rain and heat/cold cycles).	Hygrothermal cycles were performed in accordance with EAD 040083-00-0404 guideline [11] (see Table 7).	No visible surface defects (i.e., blistering, cracking) were detected in the systems during or after accelerated aging. The values of temperature measured across different layers of the ETICS were not significantly different considering the system with EPS or MW.	Norvaisiene et al. [46]

4.2. Long-Term Performance Evaluation

There are very few studies in the literature evaluating the long-term performance of an ETICS, considering outdoor natural exposure and determining the loss in performance over time (The authors considered only the studies evaluating the long-term performance of ETICS under natural aging which were specifically designed to that end (i.e., evaluating the performance over time of small-scale or large-scale ETICS). Studies reporting a field evaluation procedure of ETICS façades (e.g., evaluating the anomalies detected in ETICS façades during building service life) are not reported in this section. These studies were reviewed in Section 2). This is mainly due to the significant amount of time required to perform these tests in comparison to accelerated aging methods (see Section 4.1). However, the evaluation of the long-term performance of building materials and construction products through outdoor exposure is of paramount importance, not only to evaluate the synergistic effect of different degradation agents and mechanisms, which is not possible to entirely reproduce in laboratory conditions, but also to design and validate adequate accelerated aging procedures [101].

Griciute and Bliudzius [102] evaluated the impact of natural (long-term) and artificial (short-term) aging on the durability of an ETICS in Lithuania with the objective of designing a new accelerated aging method. The results showed similar degradation rates considering both natural and artificial aging. Interestingly, aged ETICSs obtained lower capillary water absorption when compared to the non-aged systems, which was mostly attributed to the reduction in the capillary pores in the acrylic FC after aging [103]. Similar results were obtained by Parracha et al. [17] when evaluating the durability of six commercially available ETICS specimens after two years of natural aging in urban and maritime areas in Portugal. The authors observed the highest rate of biocolonization (10 to 30% of contaminated surface) in a system finished with a lime-based mortar, which was explained by the high capillary water absorption of these specimens after aging, the formation of cracking and surface wear and the lack of a photocatalytic additive in the FC composition. As also observed by Griciute and Bliudzius [102], acrylic-based ETICSs obtained lower capillary water absorption after two years of outdoor exposure. In this study, the rendering system formulation (i.e., lime-base, acrylic-based or silicate-based) significantly affected the durability of the entire ETICS. Nevertheless, the thermal performance of the systems was only slightly affected after two years of aging, with the highest loss in thermal conductivity (6.3%) obtained for systems with mineral wool thermal insulation.

In the study of Johansson et al. [27], a test cell with ETICS façades composed of EPS thermal insulation and an organic rendering system was constructed in Lund, Sweden. The objective was to monitor the surface temperature and surface relative humidity for a period of 20 months in order to evaluate the potential of mold growth. Three theoretical indices were applied using the monitored results as inputs to evaluate biological colonization. The results showed that the ETICS presented significantly higher surface humidity when compared to façades with greater thermal inertia, thus increasing the risk of mold growth. Gonçalves et al. [30] evaluated the influence of the finishing coat color and orientation on the risk of surface condensation of two free-standing ETICS walls built in Coimbra, Portugal. The surface temperature was monitored for 24 months, and a passive infrared thermography inspection technique was also used to identify potential anomalies (i.e., blistering, cracking or water infiltration). According to the authors, the risk of biological growth is higher in ETICSs with a greater insulation capacity and finished with a white color surface, mainly due to a greater likelihood of outdoor surface condensation. On the other hand, ETICSs with a black finish obtained higher temperature amplitudes, thus increasing the risk of surface anomalies (e.g., cracking). Indeed, the color of the finishing coat had a considerable influence on the ETICS performance. Nevertheless, the authors pointed out that the optical properties of the finishing coat are currently not considered in the standard assessment methods for ETICSs, and recommended further research to evaluate the influence of solar radiation on the long-term performance of the systems. In fact, a few studies considering accelerated UV weathering tests in this regard are already available in the literature, and some of them have reported significant alterations in the surface properties and appearance of the ETICS after UV aging (see Table 8).

In another study conducted in Portugal, Barreira and de Freitas [14] evaluated the hygrothermal behavior of façades covered with ETICSs and facing the four cardinal directions (north, south, east and west). The objective was to evaluate the influence of façade orientation on surface humidification by considering both outdoor surface condensation and the effect of wind-driven rain. The results showed that the higher risk of surface condensation occurred in the west façade, followed by the east, north and south. The authors highlighted the importance of the drying kinetics in the amount of water retained on the surface, potentiating biological growth. As in the case of Johansson et al. [27] and Gonçalves et al. [30], the composition of the ETICS façades (in this case, EPS thermal insulation, cement-based base coat and resin-based finishing coat) as well as the location of the building (in this case, Porto, Portugal) were underlined as limitations of the study. Therefore, it was recommended to evaluate the influence of façade orientation on surface condensation, wind-driven rain and drying process in different locations/countries.

In summary, the long-term performance of ETICSs was evaluated in five scientific studies considering outdoor natural aging and on-site monitoring tests. These studies reported that the durability of the ETICS is significantly affected by the complete system composition (e.g., thermal insulation material or rendering system formulation). Nevertheless, these studies are mainly of local value (i.e., studies are conducted in a specific location with specific climatic conditions). Therefore, further research is needed to develop durability assessment methodologies for ETICSs using experimental and numerical data to be adaptable to different climatic zones with distinct degradation mechanisms.

4.3. Numerical Simulations

Apart from the accelerated and natural aging tests detailed in the previous sections, numerical simulations have also been used to evaluate the performance and durability of ETICSs. Table 9 summarizes the main findings of these studies. It is worth noting that some of the studies considered not only numerical simulations, but also field test campaigns or laboratory testing, which helped in validating the numerical results.

Most of the studies have focused on the hygrothermal performance of ETICSs over time, due to the greater heat losses and risk of early degradation caused by high moisture levels. The results showed that ETICS thermal performance is not significantly affected over time if the system is properly designed and well executed. However, the thermal performance and long-term durability of the ETICS can be significantly affected when the joints and window openings allow for rainwater leakage. In fact, the ETICS construction process considerably affects the long-term durability of the system [104], with the preparation of the substrate, application of the adhesive mortar and reinforcement of the rendering system pointed out as being the constructive phases that can have the most influence on the ETICS long-term performance. When there is penetration of rainwater into the system, its drying capacity toward the exterior is of fundamental importance to avoid further anomalies (e.g., biological colonization). A methodological framework to evaluate the on-site degradation factors by providing a risk priority number was proposed by Sulakatko et al. [105]. This methodology helps in the identification of the degradation factors occurring in the ETICS construction process.

Biological colonization was the theme of five numerical simulation studies on ETICSs (Table 9). This complex phenomenon is highly dependent on the presence of water (i.e., high moisture content) and is frequently identified in ETICS façades (see Section 2). This is mainly due to the undercooling phenomenon, which is quite common in ETICSs, leading to outdoor surface condensation and increasing the risk of biological growth. In fact, numerical models can be used to simulate undercooling and therefore estimate external surface condensation. However, there are a number of other factors influencing biological growth on ETICSs (e.g., nutrient availability, drying capacity and surface roughness, among others) and further research is needed on this topic.

Finally, 2 out of 15 identified studies (Table 9) predicted the service life of ETICSs by modeling the degradation of the systems or using computational models validated via on-site assessment. A reference service life of 17 and 21 years was obtained for the ETICS considering the acceptable degradation levels.

Table 9. Summary of research studies evaluating ETICS durability via numerical simulations.

Type of Study	Aim of the Study	Main Findings	Reference
Simulation	To evaluate the impact of rainwater leakage on the hygrothermal performance of ETICSs applied on wooden structures in North America and Europe.	When the detailing of joints and window openings is well performed, the results showed that there is no moisture problem in the ETICS or in the substrate, mainly because there is no rainwater leakage. On the other hand, if the water leakage cannot be avoided due to incorrect design or execution of the system, the drying process of the ETICS is fundamental for avoiding further anomalies. In this case, in order to prevent serious moisture damage, the ETICS should have a high drying capacity toward the exterior.	Künzel and Zirkelbach [106]
Simulation	To explore a quantitative risk analysis of biological growth on ETICS façades. To evaluate the most important properties contributing to ETICS defacement that should be included in a risk analysis.	The main mechanisms leading to a higher risk of biological growth in ETICSs are the following: presence of nutrients; surface RH > 100%; surface temperature between 0 °C and 40 °C; low drying capacity and presence of water on the surface due to wind-driven rain or undercooling phenomenon. The calculation of the surface relative humidity values is very complex, leading some uncertainty. There are no absolute values expressing failure, and only a strategy of scenario comparison can be considered. The stochastic nature of the input parameters led to the application of Monte Carlo simulations, using a metamodel to reduce the computation time.	Ramos et al. [107]
Simulation	To evaluate the potential of outdoor surface condensation on ETICS façades (undercooling phenomenon) using numerical models of exterior boundary conditions.	Numerical hygrothermal models are valuable tools to simulate the undercooling phenomenon and estimate outdoor surface condensation in ETICSs. The three used models provided similar results when using similar inputs of long-wave radiation. In fact, this latter characteristic is fundamental for the differences detected in the calculated values. This is because the undercooling phenomenon is caused by long-wave radiation exchange among the external surface and surroundings, occurring mostly during the night.	Barreira et al. [14]
Simulation and field test campaign	To evaluate the influence of nearby obstacles in the outdoor surface condensation of ETICSs.	The presence of obstacles significantly affected surface condensation on ETICS façades. Obstacles are a source of long-wave radiation, thus contributing to an increase in the percentage of radiation incident on the ETICS surfaces and reducing surface condensation. A new model was proposed to simulate the impact of nearby obstacles on ETICS façades, which can be used in combination with any hygrothermal model. The model determines the increase in long-wave radiation caused by the presence of obstacles, considering its geometry and emissivity.	Barreira and de Freitas [108]
Simulation	To evaluate the most critical parameters involved in the hygrothermal behavior of ETICSs.	Relative humidity, external surface temperature, atmospheric radiation and the emissivity of the rendering system were identified as the parameters that influence outdoor surface condensation the most. Additionally, wind-driven rain is mostly dependent on wind velocity and orientation, horizontal rain and the building's height, whereas the drying capacity is affected by the incident solar radiation and short-wave absorbance.	Barreira and de Freitas [12]

Table 9. *Cont.*

Type of Study	Aim of the Study	Main Findings	Reference
Simulation	To evaluate the durability of ETICS considering two numerical models (i.e., hygrothermal model and thermo-mechanical finite element method model).	Thermal shock events were lower in ETICSs with MW thermal insulation when compared to EPS-based ETICSs. This difference was attributed to the greater vapor permeability of MW compared to EPS, which allows for a greater moisture content percentage in the base coat of MW ETICSs. For this reason, during the morning, the external surface of MW ETICSs obtained a lower temperature, if compared to the external surface of systems with EPS. The risk of thermal shocks is considerably lower for solar absorbances smaller than 0.6. The risk of freeze–thaw is also remarkably lower considering solar absorbances higher than 0.3.	Daniotti et al. [109]
Simulation and laboratory testing	To evaluate algae growth in ETICSs using numerical simulation and laboratory accelerated aging tests.	An imaging pulse-amplitude modulation fluorometer was efficient in measuring algae resistance during the accelerated aging tests. The results confirmed the effectiveness of the biocide and showed that mineral rendering systems present higher algae resistance than organic rendering systems. The results obtained using accelerated tests and numerical simulations were significantly different, most probably due to the simplifications assumed in the numerical analysis (e.g., assuming the render as a uniform structure).	Werder et al. [110]
Simulation and field test campaign	To model the degradation and to predict the service life of ETICSs considering the degradation mechanisms, the type of cladding and several characteristics of the system.	Exposure to damp is the characteristic that most affects the long-term durability of ETICSs. Based on a mathematical formula, a reference service life of 17 years was obtained for the ETICS, considering a maximum level of 30% degradation severity. The results showed that ETICS façades should be inspected every 10 years to evaluate the degradation condition and to plan maintenance or repair actions.	Ximenes et al. [37]
Simulation	To evaluate the energy efficiency and the moisture performance of EIFS walls in the USA.	The inclusion of a vapor retarder on the inside of the EIFS walls did not significantly affect the energy efficiency of the systems. The vapor retarder increased the sheathing moisture content of the walls, but only by about 2 to 3% of mass. Therefore, the durability of the ETICS was not affected by this moisture increase. On the other hand, water leakage within the system significantly affects its durability. Therefore, the EIFS should be correctly designed and executed to avoid water leakage. A vapor retarder should also be used.	Desjarlais and Johnston [111]
Simulation and field test campaign	To evaluate the impact of the construction process on the degradation of ETICSs.	A technical severity evaluation model was developed to quantify the impact of technical deviations occurring during the execution of an ETICS on its performance. The results showed that the ETICS construction process significantly affected the mechanical performance, long-term durability and weather protection of the system. The preparation of the substrate, application of the adhesive mortar and reinforcement of the rendering system were the activities realized to influence the overall performance of the ETICS the most during the construction process.	Sulakatko and Vogdt [112]

Table 9. *Cont.*

Type of Study	Aim of the Study	Main Findings	Reference
Simulation and field test campaign	To develop a merged model combining four factors (technical severity, financial impact, occurrence and detectability) to evaluate the technical–economic relevance of the ETICS construction process.	A technical–economic severity evaluation model was developed to quantify the technical significance of on-site degradation factors, also considering the repair costs in the future. The technical severity was evaluated by 12 experts and the data were validated using Friedman's test, whereas the occurrence ratio, the detectability and the latency period were foreseen by five experts and validated using the Delphi technique. The results highlighted the relevance of the substrate preparation and application of the adhesive and/or base coat with reinforcement mesh. Activities related to the installation of the insulation plates and application of the finishing coat are less relevant.	Sulakatko [113]
Simulation and field test campaign	To predict the service life of ETICSs considering two computational methods: artificial neural networks and fuzzy logic systems.	A reference service life of 21 years was obtained for the ETICS considering the computational models and a sample of 378 façades located in Portugal.	Tavares et al. [114]
Simulation and laboratory testing	To evaluate the hygrothermal behavior of ETICSs.	The adhesive mortar was identified as a key feature due to the significant moisture transfer to the wall during its application. It was not possible to reach hygrothermal equilibrium after 160 days of favorable drying conditions in the laboratory. The numerical results were in agreement with the experimental results.	Bendouma et al. [115]
Simulation	To evaluate the deformation and to predict the failure of the bonding mortar in ETICSs.	The higher risk of mortar deformation occurred during summer, followed by winter, autumn and spring. Likewise, the greater risk of mortar deformation was due to wind pressure, followed by temperature and relative humidity. The maximum stress was distributed at the edges of the mortar considering the partly stick method.	Zhu et al. [116]
Simulation and laboratory testing	To evaluate the loss in performance of an ETICS and its influence on the energy consumption for the heating of buildings.	There is no significant loss in performance of ETICSs over time. The thermal performance is only slightly affected after aging. After aging (~8 years), an increase in the energy consumption for the heating of the buildings of only 2% was observed, when compared to the reference unaged ETICS.	D'Agostino et al. [117]

5. Conclusions

This paper has presented a literature review related to the durability of external thermal insulation composite systems (ETICSs), defining the required bases for their sustainable and efficient use. The aim of the study was to identify the most common anomalies detected with ETICS façades and their causes, to overview the performance of ETICSs, their performance parameters and requirements and to identify the most significant degradation mechanisms and the related failure modes. Based on the conducted review, the following conclusions can be drawn:

(1) ETICS application is a key aspect in the performance and durability of the system, especially regarding the execution of "singular points" of the façade (e.g., corners and window openings). The literature shows that most of the anomalies detected in ETICSs can be prevented with proper design, execution and appropriate assembly of the system components. Particular attention should be given to the execution of tail-

ends and protection elements, the preparation of the substrate, the alignment of the thermal insulation boards, the application of the adhesive mortar, the reinforcement of the rendering system and flashing execution.

(2) The use of the ETICS presents several challenges, mostly considering its fire behavior, water resistance, mechanical performance and thermal resistance, which need to be carefully investigated. The existence of several commercially available ETICSs with different compositions (i.e., thermal insulation, base coat and finishing coat) leads to different performances, reinforcing the importance of consistent knowledge on the durability of these systems. From the reported studies, it can be concluded that the greatest drawbacks lie in dealing with enhancing water resistance and improving the mechanical and thermal performance. Some of the reviewed studies also presented strategies toward the optimization of the fire performance of ETICS façades, especially in the case of EPS-based ETICSs. Therefore, all ETICSs must have CE marking to be placed in the EU market and be in accordance with the EAD 040083-00-0404 requirements, thus guaranteeing suitable quality and adequate performance.

(3) ETICS durability has been assessed through accelerated aging tests, long-term field exposure, on-site monitoring and numerical simulations, identifying the most significant degradation agents and the related failure modes. Most of the accelerated aging tests have considered hygrothermal behavior and UV performance for the durability assessment of ETICSs; some others have proposed a new accelerated aging method with further degradation agents (e.g., pollutants or biological colonization). Some of the studies suggested that the accelerated aging tests significantly affected the water resistance, thermal performance and appearance of the ETICS. Other studies reported no significant performance decay or surface defects after aging. Nevertheless, most studies identified the difficulty of reproducing the synergistic effect of several degradation agents on a lab scale and recommended further developments including long-term performance evaluation.

(4) The five scientific studies evaluating the long-term performance of ETICSs concluded that the durability of the system is significantly affected by the complete system composition (i.e., thermal insulation material or rendering system formulation). However, these studies are mainly of local value (i.e., studies are conducted in a specific location with specific climatic conditions). Moreover, most of the studies using numerical simulations focused on the hygrothermal performance of ETICSs over time, due to the greater heat losses and risk of early degradation caused by high moisture levels. It was concluded that thermal performance is not significantly affected over time if the system is properly designed and well executed.

Further research is needed to evaluate the possible synergistic effect of several degradation agents and mechanisms toward a development in optimized durability assessment methods for ETICSs. To obtain a reliable dataset that can be used in risk assessment analysis, the long-term performance of the systems in different climates needs to be further evaluated and systematized.

Author Contributions: Conceptualization, J.L.P., R.V., I.F.-C. and L.N.; methodology, J.L.P., R.V., I.F.-C. and L.N.; investigation, J.L.P.; writing–original draft preparation, J.L.P.; writing–review and editing, J.L.P., R.V., I.F.-C. and L.N.; visualization, J.L.P.; supervision, R.V., I.F.-C. and L.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Portuguese Foundation for Science and Technology (FCT) through research project WGB_Shield—Shielding building façades for cities' revitalization, the project 'Triple resistance to water, graffiti and biocolonization of external thermal insulation systems' (PTDC/ECI-EGC/30681/2017) and Ph.D. scholarship 2020.05180.BD (J. L. Parracha).

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge the Portuguese Foundation for Science and Technology (FCT) for funding the research project WGB_Shield—Shielding building façades for cities' revitalization, the project 'Triple resistance to water, graffiti and biocolonization of external thermal insulation system' (PTDC/ECI-EGC/30681/2017) and the research unit CERIS (UIDB/04625/2020). The first author acknowledges FCT for the Ph.D. scholarship 2020.05180.BD. The authors also acknowledge João Gomes Ferreira (IST-UL, Lisbon, Portugal) for the opportunity to analyze the case study.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript or in the decision to publish the results.

References

1. International Energy Agency and Global Alliance for Buildings and Construction. *2019 Global Status Report for Buildings and Construction*; International Energy Agency: Paris, France, 2019.
2. Laaroussi, Y.; Bahrar, M.; Zavrl, E.; El Mankibi, M.; Stritih, U. New qualitative approach based on data analysis of European building stock and retrofit market. *Sustain. Cities Soc.* **2020**, *63*, 102452. [CrossRef]
3. Iralde, N.S.I.; Pascual, J.; Salom, J. Energy retrofit of residential building clusters. A literature review of crossover recommended measures, policies instruments and allocated funds in Spain. *Energy Build.* **2021**, *252*, 111409. [CrossRef]
4. Directive EU 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on energy performance of buildings and Directive 2012/27/EU on energy efficiency. *Off. J. Eur. Union* **2018**, *156*, 75–91.
5. Kvande, T.; Bakken, N.; Bergheim, E.; Thue, J.V. Durability of ETICS with rendering in Norway—Experimental and field investigations. *Buildings* **2018**, *8*, 93. [CrossRef]
6. Luján, S.V.; Arrebola, C.V.; Sánchez, A.R.; Benito, P.A.; Cortina, M.G. Experimental comparative study of the thermal performance of the façade of a building refurbished using ETICS, and quantification of improvements. *Sustain. Cities Soc.* **2019**, *51*, 101713. [CrossRef]
7. Parracha, J.; Borsoi, G.; Flores-Colen, I.; Veiga, R.; Nunes, L.; Dionísio, A.; Gomes, M.G.; Faria, P. Performance parameters of ETICS: Correlating water resistance, bio-susceptibility and surface properties. *Constr. Build. Mater.* **2021**, *272*, 121956. [CrossRef]
8. Pasker, R. The European ETICS Market—Facts & Figures. 2015. Available online: https://www.ea-etics.eu/files/dokumente-eae/4_ETICS_Forum/04_2015-10-10_ETICS_Forum_2015_European_ETICS_market_Pasker_02.pdf (accessed on 1 March 2022).
9. Malanho, S.; Veiga, M.D.R. Bond strength between layers of ETICS—Influence of the characteristics of mortars and insulation materials. *J. Build. Eng.* **2020**, *28*, 101021. [CrossRef]
10. Parracha, J.L.; Borsoi, G.; Veiga, R.; Flores-Colen, I.; Nunes, L.; Garcia, A.R.; Ilharco, L.M.; Dionísio, A.; Faria, P. Effects of hygrothermal, UV and SO2 accelerated ageing on the durability of ETICS in urban environments. *Build. Environ.* **2021**, *204*, 10815. [CrossRef]
11. *EAD 040083-00-0404*; External Thermal Insulation Composite Systems with Rendering. Guideline for European Technical Approval. EOTA (European Organisation for Technical Approval): Brussels, Belgium, 2020.
12. Barreira, E.; de Freitas, V.P. External Thermal Insulation Composite Systems: Critical Parameters for Surface Hygrothermal Behaviour. *Adv. Mater. Sci. Eng.* **2014**, *2014*, 650752. [CrossRef]
13. Amaro, B.; Saraiva, D.; de Brito, J.; Flores-Colen, I. Inspection and diagnosis system of ETICS on walls. *Constr. Build. Mater.* **2013**, *47*, 1257–1267. [CrossRef]
14. Barreira, E.; de Freitas, V.P. Experimental study of the hygrothermal behaviour of External Thermal Insulation Composite Systems (ETICS). *Build. Environ.* **2013**, *63*, 31–39. [CrossRef]
15. Simona, P.L.; Spiru, P.; Ion, I.V. Increasing the energy efficiency of buildings by thermal insulation. *Energy Procedia* **2017**, *128*, 393–399. [CrossRef]
16. Amaro, B.; Saraiva, D.; de Brito, J.; Flores-Colen, I. Statistical survey of the pathology, diagnosis and rehabilitation of etics in walls. *J. Civ. Eng. Manag.* **2014**, *20*, 511–526. [CrossRef]
17. Parracha, J.; Borsoi, G.; Veiga, R.; Flores-Colen, I.; Nunes, L.; Viegas, C.; Moreira, L.; Dionísio, A.; Gomes, M.G.; Faria, P. Durability assessment of external thermal insulation composite systems in urban and maritime environments. *Sci. Total Environ.* **2022**, *849*, 157828. [CrossRef] [PubMed]
18. Maia, J.; Ramos, N.M.M.; Veiga, R. Assessment of test methods for the durability of thermal mortars exposure to freezing. *Mater. Struct.* **2019**, *52*, 112. [CrossRef]
19. Parracha, J.L.; Cortay, A.; Borsoi, G.; Veiga, R.; Nunes, L. Evaluation of ETICS characteristics that affect surface mould development. In Proceedings of the DBMC 2020—XV International Conference on Durability of Building Materials and Components, Barcelona, Spain, 20–23 October 2020. 8p. [CrossRef]
20. *ETAG 004*; External Thermal Insulation Composite Systems with Rendering. Guideline for European Technical Approval. EOTA (European Organisation for Technical Approval): Brussels, Belgium, 2000.
21. Michalak, J. External Thermal Insulation Composite Systems (ETICS) from industry and academia perspective. *Sustainability* **2021**, *13*, 13705. [CrossRef]

22. Thomas, R.G. EIFS troubleshooting. Part II. In *Construction Dimensions*; CMD Associates, Inc.: Vashon Island, WA, USA, 1993; pp. 12–16. Available online: https://www.awci.org/cd/pdfs/9302_b.pdf (accessed on 5 February 2023).
23. Künzel, H.; Künzel, H.M.; Sedlbauer, K. Long-term performance of External Thermal Insulation Composite Systems (ETICS). *Architectura* **2006**, *5*, 11–24.
24. Lstiburek, J. *Building Science Digest 146 EIFS—Problems and Solutions*; Building Science.com Corporation: Westford, MA, USA, 2007.
25. Daniotti, B.; Paolini, R. Evolution of degradation and decay in performance of ETICS. In Proceedings of the 11DBMC International Conference on Durability of Building Materials and Components, T42, Istanbul, Turkey, 11–14 May 2008; pp. 11–14. Available online: https://www.irbnet.de/daten/iconda/CIB13273.pdf (accessed on 5 February 2023).
26. Lengsfeld, K.; Krus, M.; Künzel, H.; Künzel, H. *Assessing the Long-Term Performance of Applied External Thermal Insulation Composite Systems (ETICS)*; IBP Report 42; Fraunhofer Institute for Building Physics: Stuttgart, Germany, 2015.
27. Johansson, S.; Wadsö, L.; Sandin, K. Estimation of mould growth levels on rendered façades based on surface relative humidity and surface temperature measurements. *Build. Environ.* **2010**, *45*, 1153–1160. [CrossRef]
28. D'Orazio, M.; Cursio, G.; Graziani, L.; Aquilanti, L.; Osimani, A.; Clementi, F.; Yéprémian, C.; Lariccia, V.; Amoroso, S. Effects of water absorption and surface roughness on the bioreceptivity of ETICS compared to clay bricks. *Build. Environ.* **2014**, *77*, 20–28. [CrossRef]
29. Parracha, J.L.; Nunes, L.; Gonçalves, F.; Pereira, J.; Borsoi, G.; Flores-Colen, I.; Gomes, M.G.; Deus, R.; Veiga, R. Mould growth on ETICS: Theoretical indices vs. in situ observations. In Proceedings of the CEES 2021—International Conference—Construction, Energy, Environment and Sustainability, Coimbra, Portugal, 12–15 October 2021; 6p.
30. Gonçalves, M.; Simões, N.; Serra, C.; Almeida, J.; Flores-Colen, I.; de Castro, N.V.; Duarte, L. Onsite monitoring of ETICS comparing different exposure conditions and insulation materials. *J. Build. Eng.* **2021**, *42*, 103067. [CrossRef]
31. Klamer, M.; Morsing, E.; Husemoen, T. Fungal growth on different insulation materials exposed to different moisture regimes. *Int. Biodeterior. Biodegrad.* **2004**, *54*, 277–282. [CrossRef]
32. Hoang, C.P.; Kinney, K.A.; Corsi, R.L.; Szaniszlo, P.J. Resistance of green building materials to fungal growth. *Int. Biodeterior. Biodegrad.* **2010**, *64*, 104–113. [CrossRef]
33. Kukk, V.; Kers, J.; Kalamees, T. Field measurements and simulation of an massive wood panel envelope with ETICS. *Wood Mater. Sci. Eng.* **2021**, *16*, 27–34. [CrossRef]
34. Palumbo, M.; Lacasta, A.; Navarro, A.; Giraldo, M.; Lesar, B. Improvement of fire reaction and mould growth resistance of a new bio-based thermal insulation material. *Constr. Build. Mater.* **2017**, *139*, 531–539. [CrossRef]
35. Krueger, N.; Hofbauer, W.; Krus, M.; Fitz, C.; Mayer, F.; Breuer, K. Effectiveness and durability of biocides in building coatings. In Proceedings of the XII DBMC International Conference on Durability of Building Materials and Components, Porto, Portugal, 12–15 April 2011; 7p.
36. de Souza, A.; Gaylarde, C.C. Biodeterioration of varnished wood with and without biocide: Implications for standard test methods. *Int. Biodeterior. Biodegrad.* **2002**, *49*, 21–25. [CrossRef]
37. Ximenes, S.; de Brito, J.; Gaspar, P.L.; Silva, A. Modelling the degradation and service life of ETICS in external walls. *Mater. Struct.* **2015**, *48*, 2235–2249. [CrossRef]
38. Madureira, S.; Flores-Colen, I.; de Brito, J.; Pereira, C. Maintenance planning of facades in current buildings. *Constr. Build. Mater.* **2017**, *147*, 790–802. [CrossRef]
39. Pereira, C.; de Brito, J.; Silvestre, J.D. Contribution of humidity to the degradation of façade claddings in current buildings. *Eng. Fail. Anal.* **2018**, *90*, 103–115. [CrossRef]
40. Asphaug, S.K.; Time, B.; Kvande, T. Moisture accumulation in building façades exposed to accelerated artificial climatic ageing—A complementary analysis to NT build 495. *Buildings* **2021**, *11*, 568. [CrossRef]
41. Brown, W.; Ullett, J.; Karagiozis, A.; Tonyan, T. Barrier EIFS clad walls: Results from a moisture engineering study. *J. Therm. Insul. Build. Envel.* **1997**, *20*, 206–226. [CrossRef]
42. Hens, H.; Carmeliet, J. Performance prediction for masonry walls with EIFS using calculation procedures and laboratory testing. *J. Therm. Envel. Build. Sci.* **2002**, *25*, 167–187. [CrossRef]
43. Šadauskienė, J.; Stankevičius, V.; Bliūdžius, R.; Gailius, A. The impact of the exterior painted thin-layer render's water vapour and liquid water permeability on the moisture state of the wall insulating system. *Constr. Build. Mater.* **2009**, *23*, 2788–2794. [CrossRef]
44. Ślusarek, J.; Orlik-Kożdoń, B.; Bochen, J.; Muzyczuk, T. Impact of the imperfection of thermal insulation on structural changes of thin-layer façade claddings in ETICS. *J. Build. Eng.* **2020**, *32*, 101487. [CrossRef]
45. Lisø, K.R.; Kvande, T.; Thue, J.V. High-performance weather-protective flashings. *Build. Res. Inf.* **2005**, *33*, 41–54. [CrossRef]
46. Norvaišienė, R.; Buhagiar, V.; Burlingis, A.; Miškinis, K. Investigation of mechanical resistance of external thermal insulation composite systems (ETICS). *J. Build. Eng.* **2020**, *32*, 101682. [CrossRef]
47. Francke, B.; Zamorowska, R. Resistance of external thermal insulation composite systems with rendering (ETICS) to hail. *Materials* **2020**, *13*, 2452. [CrossRef]
48. Steinbauer, V.; Kaufmann, J.; Zurbriggen, R.; Bühler, T.; Herwegh, M. Tracing hail stone impact on external thermal insulation composite systems (ETICS)—An evaluation of standard admission impact tests by means of high-speed-camera recordings. *Int. J. Impact Eng.* **2017**, *109*, 354–365. [CrossRef]
49. Hidalgo, J.P.; Welch, S.; Torero, J.L. Performance criteria for the fire safe use of thermal insulation in buildings. *Constr. Build. Mater.* **2015**, *100*, 285–297. [CrossRef]

50. *EN 13501-1*; Fire Classification of Construction Products and Building Elements: Part 1—Classification Using Test Data from Reaction to Fire Tests. European Committee for Standardization (CEN): Brussels, Belgium, 2018.
51. *EN 16733*; Reaction to Fire Tests for Building Products—Determination of a Building Products Propensity to Undergo Continuous Smouldering. European Committee for Standardization (CEN): Brussels, Belgium, 2016.
52. *ISO 7892*; Vertical Building Elements—Impact Resistance Tests—Impact Bodies and General Test Procedures. ISO: Geneva, Switzerland, 1988.
53. *ISO 10140-1*; Acoustics—Laboratory Measurement of Sound Insulation of Building Elements—Part 1: Application Rules for Specific Products. ISO: Geneva, Switzerland, 2016.
54. *ISO 10140-2*; Acoustics—Laboratory Measurement of Sound Insulation of Building Elements—Part 2: Measurement of Airborne Sound Insulation. ISO: Geneva, Switzerland, 2010.
55. *ISO 10140-5*; Laboratory Measurement of Sound Insulation of Building Elements—Part 5: Requirements for Test Facilities and Equipment. ISO: Geneva, Switzerland, 2010.
56. *ISO 10456*; Building Materials and Products—Hygrothermal Properties—Tabulated Design Values and Procedures for Determining Declared and Designed Thermal Values. ISO: Geneva, Switzerland, 2007.
57. Schiavoni, S.; D'Alessandro, F.; Bianchi, F.; Asdrubali, F. Insulation materials for the building sector: A review and comparative analysis. *Renew. Sustain. Energy Rev.* **2016**, *62*, 988–1011. [CrossRef]
58. Zhou, B.; Yoshioka, H.; Noguchi, T.; Wang, K.; Huang, X. Fire performance of EPS ETICS facade: Effect of test scale and masonry cover. *Fire Technol.* **2021**, *59*, 95–116. [CrossRef]
59. Zhou, B.; Yoshioka, H.; Noguchi, T.; Ando, T. Experimental study of expanded polystyrene (EPS) External Thermal Insulation Composite Systems (ETICS) masonery façade reaction-to-fire performance. *Therm. Sci. Eng. Prog.* **2018**, *8*, 83–92. [CrossRef]
60. Xin, H.; Zhaopeng, N.; Lei, P.; Ping, Z. Experimental study of fire barriers preventing vertical fire spread in ETICs. In Proceedings of the MATEC Web of Conferences, 1st International Seminar for Fire Safety of Facades, Paris, France, 14–15 November 2013; Volume 9, p. 04003.
61. Niziurska, M.; Wieczorek, M.; Borkowicz, K. Fire safety of External Thermal Insulation Systems (ETICS) in the aspect of sustainable use of natural resources. *Sustainability* **2022**, *14*, 1224. [CrossRef]
62. Uygunoğlu, T.; Özgüven, S.; Çalış, M. Effect of plaster thickness on performance of external thermal insulation cladding systems (ETICS) in buildings. *Constr. Build. Mater.* **2016**, *122*, 496–504. [CrossRef]
63. Rossi, M.; Camino, G.; Luda, M. Characterisation of smoke in expanded polystyrene combustion. *Polym. Degrad. Stab.* **2001**, *74*, 507–512. [CrossRef]
64. Hamdani-Devarennes, S.; El Hage, R.; Dumazert, L.; Sonnier, R.; Ferry, L.; Lopez-Cuesta, J.-M.; Bert, C. Water-based flame retardant coating using nano-boehmite for expanded polystyrene (EPS) foam. *Prog. Org. Coat.* **2016**, *99*, 32–46. [CrossRef]
65. *BS 8414-1*; Fire Performance of External Cladding Systems—Part 1: Test Methods for Non-Loadbearing External Cladding Systems Fixed to, and Supported by, a Masonry Substrate. British Standards Institution (BSI): Loughborough, UK, 2020.
66. *EN 822*; Thermal Insulating Products for Building Applications—Determination of Length and Width. European Committee for Standardization (CEN): Brussels, Belgium, 2013.
67. *EN 823*; Thermal Insulating Products for Building Applications—Determination of Thickness. European Committee for Standardization (CEN): Brussels, Belgium, 2013.
68. *EN 824*; Thermal Insulating Products for Building Applications—Determination of Squareness. European Committee for Standardization (CEN): Brussels, Belgium, 2013.
69. *EN 825*; Thermal Insulating Products for Building Applications—Determination of Flatness. European Committee for Standardization (CEN): Brussels, Belgium, 2013.
70. *EN 1602*; Thermal Insulating Products for Building Applications—Determination of the Apparent Density. European Committee for Standardization (CEN): Brussels, Belgium, 2013.
71. *EN 1609*; Thermal Insulating Products for Building Applications—Determination of Short Term Water Absorption by Partial Immersion. European Committee for Standardization (CEN): Brussels, Belgium, 2013.
72. *EN 12086*; Thermal Insulating Products for Building Applications—Determination of Water Vapour Transmission Properties. European Committee for Standardization (CEN): Brussels, Belgium, 2013.
73. *EN 1607*; Thermal Insulating Products for Building Applications—Determination of Tensile Strength Perpendicular to the Faces. European Committee for Standardization (CEN): Brussels, Belgium, 2013.
74. *EN 12090*; Thermal Insulating Products for Building Applications—Determination of Shear Behaviour. European Committee for Standardization (CEN): Brussels, Belgium, 2013.
75. *EN 826*; Thermal Insulating Products for Building Applications—Determination of Compression Behaviour. European Committee for Standardization (CEN): Brussels, Belgium, 2013.
76. *EN 12667*; Thermal Performance of Building Materials and Products—Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods—Products of High and Medium Thermal Resistance. European Committee for Standardization (CEN): Brussels, Belgium, 2001.
77. *EN 12664*; Thermal Performance of Building Materials and Products—Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods—Dry and Moist Products of Medium and Low Thermal Resistance. European Committee for Standardization (CEN): Brussels, Belgium, 2001.

78. *EN 29052-1*; Acoustics—Determination of Dynamic Stiffness—Part 1: Material Used under Floating Floors in Dwellings. European Committee for Standardization (CEN): Brussels, Belgium, 1992.
79. *EN 1604*; Thermal Insulating Products for Building Applications—Determination of Dimensional Stability under Specified Temperature and Humidity Conditions. European Committee for Standardization (CEN): Brussels, Belgium, 2013.
80. *ISO 7783*; Paints and Varnishes—Determination of Water-Vapour Transmission Properties—Cup Method. ISO: Geneva, Switzerland, 2011.
81. *EAD 330196-01-0604*; Plastic Anchors Made of Virgin or Non-Virgin Material for Fixing of External Thermal Insulation Composite Systems with Rendering. EOTA (European Organisation for Technical Approval): Brussels, Belgium, 2016.
82. Griciutė, G.; Bliūdžius, R.; Norvaišienė, R. The durability test method for External Thermal Insulation Composite System (ETICS) used in cold and wet climate countries. *J. Sustain. Arch. Civ. Eng.* **2013**, *1*, 50–56. [CrossRef]
83. Dirkx, I.; Grégoire, Y. Evaluation of the durability of ETICS: Additional requirements in Belgium. In Proceedings of the 4th APFAC Congress, Coimbra, Portugal, 5–7 April 2012; 12p.
84. Dirkx, I.; Grégoire, Y. Evaluation of the resistance to algae growth of ETICS. In Proceedings of the 4th APFAC Congress, Coimbra, Portugal, 5–7 April 2012; 12p.
85. Ramanauskas, J.; Stankevičius, V. Weather durability of external wall thermal insulation system with thin-layer plaster finish. *Statyba* **1998**, *4*, 206–213. [CrossRef]
86. Mandilaras, I.; Atsonios, I.; Zannis, G.; Founti, M. Thermal performance of a building envelope incorporating ETICS with vacuum insulation panels and EPS. *Energy Build.* **2014**, *85*, 654–665. [CrossRef]
87. Posani, M.; Veiga, M.D.R.; de Freitas, V.P. Towards resilience and sustainability for historic buildings: A review of envelope retrofit possibilities and a discussion on hygric compatibility of thermal insulations. *Int. J. Arch. Herit.* **2021**, *15*, 807–823. [CrossRef]
88. Norvaišienė, R.; Krause, P.; Buhagiar, V.; Burlingis, A. Resistance of ETICS with fire barriers to cyclic hygrothermal impact. *Sustainability* **2021**, *13*, 9220. [CrossRef]
89. Gonçalves, M.; Simões, N.; Serra, C.; Flores-Colen, I. A review of the challenges posed by the use of vacuum panels in external insulation finishing systems. *Appl. Energy* **2020**, *257*, 114028. [CrossRef]
90. D'Orazio, M.; Stipa, P.; Sabbatini, S.; Maracchini, G. Experimental investigation on the durability of a novel lightweight prefabricated reinforced-EPS based construction system. *Constr. Build. Mater.* **2020**, *252*, 119134. [CrossRef]
91. Lewry, A.; Crewdson, L. Approaches to testing the durability of materials used in construction and maintenance of buildings. *Constr. Build. Mater.* **1994**, *8*, 211–222. [CrossRef]
92. *ISO 15686-1*; Buildings and Constructed Assets—Service Life Planning—Part 1: General Principles and Framework. ISO: Geneva, Switzerland, 2011.
93. Landolfi, R.; Nicolella, M. Durability assessment of ETICS: Comparative evaluation of different insulating materials. *Sustainability* **2022**, *14*, 980. [CrossRef]
94. *NT Build 495*; Nordtest Method. Building Materials and Components in the Vertical Position: Exposure to Accelerated Climatic Strains. Nordic Council of Ministers: Denmark, Finland, 2000.
95. Roncon, R.; Borsoi, G.; Parracha, J.L.; Flores-Colen, I.; Veiga, R.; Nunes, L. Impact of water-repellent products on the moisture transport properties and mould susceptibility of External Thermal Insulation Composite Systems. *Coatings* **2021**, *11*, 554. [CrossRef]
96. *EN 1015-21*; Methods of Test for Mortar for Masonry—Part 21—Determination of the Compatibility of One-Coat Rendering Mortars with Substrates. European Committee for Standardization (CEN): Brussels, Belgium, 2002.
97. Daniotti, B.; Paolini, R.; Cecconi, F.R. Effects of ageing and moisture on thermal performance of ETICS cladding. In *Durability of Building Materials and Components, Building Pathology and Rehabilitation*; de Freitas, V.P., Delgado, J.M.P.Q., Eds.; Springer: Berlin/Heidelberg, Germany, 2013; pp. 127–171. [CrossRef]
98. Parracha, J.L.; Borsoi, G.; Flores-Colen, I.; Veiga, R.; Nunes, L. Impact of natural and artificial ageing on the properties of multilayer external wall thermal insulation systems. *Constr. Build. Mater.* **2022**, *317*, 125834. [CrossRef]
99. Yuan, K.; Xiong, H.; Wen, M.; Xu, J. Visualization of localized deformation of external thermal insulation composite systems during aging. *Appl. Therm. Eng.* **2022**, *206*, 118108. [CrossRef]
100. Bochen, J.; Gil, S. Properties of pore structure of thin-layer external plasters under ageing in simulated environment. *Constr. Build. Mater.* **2009**, *23*, 2958–2963. [CrossRef]
101. Jelle, B.P. Accelerated climate ageing of building materials, components and structures in the laboratory. *J. Mater. Sci.* **2012**, *47*, 6475–6496. [CrossRef]
102. Griciute, G.; Bliudzius, R. Study on the microstructure and water absorption rate changes of exterior thin-layer polymer renders during natural and artificial ageing. *Mater. Sci.* **2015**, *21*, 149–154. [CrossRef]
103. Xiong, H.; Yuan, K.; Xu, J.; Wen, M. Pore structure, adsorption, and water absorption of expanded perlite mortar in external thermal insulation composite system during aging. *Cem. Concr. Compos.* **2021**, *116*, 103900. [CrossRef]
104. Sulakatko, V.; Lill, I.; Liisma, E. Analysis of on-site construction processes for effective External Thermal Insulation Composite Systems (ETICS) installation. *Procedia Econ. Financ.* **2015**, *21*, 297–305. [CrossRef]
105. Sulakatko, V.; Lill, I.; Witt, E. Methodological framework to assess the significance of External Thermal Insulation Composite System (ETICS) on-site activities. *Energy Procedia* **2016**, *96*, 446–454. [CrossRef]

106. Künzel, H.; Zirkelbach, D. Influence of rain water leakage on the hygrothermal performance of exterior insulation systems. In Proceedings of the 8th Nordic Symposium of Building Physics, Session M3B, Copenhagen, Denmark, 16–18 June 2008; pp. 253–260.
107. Ramos, N.M.M.; Barreira, E.; Simões, M.L.; Delgado, J.M.P.Q. Probabilistic risk assessment applied to biological growth on external surfaces with ETICS. In Proceedings of the 13th Conference of International Building Performance Simulation Association, Chambéry, France, 26–28 August 2013; pp. 2884–2889.
108. Barreira, E.; De Freitas, V.P. The effect of nearby obstacles in surface condensations on external thermal insulation composite systems: Experimental and numerical study. *J. Build. Phys.* **2014**, *37*, 269–295. [CrossRef]
109. Daniotti, B.; Cecconi, F.R.; Paolini, R.; Cocchetti, G.; Galliano, R.; Cornaggia, A. Multi-physics modelling for durability evaluation of ETICS. In Proceedings of the XIII International Conference on Durability of Building Materials and Components, São Paulo, Brazil, 2–5 September 2014; pp. 514–521.
110. Von Werder, J.; Venzmer, H.; Černý, R. Application of fluorometric and numerical analysis for assessing the algal resistance of external thermal insulation composite systems. *J. Build. Phys.* **2015**, *38*, 290–316. [CrossRef]
111. Desjarlais, A.; Johnston, D. Energy and moisture impact on EIFS walls in the USA. In Proceedings of the ASTM Symposium on EIFs, New Orleans, LA, USA, 5–6 October 2016.
112. Sulakatko, V.; Vogdt, F.U. Construction process technical impact factors on degradation of the External Thermal Insulation Composite System. *Sustainability* **2018**, *10*, 3900. [CrossRef]
113. Sulakatko, V. Modelling the technical–economic relevance of the ETICS construction process. *Buildings* **2018**, *8*, 155. [CrossRef]
114. Tavares, J.; Silva, A.; de Brito, J. Computational models applied to the service life prediction of External Thermal Insulation Composite Systems (ETICS). *J. Build. Eng.* **2020**, *27*, 100944. [CrossRef]
115. Bendouma, M.; Colinart, T.; Glouannec, P.; Noël, H. Laboratory study on hygrothermal behavior of three external thermal insulation systems. *Energy Build.* **2020**, *210*, 109742. [CrossRef]
116. Zhu, K.; Jiang, W.; Yu, L.; Guo, P.; Yang, Z. Deformation analysis and failure prediction of bonding mortar in external thermal insulation cladding system (ETICS) by coupled multi physical fields method. *Constr. Build. Mater.* **2021**, *278*, 122017. [CrossRef]
117. D'agostino, D.; Landolfi, R.; Nicolella, M.; Minichiello, F. Experimental study on the performance decay of thermal insulation and related influence on heating energy consumption in buildings. *Sustainability* **2022**, *14*, 2947. [CrossRef]