External Thermal Insulation Composite Systems ETICS–
Executive summary

Forschungsinstitut für Wärmeschutz e.V. München

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This expert opinion was commissioned by:

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1 Introduction

The literature survey highlighted several gaps, shortcomings and open questions related to static and dynamic loads that have been assessed through sensitivity analysis, multi-level simulations and analytic models.

This document summarises the outputs, gaps and open questions that came up from the literature survey and the results of the numerical simulations.

1.1 Documents

The contents of the following report are based on the outputs of the literature survey described in detail in the State of Art report (Cucchi, C.; Sprengard, C.; Sieber, S.; Karrer, C. (2019): External Thermal Insulation Composite Systems ETICS – Basic literature survey and state of the art on materials, models and building physics) mentioned hereafter SoA report and on the results of the hygrothermal and mechanical analysis carried out using the software WUFI® and COMSOL® extensively collected in the simulations and analysis report (Cucchi, C.; Simon, H.; Sprengard, C. (2021): External Thermal Insulation Compo-site Systems ETCS – Hygrothermal and Mechanical simulations and analysis – Sensitivity analysis for hygrothermal performance and evaluation of the mechanical forces) which is mentioned hereafter as WP2/3 report. Furthermore, the content is also based on the report from technical experts (Oberhaus, H.; Keßler, D.; Block, K.; Becker R. (2021): Gutachtliche Stellungnahme Nr. 20.5.080 - Fassung 2.1 - 06-01-2021 - Funktionstüchtigkeit der Wärmedämm-Verbundsysteme (WDVS) - Grundlagen und Strukturen der Nachweisführung. Translation: Expert opinion No. 20.5.080 - Version 2.1 - 06-01-2021 - Functionality of thermal insulation composite systems (ETIC-kits) - Basics and structures of proof of mechanical stability).

1.2 Gaps, shortcomings and open questions

During the analysis and assessment of the hygrothermal and mechanical performance of ETICS, some gaps, shortcomings and open questions were highlighted, which are listed below.

- There is a lack of data regarding the amount of water due to wind driven-rain that enters a crack as well as the different mechanisms that could influence the water uptake.
- The information available on the effect of moisture on the mechanical performance of the system are not completed and sufficient regarding the changes in the mechanical performance related to the water content and water absorption of the product.
- An evaluation criterion to assess the risk of frost in the rendering system as well as in the thermal insulation is missing.
- The evaluation of the effect of ageing on the material insulation is missing as well as the definition of a method based on the evaluation of the deterioration of properties over time and exposure.

- A comprehensive mechanical model of ETICS is not yet available. The mechanical performance of the system is assessed through models that consider single different aspects.
- The current models are available for thin thermal insulation so far but need to be validated for thicker insulation layers since the shear force on anchors, in this case, is expected to increase.
- The standard does not consider the influence of hygrothermal loads and shrinking on the system. These loads produce deformation on the system that combined with wind load and dead load increase the shear force that act on the anchors.
- The evaluation of how the anchors can support the combination of load (wind load, dead load, hygrothermal load) in thicker systems is missing since the anchors are designed to support tensile load only and not shear load.
- The standard formulates basic design requirements for the anchors but does not cover the two different types of load-bearing behaviour (bonded and mechanical fixed). In case of no bonding or thermal insulation not sufficiently shear-stable, the anchors have to absorb the shear forces from dead load and hygrothermal effects. This means that shear forces and possibly bending moments act on anchors (use typically associated with ETAG 020). However, the standard only considers the requirements for anchors according to ETAG 014.
- The safety coefficient for the material was determined on the basis of many years of experience with ETIC systems (in the German administrative regulation template for technical building regulations). However, in case of thicker thickness, the shear force on anchors is higher and this is not in deep investigated so far. Therefore, this could lead to a higher partial safety coefficient.
- The definition of moisture conversion factors Fm for wet materials in the building environment is a pragmatic approach that enables experts to judge effortless on the thermal quality of existing insulating layers. Nevertheless, the conversion coefficients and the range of the validity for some materials have to be adjusted when revising EN ISO 10456.

2 Background and scope of the project

ETIC-system is a well-known efficient system that offers peculiar properties thanks to the cooperation and interaction of its components that make it an optimal system for improving the thermal performance of the building envelope. However, the performance of ETICS and its suitability for special applications cannot be derived only from product testing according to the identification/specification standard. The tests described by the standard, indeed, do not provide information about the sensitivity of variations of single properties, nor do they provide a full set of possible relevant properties and statements about interactions under particular conditions. The practical interactions are not described by the standards, only a set of mainly descriptive single characteristics based on a defined laboratory framework is given. Furthermore, over the last 50 years, most of the products were further developed changing their composition, thermal conductivity, water vapour transmission properties, mechanical properties and above all increased thickness to keep up with the increase of energy requirements. New products based on other thermal insulations were brought to the market as well. Therefore, the need to find a set of characteristics behind the optimal performance of ETICS and to understand the impact of the system component parameters on the system's performance has arisen. These properties need to assess the hygrothermal and mechanical performance since they are dominant for the performance of ETICS. The study focuses on the thermal insulation component (EPS and mineral wool) due to the range extension of the task.

The project was carried out during the intensive work performed by TC88/WG18 on the development of the new harmonised standard (prEN 17237). Therefore, it is raised the need to create insight into the current status and development of the knowledge on the ETICS-topic to raise questions on the validity of the available declarations on the product characteristics and on the validity of the used models and test methods.

In case of ETICS, the whole system is the product that is CE marked according to the harmonised standard. Therefore, the DoP is drawn up for ETICS by the system holder who is responsible for the conformity of the system.

Furthermore, declared values only partly represent the real values of the single products since they are given in spans of values and classes in the DoP and for each test, a specific product is tested and therefore there is no certainty that the product delivered on the building site has the same product properties as the set of declared values given by the manufacturer. Furthermore, the producers have also the possibility to declare the performance of the product in a conservative way. This means that the declared values could be (much) smaller than the test results and - as a consequence – the system performance might be different from expectations. Indeed, the main purpose of the declared value is to allow identification of a product to provide unique description for the European market and not for evaluation design purposes. The set of relevant characteristics can be called the “fingerprint” of an ETICS (detailed definition in chapter 2.4 of the SoA report). The Fingerprint stands for unique identification and its concept can assume different shades. On the material level, the relevant set of characteristics is based on declared values for the product identification based on technical regulation. In addition, the Fingerprint can represent the specific performance of a specific product determined by a full set of tests on one batch. These are product properties that identify the product and allow regulations for sale and application. However, this identification does not necessarily give sufficient information to describe the building physics behaviour of the system. Therefore, additional parameters are needed. As an extension of the Fingerprint idea, the building physics fingerprint of a system deals with material properties that are based on chemical and physical structure of the components and their interaction in the system, considering typical impositions. Besides the role of describing the components and the system, the Fingerprint can be considered as the relation between the material properties or layer properties and the system performance. This means that by identifying the Fingerprint of an ETICS, it is possible to evaluate the tolerances of the products in relation to the performance of the system. Therefore, the evaluation of this set of interlocking product and layer performances show the mechanisms behind the success and failure of an ETIC-system.

The general aim of the research project is to identify relevant characteristics in terms of material properties that are suitable for modelling the performance of an ETIC system and can give information behind its key factors.

3 Basic literature survey and State of the Art

The scope of the literature survey is to collect knowledge and give a broad approach in the frame of ETICS, considering the relevant aspects and details of the system that influence its quality and durability. Information, from different countries, articles, data and reports were collected to find the most relevant parameters and the leverages in this field. The result of this research is a detailed overview of the status of scientific information and available reports on ETICS. Different topics are handled: hygrothermal analysis, mechanical analysis, and aspects of ETICS durability.

The results of the literature survey are discussed in detail in the SoA report.

3.1 General outputs of the literature survey and State of the Art

General remark on the hygrothermal and mechanical analysis studies investigated is that the main focus is on the properties and function of individual components without considering the interactions between the different layers. The studies analyse single aspects and, thus, all the models found for mechanical and hygrothermal simulations refer to one part of the system solving very specific questions. The results cannot be generalised and therefore, it is difficult to acquire an overall view of the phenomenon. Some studies even lack a proper assessment of the results and therefore possible correlations between single properties and mechanical and hygrothermal performance cannot be done. Even studies that try to establish a correlation of properties are limited in terms of general findings, as the relationship between the properties of a product must be defined for the concrete framework conditions of the product.

The same limitation is also valid for the boundary conditions and material characterization: They refer to a specific application that does not allow to extend the validity of the results or very much limits the extension. Therefore, it is not known if the same result will also be reached with different inputs regarding both boundary conditions and material properties. Also, the boundary conditions (e.g. wind loads) are too specific and simplified. Simplifications of real conditions for the modelling are necessary and common practice in simulations, but the simplifications shall not exclude relevant parameters as the dynamic character of the loads.

Furthermore, all studies have in common that they are not considering interactions between components.

Almost all studies lack a comparison of the material properties used to feed the simulation models with properties found for typical material on the market or with declared material properties. As a consequence, it is only partly possible to extend the results to other conditions. However, more generally, the results are valid only for the type of products and applications investigated.

Furthermore, the mechanical and hygrothermal properties are not correlated to the process and raw material of the thermal insulation. This means that there is no reference on the material properties based on the chemical and physical structure of the components. There is also a lack of information about the influence of changes in the material composition (e.g. as historically developed) on the mechanical and hygrothermal performance of the thermal insulation in a system, since sensitivity analysis for spans of material values and limitations due to material properties and the correlation between most of the properties are not known.

The studies analysed provide only limited information with which it is not possible to establish a reliable correlation between the material properties (or layer properties) and the performance of the system. More information on interactions of materials and different layers are needed to understand the mechanisms behind the success and failure of an ETIC-system.

3.2 Hygrothermal analysis

The studies concerning the assessment of thermal shock mainly focus on the number of thermal shock incidents without considering the differences in the response of different materials to the events. Furthermore, the way damages occur in different parts of the ETICS as a reaction of the system to thermal shock events remains unclear as well as the role of the mechanical behaviour of the thermal insulation and the interaction of thermal shock with other loads such as the combination of high-temperature stress in combination with high wind-load.

The studies investigating the influence of initial moisture lack an assessment of the effects of high humidity on the mechanical stability of the system. High moisture contents – especially in combination with high temperatures – can cause degradation effects on mechanical properties. Additionally, higher moisture contents lead to higher energy consumption: The consideration of the additional thermal transport caused by the presence of moisture is usually done by the moisture correction factors according to ISO 10456. Depending on the material assessed and the boundary conditions found, this could underestimate the additional thermal transport by neglecting the phase changes and latent heat transports caused by evaporation, condensation and moisture movement. In this context, the standards for testing and assessment of results need to be revised and complemented.

A general limitation is connected to the simulation tools used for the analysis of wind-driven rain. Usually, the moisture uptake is considered as a percentage of the total amount of wind-driven rain given for a specific location. Furthermore, simulation programs for combined heat and moisture analysis cannot consider atmospheric pressure changes. Therefore, the extra pressure on the moisture film on the surface of the building provided by the wind is not considered. Attention has to be paid as well to faulty or damaged connections of the system with adjacent building parts, e.g. on window sills and joints in the façade where the water can enter the ETICS.

The moisture content is a parameter with a high impact on the insulation system. It not only causes damages but is difficult to avoid and therefore the system needs to be resilient to it. In fact, some water always penetrates the rendering system and enters the thermal insulation, especially in the joints between windows and walls even in the absence of wind.

3.3 Mechanical analysis

Mechanical simulations and analysis of the stress-distribution are based on a homogeneous and isotropic behaviour of the insulating layer. There is a lack of information and data about the behaviour of anisotropic material and therefore, its mechanical behaviour cannot be simulated and assessed. The model needs to be checked depending on the isotropy and homogeneity of the material itself.

Furthermore, the simulations are performed for specific configurations, which are usually ideal. This means that some situations such as immerged anchors, which can lead to further stresses, are not covered.

According to the findings, moisture (relative humidity and rain) has an influence on the bond strength between thermal insulation and reinforced base coat. The results of this influence depend on the type of material and even on the type of product. The increase of relative humidity can lead to a decrease of the mechanical performance. The influence of rain and frost affects in the same way the mechanical performance. Therefore, these factors should be taken into account in the material-specific evaluation of the mechanical properties of the insulating material.

3.4 Durability aspects

The majority of the study concerning durability aspects focus on the analysis of damages coming from atmospheric agents and errors during installation. Since most of the impacts such as UV radiation, moisture, wind and temperature changes directly affect the rendering system, it results that the durability of ETICS mainly depends on the aging process of this component. Therefore, the ageing methods proposed are related to the ageing of it, neglecting the role of the other layers and their performance in the overall ageing of the system.

Furthermore, the ageing of ETICS is directly linked to specific climatic conditions and, since temperature and humidity are very specific for the regions, it is not possible to develop a general and fixed ageing process for all over Europe without further investigation.

The literature survey also provides suggestions and improvements to the ageing method proposed by the standard (hygrothermal wall). Mentioned shortcomings are: frost attacks are not included in the procedure; the frost durability is represented only by the water absorption properties; heat-rain cycle and the heat-cold cycle are performed separately offering the possibility to dry the sample and no longer representing the critical condition of a wet sample in a cold region; the exposure to agents such as rain, sun and frost is performed on different samples than the one used to test the wind effects; the ageing test is only performed on the sample section, while most failures occur in the building details (corners and fixtures); the interaction between ETICS and their support system is not considered even though the stress of the structure is often the cause of damages such as cracking; a scale on which it is possible to compare the failures after short and long term tests is not identified.; not all factors that cause ageing are considered (such as the repetitive action of wind).

EAD 40083-00-04-04 also provides a procedure to test the tensile strength of thermal insulation in wet conditions if the product shows degradation and some studies have questioned the severe conditions used in this test. However, this kind of test has the scope to set quality level for the tensile strength that the products have to pass. It is not provided how the system will function in the long-term evaluation as this test is not connected to an accelerating factor that would allow a calculation of performance over time. This is one of the most general gaps of most ageing tests and a solution for this can only be found through comparative testing at different ageing conditions in comparison to real ageing.

There is a general lack of information regarding the behaviour of the components in long-term use. This phase has not been performed in the documents collected for this study. Also, the differences in the ageing mechanisms coming from the materials themselves are not taken into account in the ageing tests. As a consequence, comprehensive simulations of the degradation mechanisms and the ageing processes cannot be performed due to the lack of parameters of the materials and specific parameters of interaction between the layers.

Furthermore, there is a strong recommendation for regular care and maintenance, which are key to tackle stress and ageing of an ETIC-system and for maintaining its performance over time, with regular maintenance of the facades the service life of ETICS can be extended massively.

The literature survey provides a detailed description of the causes and consequences connected to failures, but does not clarify a full set of properties of the components nor does it allow to explain the reason why ETICS work and which are the properties that allow this.

4 Hygrothermal performance

The outputs of the literature survey regarding the hygrothermal analysis are collected in the SoA report chapter 7 and the results of the numerical simulation are presented in WP2/3 report chapter 3 to 7.

4.1 Sensitivity analysis

The quality and functionality of an ETIC-system depend on the interlocking of the performance of the layers as well as on the single material properties, especially if the system's characteristic is sensitive to their variation. Therefore, the variation of these material properties has an impact on the final performance of the kit. In the literature survey, it was highlighted a lack of information in this respect; thus**, it was not possible to define a correlation between system performance and the material properties and their span of values.** Therefore, the goals of the sensitivity analysis are:

- to investigate the main influencing factors for the functionality (or non-functionality) of ETICS in practice in typical European climates and for typical types of ETICS;
- to define a set of key and essential properties as well as their appropriate span of values to ensure optimal performance of the system;
- to clarify the characteristics of the thermal insulation that have a dominant influence on the hygrothermal behaviour of the system as well as to identify areas of potential concern.

The sensitivity analysis is carried out assessing the magnitude of variation of the ETICS performance in terms of temperature, relative humidity, and water content due to the changing of the material parameters of thermal insulation and rendering system, type of substrate as well as indoor climate. This means that the results of a system taken as a basic model for the analysis are compared with the outputs of other models where the settings and spans of values are switched case by case in order to observe and analyse the difference in performances depending on the material parameter changed. The assessment is carried out through a WUFI model that consists of a substrate and an ETIC-system that is divided into 4 layers: finishing coat, base coat, thermal insulation and adhesive.

The results of the numerical simulations are:

- <u>Influence of the material properties of the rendering system</u>: The properties of the rendering system that affect the profile of the hygrothermal factors within the system are the solar absorbance, i.e. the colour of the render, thickness, water vapour diffusion resistance (equivalent air layer thickness) as well as water absorption. This means that the variation of the value of these material properties leads to an increase or decrease of temperature, relative humidity and/or water content within the thermal insulation. For this reason, these material properties are considered influent on the overall performance of the system. Among these parameters, the water vapour diffusion resistance and water absorption play a key role in the moisture and water content within the thermal insulation, whereas solar absorption is mainly responsible for the temperature variation. The influence of these factors is localized in correspondence of the external layers of the system, rendering system and first centimetres of the thermal insulation, and then the influence decreases gradually toward the indoor space.
- <u>Influence of the material parameters of the thermal insulation</u>: Material properties of the insulation layer that influence the variation of moisture and water content are thickness, porosity, water vapour resistance as well as sorption isotherms.

Among them, however, the moisture storage function is the most influential. The moisture storage function is an intrinsic property of the material that depends on the composition of the material itself and therefore it differs from material to material. It describes the amount of the water content at given values of relative humidity from dry (0%) to wet (100%). This parameter is required in the simulation software for the calculation of the moisture distribution. The material moisture, depending on the sorption isotherm as a material property, influences the thermal conductivity of the material and thus the temperature distribution inside the material.

- Influence of the type of substrate: The analysis compares a full brick 300 mm thickness, a lime-silica brick 240 mm thickness, and a concrete wall 200 mm thickness and shows that the type of substrate affects mainly the moisture content between the thermal insulation and the substrate itself. Therefore, the amount of moisture in the area next to the rendering system does not change depending on the chosen substrate. Among the analysed substrate, full brick masonry is the configuration that brings more moisture into the insulation layer. Therefore, in this case, an insulation layer that allows a quick dry-out process – like mineral wool - can be applied. Indeed, mineral wool allows the system to dry in one year and a half, whereas EPS requires around 4 years to meet the same level of moisture in the substrate as with mineral wool. However, a quick dry-out process is not always an advantage since this leads to an increase of the moisture content in the rendering system, especially if the finishing time of the construction is in winter, and this could lead to damages due to frost.
- Influence of the indoor climate: The variation of the indoor climate from a medium moisture load (relative humidity between 30% and 60%) to a high moisture load (relative humidity between 40% and 70%) has a neglectable influence on the moisture content within the thermal insulation. The increase of relative humidity in the indoor space leads to an increase of the moisture content only in the substrate.

The variation of the moisture content in the insulation layer is linked to seasonal fluctuations due to periodic redistributions of the moisture as well as to the dry out process, which occurs in the first years. Furthermore, no water accumulation due to diffusion, convection, or capillarity processes occurs. Therefore, the span of values assessed does not show potentially critical issues. However, since the main function of ETICS is the insulation of buildings, the decrease in insulation properties caused by the moisture amount and especially by possible moisture movement in the system is evaluated.

The changes in thermal conductivity due to moisture content do not jeopardise the quality of the thermal insulation and therefore of the whole system if calculated according to ISO 10456 in combination with the moisture contents found by simulations.

Indeed, the maximum water content within the thermal insulation is far less than 2 Vol.% that is a commonly used threshold value (in absence of better knowledge) below which the variations in thermal conductivity are considered negligible. This consideration is based on the calculations of the heat loss that occurs in a wet material according to ISO 10456 where the thermal conductivity at a water content of 2 Vol.% increases by 3 mW/(m·K) compared to the dry value.

However, the assessment according to the EN ISO 10456 shows some inconsistency regarding the definition of the moisture related effects incorporated in the term thermal conductivity and the magnitude of the validity range for the moisture conversion coefficients. ISO 10456 specifically excludes all effects that have to do with moving moisture and phase changes of involved water, but on the other hand offers a very wide span of validity for the application of the given coefficients. When measuring thermal transport of materials with such high moisture contents, these effects cannot be avoided in the measurements. This validity range needs revision and it should be limited to low moisture contents, e.g. below 0.5 % by volume.

For insulating materials that have higher moisture contents (e.g. wetted and damaged samples) an assessment of the measurements according to ISO 10051 shall be done to determine the effects of moisture on thermal transport correctly – e.g. using thermal diffusivity instead of thermal conductivity. The relation to ISO 10051 needs to be implemented in ISO 10456.

The choice to use the value of 2 Vol.% as a limit value until which the effect of moisture on thermal conductivity is considered to be of minor importance is based on the lack of a general evaluation criterion for moist materials. Therefore, further research is needed to redefine the moisture related effects and the boundary conditions for all materials typically used in an ETICS.

In addition, also the moisture conversion coefficients themselves need to be checked and partly adjusted, based on latest measurements. This is not only the case for mineral wool and EPS as outlined in the hygrothermal and mechanical report, but refers to coefficients of other materials in ISO 10456 as well, e.g. for PU and Wood Fibers and many building materials. In order to extend Table 4, also coefficients of “new” materials need to be added, e.g. for aerogels and energy efficient renders.

Further investigation and testing are also necessary to define the influence of the material parameters in terms of mechanical performance and bond strength under different moisture contents. Also, the moisture storage function is an intrinsic property of the material that is used in simulation software and, thus, no requirements are defined in the regulations for ETICS in this regard. Therefore, it should become part of the initial investigation of ETICS. Indeed, further measurements are needed that incorporate additional moisture uptake and moisture transport mechanisms within and into a material.

4.2 Distribution of water

Moisture in ETICS can be caused by different reasons and it can cause damages on parts and the whole system. Even if the system shows good performance in the framework of the analysed values of the sensitivity analysis, the water penetration through defects on the surface can change the water content balance of the system.

Moisture can cause degradation effects on mechanical properties and reduce the thermal performance of the system, leading to higher energy consumption. Although many studies consider various phenomena related to moisture in ETICS, there are still some effects rather unclear. Therefore, the analysis aims:

- to clarify the influence in terms of water content of imperfections on the ETICS surface, i.e. cracks, considering the influence of the rendering system as well;
- to investigate how the water vapour diffusion affects the water distribution inside the thermal insulations if the water is accumulating around weak spots or is distributed inside the insulation layer.

The issues are analysed through a WUFI model that consists of an ETIC-system (rendering system, thermal insulation and adhesive) and a full brick masonry as a substrate. The crack on the surface is modelled by imposing a moisture source of 1 mm width and 6 mm depth in the rendering system. A general limitation is connected to the moisture source: The simulation tools usually consider the moisture uptake as a percentage of the total amount of the wind-driven rain given for a specific location. The amount of 1% of wind-driven rain is used for the simulations, which was validated in North American studies. However, this value is used due to the lack of information about the amount of water entering the system through a crack and the negligible difference in terms of water content between the different percentages of wind-driven rain analysed (0.5 and 2%). Depending on the crack dimensions, the driving forces could be either air-pressure to force the water into the crack or capillary effects e.g. for smaller crack-width. The analysis compares the water contents in different areas of the thermal insulations MW and EPS for different cracks and the different types of renders.

According to the findings:

- The amount of water, which penetrates into the system, remains in the outer area of the thermal insulation next to the base coat, leaving the remaining part of the thickness almost dry. The distribution of water depends on the type of material mainly due to the water vapor resistance. In materials with higher water vapour resistance, the water remains around the damage and in the first millimetres of the product. In materials characterised by a lower water vapour resistance, instead, the moisture spreads more homogeneously in a wider area and reaches deeper into the layer.
- The total amount of moisture entering the system is almost unaffected by the appearance of failure. The crack investigated (typical dimension and depth) has only a minimal influence on the overall water content of the system. The influence is limited to a thin layer of the total cross section of the insulation and limited to a short period after the wind-driven rain incident.
- The choice of the type of rendering system has a much stronger impact on the water content of the thermal insulation. This depends on the water absorption value of the A rendering system with a water absorption greater than 0.5 kg/(m^2h^{-1}) leads to a larger water content within the thermal insulation than an organic rendering system with lower water absorption.

As the additional water uptake in cracks is considered to be small in comparison to the water uptake of the render itself from wind-driven rain, also the impact on thermal performance is considered to be low. Nevertheless, this statement is based on the evaluation criterion of 2% by Vol. and based on the coefficients given in ISO 10456. However, this is rough and pragmatic approach that does not take into account relevant heat transport phenomena that occur in wet porous materials at higher moisture contents.

Furthermore, the simulation programs for combined heat and moisture analysis allow the representation of reality through the use and the application of simplifications. This means that some aspects are not taken into account such as the extra pressure on the moisture film on the surface of the building provided by the wind, the effects in water distribution and accumulation due to, for example, gravitation, and typical values for the water holding capacity (for liquid water, not covered by the moisture storage function) for all materials. Depending on the crack-dimensions, also capillarity effects could take place and might worsen the situation for thin cracks. Hence, the findings can be used as a starting point for further experimental studies and investigations on the mechanisms that lead to the water uptake through cracks.

Since the mechanical performance of the system is influenced by moisture and the water remains in the outer layer of the thermal insulation, the effect of moisture on the bonding strength between the thermal insulation and the rendering system should be investigated. Therefore, further assessment is required regarding the influence of the water content on the mechanical performance of the system and bond strength related to the water content and water absorption of the product. This is also to be seen in the context of the durability of the system (chapter 4.4).

4.3 Risk of frost damage

One of the most typical loads affecting the building envelope in cold climates is frost. Although the analysis in the framework of sensitivity analysis and water distribution does not show a critical level in terms of moisture content, several studies highlight the risk of frost damages that ranges from crack formation to detachment of the render, undermining the durability of the system in the long-term and decreasing the mechanical performance. Therefore, the investigation aims to assess the incidence of frost damages in the rendering system depending on the thermal insulation as well as the performance of the thermal insulation itself, offering a starting point for further researches and studies. The magnitude of the impact of the factors responsible to induce and increase the probability of risk of frost damages is analysed in the system and the critical area liable to frost events is localised.

The boundary conditions factors (number of events of freezing temperature and water content, number of zero-crossing and freezing speed) and the profile of moisture and temperature over the cross-sections of the finishing coat are evaluated with WUFI during the half-year of the winter and depending on the type of thermal insulation as well.

In all the assessed locations the temperature drops below zero. Therefore, frost damages should not be underestimated in locations with milder winters as well. However, systems in climates characterized by rainfall followed by freezing events can be more susceptible to frost damages since temperature below zero does not cause damages unless the component is wet at the freezing point.

In all the configurations analysed – organic and inorganic rendering systems with different thermal insulations – the rendering system shows no critical performance when the temperature drops below zero according to the evaluation criterion used to assess the critical limit of water content within the material at negative temperatures based on the saturation ratio. The water increases its volume by about 10% during freezing and the same amount should be available as space in the pore to avoid possible damages. The saturation ratio is the fraction between the water content within the material and the maximum water content defined by the pore volume and therefore indicates the remaining space available in the pores. This means that a degree of saturation up to 0.9 could be theoretically acceptable to have damage-free systems. Indeed, the highest saturation level does not exceed 40%, leaving plenty of free space for the ice formation without leading to further internal pressures and tensions. However, the risk of frost damage in the rendering system is closely related to the distribution and size of the pores, which cannot be considered in the simulation software.

In the thermal insulations (EPS and MW), due to the highly porous structure of the material, the saturation ratio is not the most appropriate criterion for evaluating the behaviour of this layer at temperatures below zero.

Therefore, the critical threshold needs to be supplemented with further investigations that will help to plot a risk function that correlates the boundary conditions and the characteristics of the rendering system. The definition of a frost risk function is required for the thermal insulations as well. This function indicates the maximum number of cycles for which the material still does not suffer from deterioration of performance in terms of mechanical behaviour such as compressive and tensile strength to test before and after the freeze-thaw. Also, material related deterioration mechanisms need to be taken into account, e.g. the effect of moisture and frost on binding agents and hydrophobization.

4.4 Durability aspects

The durability in ETICS is addressed through the threshold approach, where the components are exposed to severe boundary conditions and specific properties are tested before and after the exposition. The test is considered acceptable if the result achieves a threshold value. The climate conditions set in these tests are usually rather severe since the tests have to be reproducible, fast and especially have a great and visible effect on the material.

The proposed test according to EAD 040083-00-0404 is the hygrothermal wall, which aims to check if the system meets the required resistance requirements, i.e. if no surface damage appears due to exposure to the cycles. After the test, the bond strength between the base coat and thermal insulation and the bond strength of the finishing coat is tested. However, different research reports identify the need to adjust or amend the existing EOTA test. Furthermore, the regulation provides a procedure in wet conditions to use on the thermal insulation to which the strict boundary conditions (70°C and 95% r.H.) have been questioned. Therefore, a first analysis of the hygrothermal conditions used in the tests is carried out.

In the future, the durability could be assessed by applying a different methodology based on the testing and evaluation of the deterioration of properties over time and exposure, where accelerating factors can be derived for specific properties depending on the exposure, the severity of the exposure and its duration, material-specific and application-specific. This would allow planners and users to estimate the performance of the product at a given time and for a given specific application, allowing tailored estimation for service life. Nevertheless, research is only at a starting point for these approaches for most conventional insulating materials. More research on deterioration mechanisms for the design properties of the materials and the material interactions are needed for such an approach.

As a starting point for this change of paradigms, the investigations reported in the “Hygrothermal and Mechanical Report” assess temperature and relative humidity on the ETICS surface and on the thermal insulation surface with WUFI in six European locations defining the expected temperature and relative humidity in different countries and climates to clarify the boundary conditions used for ageing assessment and testing. The frequency of the events is determined as well. Since the values of temperature and relative humidity change according to the observation point in the materials, the validity of the results is linked to the chosen boundary conditions.

The results highlight that the thermal insulation is loaded with a combination characterized either by high temperatures around 50-60°C and relative humidity lower than 50% or high relative humidity above 80% with low temperatures below 30°C. The greatest frequency peaks are achieved at relative humidity between 90% and 100% according to the study of the number of hours of the combinations of temperature and relative humidity.

On the surface of the system, typical conditions calculated are represented by the exposure to a temperature range between 20 and 30°C and humidity above 90%.

Therefore, the results found through the simulations suggest an overestimation of the temperature and an underestimation of the relative humidity in the EOTA hygrothermal wall test. The test settings could be changed by increasing the moisture (from 30% to a value above 80%) and decreasing the temperature applied (from 70°C to a range between 40-50°C). The same evaluation can be applied to the tensile strength test in wet conditions, where the material is exposed to extreme temperature and moisture conditions that never occur in the practical application.

However, this analysis is based only on simulation results. This means that the impact of these different boundary conditions has to be tested on the hygrothermal and mechanical performance of the system to check if the effects reflect the same results of the exposition in the real conditions. This involves studies on the failure mechanisms in different materials and material-material interactions. Furthermore, the assessment of the timeframe of each cycle and the limit value for evaluating the product performance is still unknown for other boundary conditions. The results must also be sustained and validated by experimental tests and, ultimately, the results must also be substantiated by a correlation between short- and long-term exposure.

In addition, the possible implementation of the approach based on the concept of the performance over time will need far more testing and research on the material-specific degradation mechanisms of all components of an ETICS, limit values for key properties and the accelerating factors.

5 Mechanical performance

The outputs of the literature survey regarding the mechanical analysis are collected in the SoA report chapter 8 and the results of the numerical simulation are presented in WP2/3 report chapter 8 to 13.

Due to the high dynamic of the standardisation process an essential rewriting of the standard took place during the last year (2021), not only, but also triggered by the findings of the expert’s report. An evaluated update for the current version of the standard is not included in this FIW report. It represents the knowledge from beginning of 2021.

The standard prEN 17237 specifies basic requirements for the assessment of ETICS thermal insulation. These requirements differ in part significantly from the requirements in the general building inspectorate approvals (abZ) or general type approvals (aBg) in Germany. The following is based on an own assessment of the prEN 17237 and additionally on the opinion of the technical experts.

The standard prEN 17237 sets requirements for deviations in length, width, and thickness, as well as for deviations from squareness and flatness, which are different from the requirements for dimensional accuracy in Germany. Concerning the evenness of the system surface of MW the insulation materials might no longer be produced in accordance with the standard. In the case of EPS insulating materials, the requirements in Germany are too generously regulated. The prEN 17237 fails to improve this situation. The standard also falls short of the requirements in Germany for PU and PF insulating materials, which were defined according to technical possibilities and necessities.

The prEN 17237 also sets requirements for the dimensional stability of ETICS insulation materials. In the case of EPS insulating materials, the requirements are already too generous compared to the German approvals and type approvals. The standard fails to eliminate this deficiency. The requirements for the dimensional stability of XPS insulation boards could, due to the great rigidity of the boards, lead to rupture in the render systems tearing over the board joints. For PU and PF insulation materials, the standard again falls short of the requirements in Germany, which were set according to technical possibilities and necessities.

According to prEN 17237, the tensile strength perpendicular to the wall plane is given as a mean value. It would make more sense to specify all individual values so that a statistical evaluation (or a threshold approach) would be possible. Neither is it possible according to the standard to know the smallest values of the measurement series, nor the scatter. However, the former plays a role in national approvals. If the minimum values are no longer known, the safety factor for the scatter would have to be increased significantly.

The effect of the different partial safety coefficients can be shown using the example of bonded mineral wool lamella insulation boards. The largest permissible resistance to wind suction is we = 1.60 kN/m² or, with a double partial safety factor, only we = 0.80 kN/m². If the wind suction forces are determined according to the simplified method from EN 1991-1-4, the insulation board can be used in the first case for buildings in the four wind zones up to a height of 25 m (and above). In the case of a double partial safety factor, the application is limited to wind zone 1 and in wind zones 2 and 3 only to inland areas with a maximum building height of 18 m and 10 m respectively.

For bonded and anchored ETIC systems with mineral wool insulation boards, the permissible wind action, which depends on the number of anchors, is halved if the partial safety factor is doubled. Conversely, this means that in this case a very high number of anchors is necessary to achieve the permissible wind suction effect of we = 1.10 kN/m². Under certain circumstances, such a system is then no longer economical even for standard buildings.

An alternative to the 5% quantile could be the specification of the mean value and the coefficient of variation from the measurement series, as it has already been implemented in the MVV TB. To determine the design value of the tensile strength, an additional partial safety factor is then inserted.

The prEN 17237 formulates basic design requirements for the mechanical fasteners (plate, spiral and collar anchors). However, the standard does not cover the fact that two different types of load-bearing behaviour can occur (and at the same time), at least for the plate and collar dowels.

In the first case, with ETIC systems with adhesive bonding and sufficiently shear-stable insulation materials, the insulation material and the adhesive take over the transfer of the shear forces from dead load and hygrothermal effects to the substrate. The anchor only supports this load transfer and, as long as the bond does not fail, absorbs the wind suction forces proportionally or, in case of (partial) failure of the bond, the wind suction forces completely. This typically involves the use of anchors according to ETAG 014.

In the second case, for systems without bonding or with insulating materials that are not sufficiently shear-stable, there is a deviating load-bearing behaviour. The anchors must also absorb the shear forces from dead load and hygrothermal effects. This is associated with the permanent effect of shear forces and possibly bending moments on the fastening elements. This typically is associated with the use of anchors according to ETAG 020. However, the standard only considers the requirements for anchors according to ETAG 014, i.e. for wind suction.

As a rule, the anchors are designed for tension. They form the tension strut in the bracket support model for anchored systems and also take up the load in the case of wind suction. The anchors are normally not intended for the shear load that could be problematic with increasingly thicker and thus "softer" systems. The thicker the insulation material, the smaller the bedding stiffness. This means that with increasing insulation thickness, the displacement of the system in the plane of the slab increases and thus also the shear stress on the anchors.

The prEN17237 is on rigid substrates only, not for timber like substrates etc. Hence the system variant of soft wood fibre insulation boards, which are fixed to the timber construction exclusively with screws and plates as well as staples, is missing. This variant is comparable to type (V) in the standard, the purely mechanically fastened ETICS with plate anchors.

From the basic requirements for the adhesive mortar or adhesive, it follows that adhesive mortar or adhesive or adhesive foam are involved in the transmission of forces, which must be taken into account in the intended load-bearing model and verification concept.

If one compares the basic requirements for the insulation material with the previous building authority approvals, it becomes apparent that the dimensional stability of the insulation materials is regulated very "generously" in the standard. The dimensional stability limits mean that cracks can develop in the rendering system, which in turn can lead to increased water absorption and reduce durability in the long term.

A serious deficiency concerns the tensile strength test perpendicular to the plane of the wall. The results must not only be given as an average value, all individual values should always be given so that a statistical evaluation is possible. The inaccuracy of stating only the mean values leads to the fact that neither the smallest values (which form the basis of the currently valid national principles) nor the scatter of the test series are known. In order to achieve the desired system safety, the partial safety factor "spread" would then have to be significantly increased, which could lead to systems conforming to standards not being applicable in practice in many cases.

PrEN 17.237:2020 defines system variants for which, in part, there is insufficient experience regarding shear capacity. No suitable tests are planned to be able to assess the stability in this respect.

Solely bonded systems with a bonded surface proportion of at least 40 % are described with rendering weights of up to 30 kg/m² and insulation thicknesses of up to 400 mm. This corresponds to our experience in Germany, but not with elasticised EPS. In the system with a bonded area of at least 40 % and anchors, the rendering weight is even increased to 40 kg/m², with no restriction to certain EPS types (e.g. with minimum shear modulus and shear strength).

Solely bonded systems with a bonded surface proportion of at least 40 %, rendering weights of up to 30 kg/m² and insulation thicknesses of up to 400 mm correspond to the research result in Germany in connection with mineral wool lamella insulation boards, not with mineral wool insulation boards, whereby these are also not provided for in the standard for exclusively bonded systems.

The bonded and anchored systems, in connection with mineral wool insulation boards, must be examined and assessed with great care, as the insulation boards no longer have any reserves. For mineral wool insulation boards, shear modulus and shear strength are not defined in prEN 17237. An examination according to the current state of the standard would not be sufficient for a qualified assessment. This system structure would have to be additionally examined according to national principles, which does not correspond to the purpose of the standard.

With rigid insulation materials, such as XPS boards, which have a high load-bearing capacity, it would in principle be possible to design a functional system structure according to the standard. However, the defined adhesive tensile strength of the adhesive in the wet state with $\sigma_{Hz,ns} \geq 30$ kPa would be too low, so that there is a risk of large-area detachment.

5.1 Thermal expansion and thermal shock

ETICS are subject to a permanent temperature change that occurs either slowly over the seasons or daily over a night/day course. The increase in temperature leads to an expansion of the materials and vice versa. Since slow temperature change slowly penetrates the system giving time to the system to react to it with a corresponding adjustment of its geometric dimensions, the investigation aims to analyse the influence of sudden temperature changes on the components. Indeed, the role of the mechanical behaviour of the materials regarding damage mechanisms is unclear.

The issue is assessed by replaying an abrupt change of temperature on the surface of the system. The warmed-up façade at 60°C by the solar radiation is suddenly hit by a cool rain at 10°C.

A simple model consisting of an organic rendering system and thermal insulation (EPS) bonded to the sand-lime brick substrate is used. The analysis considers only temperature and it is assumed that the render is thermally decoupled by the thermal insulation. This means that the temperature wave does not reach the insulation layer in the period under consideration, whose temperature remains unchanged. For these reasons, the insulation type should have no influence on the result of the simulation.

The sudden temperature difference within the rendering system causes residual stresses that subside as the temperature penetrates further into the depth of the render and the temperature difference within the layer decreases. The residual stresses that occur may possibly be related to cracking in the plaster during a so-called "thermal shock".

However, the investigation is highly simplified. It provides a starting point for further investigations on the topic. Furthermore, further work on the refinement of the material parameters and boundary conditions and the contribution of the water content on the strain are also recommended. This could lead to a better definition of the load on the material and the failure probability.

5.2 Impact of loads on ETICS

The wind load acts on the ETICS depending on the location and height of the building and it can be a dynamic pressure or wind suction. The investigation aims to assess the impact of the wind load on the system in terms of deformation distribution and stresses in the thermal layer and rendering system.

The mechanical impact of the wind load is assessed on an ETICS with EPS of 150 mm thickness. The system is simulated as bonded to the substrate through the point-bead method, which covers 40% of the thermal insulation surface, and anchors. The wind load is applied as an extremely high suction of 5 kPa.

The wind load does not lead to major deformations (about 0.18 mm in the middle between the anchor and the edge of the panel) and stresses (maximum around 0.45 N/mm² in the rendering next to the anchor plate) in the system and, therefore, no damages are expected. However, the method used is a static approach. This means that further researches are needed to assess how the system behaves in relation to dynamic wind loads, as would be the case in nature.

Since wind is not the only load that acts on the ETICS surface, further investigations are carried out to assess the impact of temperature, moisture and dead load on the system in terms of distribution of the stresses and deformations.

The study is performed on an ETICS with 400 mm EPS and 12 mm rendering system, which is simplified as one layer. The substrate is instead not modelled. The thermal insulation is fixed on its underside (inside), which corresponds to a full-surface bonding. The model represents an entire façade with ETICS (50 m long and 25 m high) but for symmetry reasons, only a quarter is modelled (25 m long and 12.5 m high). There are also two window sections - one in the middle area of the façade, and one in the edge area. The render is considered as an elastically bedded slab on which dead load and hygrothermal loads act.

The hygric loads lead to a greater deformation than the thermal loads. The deformation due to dead load is small. In practice, these effects normally cannot be separated, as dead loads are always present and temperature changes are accompanied by changes in moisture content. The largest deformations occur in the edge area with the maximum value in the corner. The expansion of the central area is hindered by the surrounding areas. However, the analysis takes into account only a single façade. This means that the values of the deformation at the edge and the corner may be influenced by adjacent walls.

Several topics have been touched upon to show the possibilities that arise when the system is broken down and sub-areas are considered. Each of these topics would need to be explored further. Furthermore, further testing of material properties and material-material interaction are needed, in order to validate the models and align them with experience from practice. Additionally, large-scale effects need to be considered such as constraints from adjacent building parts, windows, corner-corner intersections, roof-wall areas etc.

6 Summary

ETICS show a good hygrothermal performance within the range of the values and boundary conditions analysed. The rendering system and its properties such as water absorption and water vapour resistance play an important role in the moisture balance of the system and, therefore, in its functionality. Numerous mechanical and hygrothermal models were set up and validated during this project as planned and can now be used for future research and investigations on various topics identified in the course of this work.

Additional gaps, lack of information and shortcomings on statical issues were identified by the external experts' report, that need to be addressed within the discussions of the standardization committees, e.g. if the partial safety factor for the load-bearing capacity of the anchors needs to be increased because of no longer knowing the statistical scatter or the minimum values. This might lead to a higher number of anchors, which may make the systems uneconomical. However, in the meanwhile WG 18 started to revise prEN 17237 to address this shortcoming.

On the other hand, changes in the system components led to changed behaviour of the whole system. In recent years, there has been a trend towards thicker composite thermal insulation systems. With thicker systems, the bedding stiffness is lower than with thin ones, which leads to greater deformations. This must be taken into account in the future for systems that might become even thicker.

7 Recommendations for next steps and future work

The unsolved questions are related to the effect of static and dynamic loads on the hygrothermal and mechanical performance of ETIC-system and the influence of its characteristics on the response to the impact of the load. This is also correlated to the ageing mechanisms that occur in the system influencing its performance.

- Thermal conductivity in moist materials: The impact of moisture on the hygrothermal performance of the system is considered in design values by the pragmatic approach in ISO 10456. However, this approach might underestimate the heat-transport in wet materials in some boundary conditions due to neglecting latent heat and phase changes. Especially the conversion coefficients and the range of the validity for some materials have to be adjusted. This involves systematic testing of different materials and material groups with several moisture contents and several different boundary conditions. Measurement could be carried out at dry conditions, 0.1%, 0.5%, 2% by Vol.), considering different thermal insulation materials (organic / inorganic or open / closed structured, sustainable etc.) and material parameters (e.g. water vapour diffusion resistance).

- Influence of moisture on the mechanical performance: Moisture influences the mechanical performance of the system affecting both the performance of the thermal insulation itself and the interaction between the insulation layer and the rendering system. The bond strength between these two layers changes due to relative humidity and in case of rain and frost as well. Since the amount of water that penetrates the system remains in the outer layer of the thermal insulation next to the base coat, the effect of moisture on the interaction between the thermal insulation and the rendering system could be amplified.

  This could be tested by analysing the impact of different amounts of moisture contents on the bond strength (possible steps could be dry, 0.5%, 2%, 10%), considering different thermal insulation materials (MW, EPS, Wood fibre, etc.) and rendering systems (organic and inorganic) as well as other material parameters (e.g. water absorption). Testing shall also consider the impact of repeated wetting and drying – with and without frost.

- The analytical calculation of the deformation of an ETICS system is generally carried out on the model of the elastically bedded slab strip. It is assumed that the axial rigid rendering is connected to the shear-stiff insulation material and that this in turn is connected on its opposite side to the rigid substrate.
  The shear modulus of the insulation material is an important material property for the ETIC system. In connection with the insulation thickness, the bedding stiffness for the plaster system results. Whereby with the same loads and axial stiffness of the rendering, the displacement of the system become greater with smaller bedding stiffness and vice versa.
  The thicker the insulation material, the smaller the bedding stiffness. This means that with increasing insulation thickness, the displacement of the system in the plane of the slab increases and thus also the shear stress on the anchors.
  As a rule, however, the anchors are designed for tension. They form the tension strut in the bracket support model for anchored systems and also take up the load in the case of wind suction. The anchors are normally not intended for the shear load mentioned above, which could be problematic with increasingly thicker and thus "softer" systems.
  It is therefore proposed to analyse the shear loading of the anchors in the context of thick insulation systems for different insulation materials. The study could be carried out for EPS, mineral fibre and wood fibre insulation or others. The shear moduli for the insulation materials mentioned are known within a range. In

addition, these values, especially for wood fibre insulation, can be validated by determination in the laboratory.
The studies should first be carried out on a theoretical model, whereby a linear-elastic behaviour is initially assumed for the insulation material within the deformation range. The displacements should be determined numerically and compared with the analytical solutions. The determination of the forces acting on the anchors and the response of the anchors should again be carried out using FEM.
Experimental investigations can also be carried out to validate the calculations, although the set-up would still have to be agreed in the expert group. In this case, FIW proposes sample size and sample thickness regarding the increase of thickness in ETICS.

- Durability aspects: The evaluation of the ETICS durability is performed through the threshold approach, in which the properties are tested after the exposition to hygrothermal conditions to check if the threshold value is reached. The use of this method does not guarantee the evaluation of the service life and the gradual deterioration of the material is not considered. The projection and calculation of the service life would be possible instead through the approach based on the evaluation of the deterioration of properties over time and exposure if the deterioration is known in dependence of boundary conditions and a failure criterion is defined. This method requires the investigation of the material-specific degradation mechanisms, the limit value for key properties, the accelerating factors and the comparison between short- and long-term exposure. The study has to be carried out for the relevant material and for the parameters of their interaction (rendering system, thermal insulation, adhesive) firstly limited to typical products in each product group.

  Analysis of the hygrothermal and mechanical influence on the relevant properties of components and the interlocking between layers through laboratory test under accelerated exposure, i.e. comparison of the deterioration of the same property at different severities of the exposition (temperature range between 20°C and 70°C and relative humidity range between 30% and 90%). Determination of the accelerating factor for each exposure by comparison (possible use of established relations, e.g. Arrhenius Law).

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Forschung und Entwicklung auf dem Gebiet des Wärme- und Feuchteschutzes

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