The effect of temperature, humidity and mechanical properties on crack formation on external thin plasters of ETICS

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Abstract. External Thermal Insulation Composite Systems (ETICS) are widely used in the northern hemisphere in retrofitted and new external walls. The outer layer of ETICS is usually a thin layer of plaster. The effects of temperature and humidity on the hygrothermal behaviour and mechanical properties of thin plasters have been quantified by conducting several experiments to determine the possibility of crack formation. Combinations of plasters using four types of binders are tested: mineral, polymer, silicate and silicone. Plasters are tested as four systems consisting of a base coat, a glass-fibre reinforcement mesh and a finishing coat. Sorption curves of the plaster systems are determined to gather data for numerical simulations. The coefficients of thermal and hygroscopic expansion are determined. The modulus of elasticity and tensile strength of four different plasters are measured to allow the calculation of crack formation in ETICS and suggest the distances between the deformation joints. The method demonstrated in this paper makes it possible to calculate the crack formation caused by the temperature and moisture shrinkage in the thin exterior plaster of ETICS.

1. Introduction
As building envelopes are in a need of renovation due to ageing, one of the most affordable ways to restore the decent look of a façade and improve the energy performance of a building envelope is through the application of External Thermal Insulation Composite System (ETICS). The system consists of several layers – thermal insulation layer with adhesive mortar and anchors for on-site application; a reinforced base coat of render to cover up and protect the insulation from weather impact and a finishing outer decorative layer. In the European Union, guidelines for evaluating the various aspects of such systems have been drawn up – ETAG 004. Systems that are in accordance with the guidelines for European Technical Approval get ETA certification, which confirms to the user that all components suggested by the manufacturer, if installed as instructed, work well as a system, thus making the manufacturer partially responsible for the performance of ETICS [1]. However, it has been observed that even certified ETICS tends to crack and deteriorate under certain climatic conditions [2] and the need to gain a better understanding of those conditions is vital to get crack formation under control and ensure the avoidance of them in the design phase. Visual inspection of renovated ETICS facades in Estonia identified external defects already appearing within 1-6 years after the installation of ETICS with cracking of the facade found to be the most common defect - 30\% oriented cracks and 4\% non-oriented cracks [3]. The review conducted by [4] has shown that one common cause of defects is the incorrect assembly of ETICS components. The lack of studies on the durability of ETICS is noted by [5] and a method focusing on a service life of thin rendering is proposed.

The most effective way to test the durability of rendering systems is through the construction of a test wall and then cycling the system in a climatic chamber. While it is an effective method, it is also time consuming and relatively expensive to conduct with an excessive amount of ETICS variations. To

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pre-evaluate the plaster systems of interest (base coat + glass-fibre mesh + finishing coat), a series of experiments was designed. The effect of temperature and humidity on the hygrothermal behaviour and mechanical properties of thin plasters has been quantified to determine one of the most common causes of plaster failure, crack formation.

Several studies have already been done with the goal of understanding various kinds of crack formation mechanisms in different types of rendering, for example; research carried out by [6] concentrates on modelling impact factors of the construction process on the degradation of the rendering and crack formation. Research [7] determined the dimensional changes of different plaster systems exposed to different climate conditions and cycling. The study by [8] analysed hygrothermal and mechanical behaviour and detected that the thermal expansion coefficient of the exterior rendering of the ETICS system, together with the climatic conditions, was critical to the appearance of cracks along the joints of the plate. Study [9] examines climatic conditions at the application, curing conditions and the water absorption of the background to determine the impact on crack formation through tensile strength.

However, this study focuses on determining the modulus of elasticity to predict possible crack formation caused by changes in the temperature and moisture content of the render systems. A theoretical simplified method is then used to calculate the distance between the deformation joints as suggested in ETAG 004 and the critical changes in temperature and moisture content are calculated.

2. Methods

2.1. Materials used and combinations of render systems
In this study, four combinations of plaster binders were chosen: mineral, polymer, silicate and silicone.

- Combination 1 (C1): polymer base coat (Sto-Armierungsputz) + polymer finish coat (Stolit MP)
- Combination 2 (C2): polymer base coat (Sto-Armierungsputz) + silicone finish coat (StoSilco MP)
- Combination 3 (C3): mineral base coat (StoLevell Uni) + primer (StoPrep Miral) + mineral finishing coat (StoMiral MP)
- Combination 4 (C4): mineral base coat (StoLevell Uni) + primer (StoPrep Miral) + silicate finishing coat (StoSil MP)

All specimens were composed as thin-layer rendering systems, polyethylene plastic was chosen as a base for preparation and curing. All base coats were applied with a 6 mm notch trowel held under 45° to ensure an even coat thickness of 5-7 mm and reinforced with an alkali-resistant 6 x 6 mm glass-fibre mesh. Approximate location of the reinforcement in a cross-section was between 1/2 and 1/3 from top of the layer of the base coat. Each layer of the system was applied after the previous layer had cured for 24 h. The age of specimens is counted since the application of the first layer.

2.2. Tensile strength and modulus of elasticity
To determine the resistance of the thin-layer render resistance to tensile stress, a render strip tensile test can be used as described in ETAG 004 §5.5.4.1. The test mainly focuses on the determination of the characteristic crack width $w_{cr}$. Render strips with dimensions 600 x 100 mm² go through 10 loading-unloading cycles, with loads up to 50% of expected strength at cracking (for polymer rendering systems up to 250 N). On the 11th cycle, the load increases with a rate of strain 0.5 mm/min. The loading process is interrupted at 0.3%, 0.5%, 0.8%, 1.0%, 1.5% and 2.0% elongation and the quantity and width of visible cracks are counted and measured on both sides of the render strip. Subsequently, the characteristic crack width is calculated using the 95% quantile with a confidence level of 75% [1].

The goal of this research was to measure the tensile strength of a render strip. It was determined with pre-testing, that rectangular specimens as suggested by ETAG 004 were not suited for measuring tensile strength, as the specimens tend to break at the border of a clamp. As a result, a new shape of the specimen was chosen to optimise the conditions for tensile stress distribution (see Figure 1). Other test execution aspects were followed as requested by ETAG 004. The chosen width reduction was enough to prevent cracking near the metal plates.
The failure of tensile resistance was considered to be the moment when the first penetrating crack was observed. Strain and stress were measured with the test device, considering the strain applied during preloading. The test specimens for this experiment were cured in environments of RH=33% and RH=95% at 20 °C to see if the change in relative humidity has an impact on tensile strength and crack formation. The specimens were tested on the 39th day after the first layer of render was applied.

2.3. Sorption curve

Both absorption and desorption curves were measured in climatic boxes that contained saturated salt solutions described in EN ISO 12571:2013 [10], the reference relative humidity levels were taken from the research of Washington’s National Bureau of Standards [11]. The boxes were equipped with fans to ensure even distribution of humidity in the box and to speed up the hygroscopic processes. The specimens were hung through the lid to make the weighing process more convenient and minimise the disturbance of the environment inside the box during weighing.

According to the ISO 12571:2013, the specimen must have a mass of at least 10 g, in this case the specimens mass varied between 35 g and 60 g with dimensions 100 x 50 mm. The specimens were cured for 28 days at 20 °C RH=65% as suggested by the manufacturer. On the 29th day, the specimens were placed in a drying cabinet at 60 °C to determine the dry weight.

2.4. Expansion coefficients

To determine the thermal and moisture expansion coefficients, the test specimens with dimensions of 100 x 300 mm² were prepared and cured for 28 days at 20 °C and RH=65% conditions. The specimens were prepared on three different substrates – PE film (no substrate), mineral wool and expanded polystyrene. Afterwards, the gauge plugs were glued with two-component epoxy adhesive. The test specimens were then placed in a 20 °C and RH=30% environment until mass equilibrium was achieved, to ensure similar starting conditions (the moisture content of all four combinations of render systems tested is similar in this environment, as seen on the sorption curve, see Figure 3).

To measure the thermal expansion coefficient, the absorbed moisture was then trapped in the specimens by wrapping the individual specimens in PE film, making sure that the changes in RH in the climatic chamber would not affect the moisture content of the specimens. Measurements of length change were taken with a 0.01 mm mechanical dial gauge located outside the climatic chamber, reducing the thermal expansion of the dial gauge. The test specimens were acclimatised for 3 hours at each temperature level. The experimental temperatures in order were +20 °C → +40 °C → +60 °C → +20 °C → +5 °C → -20 °C. To measure moisture expansion coefficients, the specimens were placed under water for two weeks, after that the specimens were left to dry and the length change measurements were taken during the drying process with a digital calliper, as the wet specimens tended to bend under the dial gauge.
2.5. Analysis of the effect of temperature on crack formation through mechanical properties

In this research, the expansion coefficients $\alpha$ and $\beta$, the Young’s modulus of elasticity $E$ (MPa) and the ultimate tensile stress at crack formation $\sigma_{\text{cracking}}$ (MPa) are experimentally determined. From that, a critical deformation $\varepsilon_{\text{critical}}$ at crack formation can be calculated using the Hooke’s law. Knowing the expansion coefficients of rendering systems, the ultimate deformation caused by changes in temperature and moisture content $\varepsilon_{\text{max}}$ can be calculated with Equation 1, where $\alpha$ is the thermal expansion coefficient, $\beta$ is the moisture expansion coefficient, $\Delta T$ is the change in temperature of interest, $\Delta u$ is the change in moisture content.

$$\varepsilon_{\text{max}} = \alpha \cdot \Delta T + \beta \cdot \Delta u \tag{1}$$

The final distance between the deformation joints can be found through the quotient of displacement of 1 m of rendering system $U_{\text{critical}}$ calculated through previously known $\varepsilon_{\text{critical}}$, that is the maximum tensile deformation of the material before rupture and $\varepsilon_{\text{max}}$.

$$L_{\text{max}} = \frac{U_{\text{critical}}}{\varepsilon_{\text{max}}} \tag{2}$$

To assess the stress in the material caused by the change in temperature and moisture content that can be compared with the tensile strength of the material and therefore evaluate the risk of crack formation, Equation 3 can be used.

$$\sigma_{\text{at cracking}} \geq E \cdot (\alpha \cdot \Delta T + \beta \cdot \Delta u) \tag{3}$$

3. Results

3.1. Tensile strength, modulus of elasticity

The tests were conducted on four combinations of thin-layer rendering systems, the systems shown in Chapter 2.1. The effect of temperature and relative humidity appeared to have a random effect on the results of the tensile test (see Table 1). Randomness could have been caused by an insufficient number of specimens, since the application of rendering systems is not a standardised procedure and prone to errors, it was nearly impossible to achieve identical specimens to produce comparable tensile test results. To increase the number of specimens, the results of the tensile tests were combined into one value that does not depend on the curing condition. The results are represented as a 95% quantile with 75% confidence (see Table 2).

| Table 1. | The results of tensile strength and modulus of elasticity of the four rendering systems cured at different temperatures and relative humidity conditions are represented as a 95% quantile with 75% confidence. |
|---|---|
| $t$, °C | $\sigma$, MPa | $E$, GPa |
| RH, % | 17 | 33 | 50 | 95 | 88 | 60 | 20 | 20 | 20 | 20 | 5 | 60 | 33 | 50 | 95 | 88 |
| C1 | 3.52 | 3.97 | 3.25 | 4.20 | 3.72 | 0.21 | 0.26 | 0.20 | 0.19 | 0.19 |
| C2 | 2.29 | 5.59 | 3.16 | 1.41 | 3.15 | 0.20 | 0.21 | 0.21 | 0.12 | 0.19 |
| C3 | - | 0.29 | 0.70 | 0.29 | 0.34 | - | 0.25 | 0.16 | 0.27 | 0.17 |
| C4 | 0.35 | 0.41 | 0.64 | 0.32 | 1.67 | 0.14 | 0.19 | 0.19 | 0.23 | 0.18 |

| Table 2. | The mechanical properties of the rendering systems calculated from the results of the tensile tests are represented as 95% quantile with 75% confidence. |
|---|---|
| Rendering system | $\sigma_{\text{cracking}}$, MPa | $E_{\text{max}}$, GPa | $\varepsilon_{\text{critical}}$ | Elongation at rupture, % |
| C1 | 2.67 | 0.22 | 0.0122 | 1.22% |
| C2 | 3.39 | 0.18 | 0.0186 | 1.86% |
| C3 | 0.42 | 0.17 | 0.0024 | 0.24% |
| C4 | 0.10 | 0.15 | 0.0006 | 0.06% |
The points at which the primary data was collected to calculate the properties presented in Table 2 are presented in Figure 2.

The most plastic rendering system turned out to be the one with a polymer base coat and the silicone resin finishing layer, i.e., C2, and the most elastic is the rendering system with polymer finishing, i.e., C1. It is hard to say if the polymer finishing coat of the rendering system C1 makes a significant impact on the tensile strength of the specimen as the C2 results are slightly more scattered than C1.

![Figure 2. Position vs. stress graphs typical for polymer (green) and mineral (black) specimens recorded by the tensile device.](image)

The information gained from these tests will be later used to analyse changes in temperature to determine crack opening tensile strength.

3.2. Sorption curve

It was determined that the difference in finishing coat had insignificant influence on the outcome, so to complete the goal of the research and present curves that are reliable for use in modelling, the combined average values of moisture content for rendering systems C1 and C2 can be observed in Figure 3.

The difference in moisture content between the mineral and polymer rendering systems at different temperatures can be seen in Figure 3. Mineral rendering systems being more porous, they absorb 2 to 5 times more moisture (depending on the temperature and RH) from the air than polymer renders, making them more vulnerable to a damp environment and freeze-thaw cycles.

![Figure 3. Sorption curves of rendering systems with polymer base coat at 5 °C (blue) and 24 °C (red). Adsorption curves of rendering systems with mineral base coats (green) at +5 °C and +24 °C.](image)
3.3. Expansion coefficients

The results of the measured expansion coefficients for four combinations of rendering systems are shown in Table 3. The deviation from the linear trend of thermal expansion appeared to be minimal, so the results of thermal expansion coefficients $\alpha$ can be considered suitable for use in basic thermal performance modelling. Moisture expansion coefficients $\beta$ are measured from the difference between dry and wet specimen’s length, where dry stands for hygroscopic range and wet means immersed for 2 weeks in water. The results of the moisture expansion coefficient for the rendering system C4 could not be quantified as it became too damaged after being immersed in water, the results on C3 on mineral wool could not be quantified as the deformations were so small that the trend was not observable.

| Table 3. Expansion coefficients of four combinations of rendering systems. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | C1              | C2              | C3              | C4              |
| $\alpha_{\text{no substrate}}$, m/(m·K) | 22.3×10^{-6} | 19.9×10^{-6} | 7.5×10^{-6} | 13.1×10^{-6} |
| $\alpha_{\text{mineral wool}}$, m/(m·K) | 16.6×10^{-6} | 17.2×10^{-6} | 8.9×10^{-6} | 5.0×10^{-6} |
| $\alpha_{\text{EPS}}$, m/(m·K)       | 16.7×10^{-6} | 16.9×10^{-6} | 8.8×10^{-6} | 5.7×10^{-6} |
| $\beta_{\text{no substrate}}$, m/(m·(m³/m³)) | 3.5×10^{-3} | 2.7×10^{-3} | 0.5×10^{-3} | -             |
| $\beta_{\text{mineral wool}}$, m/(m·(m³/m³)) | 3.1×10^{-3} | 1.4×10^{-3} | -              | -             |
| $\beta_{\text{EPS}}$, m/(m·(m³/m³))     | 3.7×10^{-3} | 3.4×10^{-3} | 1.8×10^{-3} | -             |

3.4. Analysis of the effect of temperature on crack formation through mechanical properties

The temperatures for the render application recommended by the manufacturer of tested rendering systems varies from +5 °C to +30 °C. Presuming the temperature of façade in the winter is -30 °C and +30°C during the application of the rendering system on EPS board, the extreme possible temperature changes that are likely to appear are $\Delta T$=60 °C. The greatest moisture deformations are caused by the complete drying of the rendering system, making $\Delta u$ maximum moisture content. An example of the distance between the deformation joints $L_{\text{max}}$ of rendering systems C1, C2 and C3 is presented in Table 4.

| Table 4. An example of theoretical distances between the deformation joints in the rendering. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Rendering system | $\sigma_{\text{crackings}}$, MPa | $E_{\text{max}}$, GPa | $E_{\text{critical}}$, m/(m·K) | $\Delta T$, K | $\alpha$, m/(m·K) | $\Delta u$, m/(m³/m³) | $\beta$, m/(m·(m³/m³)) | $\varepsilon_{\text{max}}$, m | $L_{\text{max}}$, m |
| C1              | 2.67            | 0.22            | 0.0122          | 60            | 16.7×10^{-6} | 0.172           | 3.7×10^{-3} | 0.0016         | 7             |
| C2              | 3.39            | 0.18            | 0.0186          | 60            | 16.9×10^{-6} | 0.168           | 3.4×10^{-3} | 0.0016         | 12            |
| C3              | 0.42            | 0.17            | 0.0024          | 60            | 8.8×10^{-6}  | 0.231           | 1.8×10^{-3} | 0.0011         | 2             |

The example of maximum displacement of a 1 m rendering strip caused by the extreme changes of temperature and moisture content is presented in Table 5. It can be seen that the displacement caused by the temperature and moisture content affects the polymer rendering systems C1 and C2 3-4.5 times less than the changes affect the mineral rendering system C3. Therefore, it can be concluded that polymer rendering systems do not tend to crack due to changes in humidity and temperature alone. The remaining displacement of a 1 m mineral rendering strip is 1.46 mm indicating that small tensile strength of a mineral rendering system makes the thin-layer mineral plasters more susceptible to changes in temperature and moisture content lessening the ability to resist to other causes for rupture by 39%.

| Table 5. The length changes of a 1 m rendering strip caused by the decrease in temperature and moisture content and the remaining displacement before rupture of the rendering system. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $\Delta T$, °C  | $\Delta u$, m³/m³ | Length change from $\Delta T$, mm/m | Length change from $\Delta u$, mm/m | % of whole displacement before rupture | remaining displacement before rupture from other causes, mm/m |
| C1              | 60              | 0.172           | 1.002           | 0.636           | 13%                     | 10.61           |
| C2              | 60              | 0.168           | 1.014           | 0.571           | 9%                      | 17.05           |
4. Discussion and need for future research

The results of the tensile strength of the render was compared with Portuguese research [9] where similarly shaped test specimens were used and cured at the similar conditions. The tensile strength of the mineral rendering system presented in this paper was 23% greater.

To get some approximate indication of the reliability of the sorption curves presented in this study, another similar research published in 2015 was examined [12], unfortunately the moisture content of cement-based plasters was very different, so other methods of analysis had to be used. The manufacturer declares the moisture content of absorption at 23 °C and RH=80%, the moisture content in this study exceeds the declared value only by 4%, so it increases the reliability of the current results.

A simplified method for eliminating crack formation by adding deformation joints in the plastering system of ETICS was suggested, as well as an equation to calculate the stress caused by changes in temperature and moisture content, which allows evaluating the possibility of crack formation (see chapter 2.5).

Based on the results of this study, the extreme changes in temperature and moisture content lessen the ability to resist the tensile stress by 32% for mineral rendering systems and 7-11% for polymer rendering systems, indicating that changes in temperature and moisture content does not result in rupture of the polymer rendering system but makes mineral rendering systems more prone to cracking as it decreases crack resistance ability by a third.

At the most common ΔT=60°C in the northern hemisphere, the distance of the deformation joints for an polymer rendering system is around 9.5 m and around 2 m for cement based rendering systems at maximum moisture content indicating that ETICS might not be suited for application in climates with constant rain, as it was also stated by Kvande et al 2018 [4].

As oppose to Ximenes et al. [5] model of degradation and service life of ETICS, that allows predicting the degradation of the façade based on a large scale field study and quantification of façade defects in correlation with exposed climate and age of the façade, this model will allow taking into consideration the execution conditions and quality of installation, if documented correctly, giving the opportunity to predict critical changes in temperature and moisture content and their effect on tensile stress resistance. To use this model, laboratory tensile strength tests and measurements of thermal and moisture expansion coefficients must be performed for the materials of interest.

The method has a lot of simplifications. It does not take into account the uneven distribution of temperature and moisture throughout the whole thickness of the rendering system as it most likely is in reality during the application. Moisture content and temperature fluctuate more near the surface of the rendering system where the higher stress levels concentrate making the unreinforced finishing layer more susceptible to formation of the first cracks.

To increase the effectiveness of this method and propose guidelines for execution of the experiments, a bigger database of tensile strengths, modulus of elasticity must be collected, including the impact of extreme application and exploitation conditions on the mechanical properties of different rendering systems, bearing in mind that tensile strength of rendering system tends to decrease while frozen when damp. The proposed method by using equations 2 and 3 presented in chapter 2.5 should be validated against measured results through large-scale experiments on a test wall to increase the reliability of the proposed method.

5. Conclusions

A method demonstrated in this paper enables determining the impact of temperature and moisture shrinkage on the crack formation in the external thin plaster of ETICS. Temperature and moisture shrinkage as well as mechanical properties of rendering systems, such as the relationship between tension and deformation, as well as destructive tensile strength, were experimentally measured for four thin plastering systems. The distances required between the deformation joints to avoid cracking due to exceeding the tensile strength can be calculated using Equation 2. By using a representative temperature drop (from the maximum acceptable application temperature for plaster to minimal, depending on the climate), moisture decrease (from fresh, moist plaster to the hygroscopic range), and a modulus of
elasticity by using Hooke’s law, an acceptable tensile tension to avoid plaster cracking can be calculated by using the proposed equation 3. By applying a proposed theoretical method on plasters used in this study, it is found that polymer renders do not tend to deteriorate solely from effect of temperature and humidity change as opposed to cement based rendering systems.

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