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Failure Analysis of a Total Damage by Hail Impact of an External Thermal Insulation Composite Systems

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Abstract. *A hailstorm has heavily damaged a glass fibre mesh reinforced mineral render of an externally insulated composite system (ETICS) of a family house. While a neighbouring house of identical design and of the same age showed only minor defects, for the house under investigation it was a total failure of the render. Material probes were taken from the damaged façade and analysed physically and chemically. Before renovation, the hail resistance of the façade was determined with a unique artificial hail impact test method: Clear ice balls were shot against the façade with the help of a launcher, where the kinetic energy of the projectile can precisely be controlled. The type of damage due to natural hail could be reproduced. The impact energy needed to cause a damage similar to the one caused by the natural hail was determined. The hail impact damage was also identical to results from hail testing performed in the laboratory on similar systems. Since the amount of rendering material on the façade was not according to standards of the Swiss Society of Engineers and Architects - it was by far too thin - specific laboratory tests were performed with specimens not only made of similar materials but also with a comparable thin render layer. By systematic variation of the projectile size and its velocity, the impact parameters were studied and correlated to the type and extent of the hail impact damage. A threshold, associated with the first appearance of full circle cracks in the render, was found to be a kinetic energy of 2.5 J. The assessment of a supposed thickness effect and an effect of doubling the reinforcement on the hail impact resistance and the effect of the age of the façade however was a challenge. The methodological limitations given by the circumstances and the approach used are discussed in this paper.*

Keywords: *ETICS, Hail Damage, Impact, Ageing, Testing.*

1 Introduction

The effect of ageing on the durability of building elements, such as façades has been addressed in the last years by the scientific community of construction engineering and materials science (Bochen, 2009; Bochen and Gil, 2009; Daniotti *et al*., 2015; Daniotti, Paolini, and Re Cecconi, 2013; Griciute, Bliudzius, and Norvaisiene, 2013; Norvaišiene, Norvaišiene, GriciutĖ, Bliudzius, and Ramanauskas, 2013). Building insurances of Germany, Austria and Switzerland have established a register of products for building elements, which are certified for resistance against hail impact (ACFI, 2020). The certification is based on an artificial hail impact test, which classifies the product in one of five hail resistance classes. A weakness of this certification is the fact, that products are tested and classified when they are new. The certification does not cover any deterioration of the hail resistance with the age of the product. It is an open question how much a product in service loses hail resistance with its age.

On first of August 2017 a heavy thunderstorm accompanied by hail passed the region of Winterthur, Eastern Switzerland. The building insurance of Zürich was informed by a house owner of a medium sized family house, that the façade oriented to northwest, from where the hailstorm came, has been heavily damaged. In the view of the building insurance, the ETICS on that façade should have resisted such a hailstorm and therefor the heavy damage was not expected. Swiss Federal Laboratories of Materials Science and Technology (Empa), Natural Hazard Prevention of the Association of Cantonal Fire Insurance Companies (ACFI) and the Building Insurance of Zürich (GVZ) have initiated thereafter a case study to get a deeper understanding of the cause of this damage.

2 Design of the Case Study

The idea of the study was that the façade, which was 17 years old, had a reduced hail resistance due to ageing. During the course of the study additional factors have been considered, such as the thickness of the render (amount of material applied) and the reinforcement. The case study had the following parts:

1) Description of the thunderstorm
2) Detailed description of the hail impact damage on the ETICS
3) Determination of the hail resistance of the ETICS on-site; measurement of the hail resistance in the aged condition
4) Fabrication of a representative peace of the façade in order to determine the hail resistance of a new façade of the same design
5) Comparison of the hail resistance of the new façade with the aged façade

3 The Thunderstorm of August 1st 2017 in Winterthur

August 1st 2017 was a typical high summer day with a flat atmospheric pressure distribution over Europe. In the meteorological forecast for Eastern Switzerland the development of thunderstorms was expected with hail of hailstones up to 4 cm in diameter. Observations of hail in the neighborhood of the house under investigation stated hailstones of as large as 32 mm, s. Fig 1.

Figure 1. Hailstones of the thunderstorm on August 1st 2017 in Winterthur.

These observations confirmed a hailstorm of class 3, which has an occurrence probability of one in in 5 to 20 years in this region. Therefore such a hailstorm as to be considered in the design of a building, because a building should last for 30 to 40 years, (Kempton, Chap, and Alani, 2002). According to CFIA standards, the façade should be class 3 hail resistant, which means, that this specific event should have been survived undamaged. The first conclusion was, that the façade was not as strong as it should be according to CFIA regulations.

4 Damage Description of the Affected Façade

The house was exposed to Northwest. An aerial view of the house with the affected façade from West is shown in Fig. 2. A detailed visual inspection showed 147 damage locations evenly distributed over the façade's area of 70 m^2. The damages found were classified in three categories: cracks (low level damage), full circle fracture (medium level damage) and breakout of the render with uncovering of the reinforcement (high level damage). Typical representations of these three types of damage are shown in Fig. 3. 71 locations showed a low level, 51 a medium level and 21 locations a high level damage. The morphology of these damages was similar to damages found in artificial hail tests on ETICS (Steinbauer, 2016).

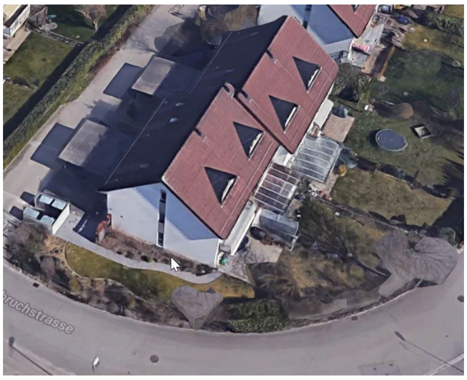

Figure 2. Aerial view of the façade from West.

Figure 3. Representations of the damage classes: crack (left), full circle fracture (center) and breakout (right).

5 Construction and Background of the Façade

The house was built in 2000. According to the drawings, the façade was based on a brick wall on which a thermal isolation of 10 cm thickness was bonded, covered by a rendering. This is a classical design of a modern ETICS. The originally used products could not be found out. Therefor 15 material probes were taken from the façade and analyzed physically and chemically.

The thermal isolation was a polystyrene foam with grain size of 2.8 mm and a density of 19.2 kg/m^3. The rendering was characterized with Thermal Gravimetric Analysis (TGA), Infrared Spectroscopy (IRS), and X-Ray Diffraction (XRD). The render was cement-bound. The main crystalline phase was calcite (aggregate, filler and carbonated binder). In addition, it contains dolomite, quartz and layer silicates as aggregates and filler. The calcium hydroxide was no longer visible from the cement, because it was carbonated (also not visible in the TGA). However, residues of the cement clinker phases were still visible. Mono-carbonate was seen as the hydration product. Some gypsum was also found. The chemical composition was as for a typical high strength mineral render bonded with Portland cement for thin layer application. The rendering was reinforced with a single or double layer of a mesh of glass fibers with an acrylic and polystyrene coating. The dimensions of the different layers were measured, s. Fig. 4. and table 1. Some those findings quality questions arose.

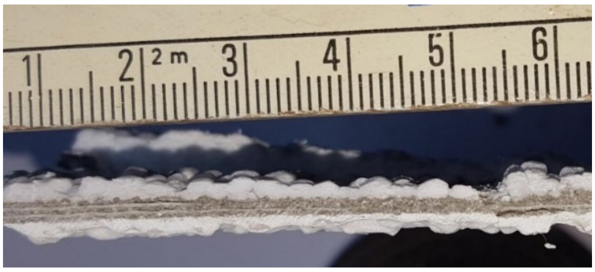

Figure 4. Cross section through the rendering (inside up – outside down): double reinforcement on the left, single reinforcement in the middle and on the right.

Table 1. Average and ranges of thickness of the different layers of the rendering of the façade.

Base coat, including the reinforcement	Finish coat, with sand grains	Paint coat	Total
mm	mm	mm	mm
1.5	1.4	0.2	3.1
1.4 – 1.6	0.4 – 1.6		2.5 – 4.5

For the strength of the rendering system, the paint coat and the finishing coat are of secondary importance. Therefore, in order to assess the quality of the rendering system, the focus was on the thickness of the base coat. According to the Swiss standard for Engineers and Architects SIA 243 (SIA, 1998), the base coat must have a thickness of 2 mm to 7 mm. Also the Austrian standard ÖNorm B 6410 specifies a minimum layer thickness of 2 mm. A new version of this standard requires an average layer thickness of 3.0 mm and a reinforcement mesh which must be covered with a minimum of 1.0 mm to a maximum of 3.0 mm of concealed render. Therefor we concluded, that the layer structure of the rendering of the façade under investigation was seriously defective and thus not carried out in accordance with the state of the art.

6 Determination of the Hail Resistance

6.1 Onsite Determination of the Hail Resistance of the Façade

6.1.1 Materials and Methods

The hail resistance was determined according to CFIA guidelines (ACFI, 2020). The test took place 8 month after the hailstorm in sunny weather (17°C / 40% r.h.). The facade was bombarded horizontally with clear ice balls at an angle of 45° with an ice ball launcher, see Fig. 5. This test equipment allows to precisely accelerating the projectiles.

Figure 5. On-site determination of the hail resistance with an ice ball launcher.

In total 19 ice balls, 15 with a diameters of 30 mm and four of 40 mm, were shot. The aim was on the one hand to determine the hail resistance class according to ACFI regulations and on the other hand to assess the energy required to provoke damage of the levels mentioned above. An energy threshold for a full circle fracture and the threshold for a breakout of the render could be determined.

6.1.2 Results

The damage caused by the artificial hail, e.g. the bombardment with ice balls, largely corresponded to the damage caused by the natural hailstorm of August 1st 2017. The shot with the lowest kinetic energy provoking a damage was 2.5 J, which corresponds to a natural hailstone of approx. 25 mm diameter in free fall. It resulted in a dent and a full circle fracture in the façade. When the façade was bombarded with 40 mm ice balls and with an energy beyond 10.0 J also breakout of the render was observed. The façade did not show a class 3 hail resistance according to the ACFI guidelines.

6.2 Determination of the Hail Resistance of Reference Specimens

6.2.1 Materials and methods

Two reference specimens representing the rendering with reinforcement built up on the thermal isolation plate were fabricated. The first was equipped with double reinforcement, as applied in the area of house edges and window cut-outs. The second reference specimen was fabricated with a single reinforcement only. Both specimen had two sections: The first section was fabricated with a base coat of only 1.5 mm thickness, representing the façade under investigation. The second section was fabricated according to SIA standards, e.g. with a base coat thickness of approx. 4 mm. For the production of the reference specimens an equivalent rendering system was chosen which had similar chemical composition and mechanical properties. The specimens were put on the roof of the Empa laboratory for hardening under natural weathering condition for 2 and 7 month, respectively. The rendering of the reference specimens had the following dimensions:

Table 2. Average thickness of the different layers of the rendering of the reference specimens.

	Base coat, including the reinforcement	Finishing coat, with sand grains	Paint coat	Total
	mm	mm	mm	mm
Thin section 1	2.3	1.3	0.2	3.8
Standard section 1	3.8	1.8	0.2	5.8
Thin section 2	1.1	1.1	0.2	2.4
Standard section2	4.5	1.1	0.2	5.8

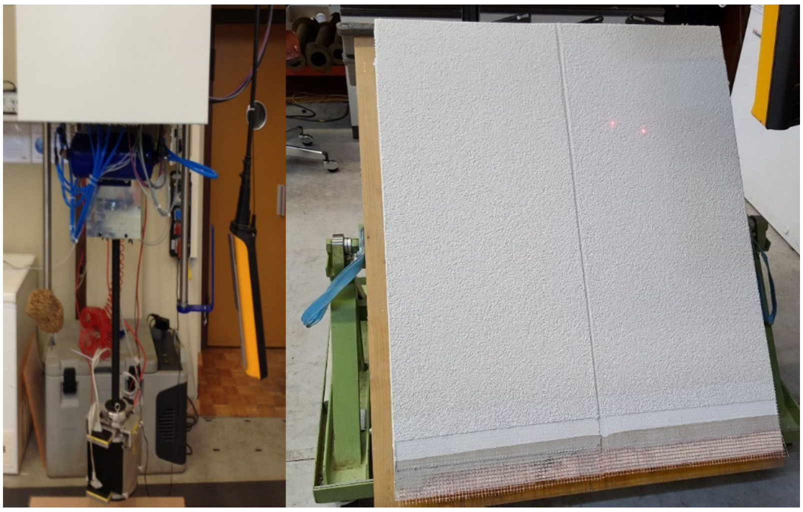

Figure 6. Air gun for artificial hail tests (left) - reference specimen before hail testing (right).

The hail tests were carried out with the Empa air gun for hail testing as well as with the ice ball launcher used onsite, see Fig. 6. The tests were carried out according to CFIA regulation No. 8 (ACFI, 2014). Both specimens were bombarded with 20 mm, 30 mm and 40 mm ice balls, which were made by the melting method from natural ice. The tests were performed at 23 °C / 50 % r.h. The aim was to reproduce the damage caused by the bombardment on the façade and to determine the threshold values for a crack, a full circle fracture and breakouts.

6.2.2 Results

A total of 67 shots were fired on the first specimen, 60 shots on the second specimen, evenly distributed over the two sections each. The results of the hail shots are summarized in table 3 and compared to the results of the shots on the façade. The façade was 17 years old and had a thin layer of base coat with a single layer of reinforcement. The reference specimens were new with a thick layer of base coat on one side and a thin layer of base coat on the other. One specimen had a single reinforcement and one a double reinforcement. Thus, the results can be analyzed with regard to a thickness effect, a reinforcement effect and an ageing effect by comparing the values pairwise.

Table 3. Threshold for damage levels determined on the reference specimens and the façade.

base coat: reinforcement: age:	thick double new	thick single new	thin double new	thin single new	thin single aged
	J	J	J	J	J
Threshold for a crack	1.3	2.6	1.8	2.8	-
Threshold for a full circle fracture	1.9	2.9	3.3	2.8	2.5
Threshold for a breakout	15.4	11.7	12.4	11.6	10.0

No clear effect of the thickness can be seen: For double reinforcement, a thicker base coat may be favorable or unfavorable, depending on the damage level. For single reinforcement, the respective threshold values hardly differ. An effect of the reinforcement can also not be identify in the data: A double reinforcement is unfavorable for low damage level, but favorable for high damage level. An effect of ageing is weakly recognizable, both for a circle crack and a breakout: Both threshold values decrease with age, but only by approx. 15%.

7 Discussion and Conclusions

7.1 Discussion

The overlapping of three major influences makes it difficult to distinguish their individual impacts on hail resistance: For a complete investigation of all effects, not only a façade in the state "aged/too thin" would have had to be present, but also a façade "aged/standard layer". With the reference specimens the two states "new/too thin" and "new/standard layer" were available. Thus, on the one hand, the layer thickness effect could only be quantified in the "new" state and, on the other hand, the ageing effect could only be determined in the "too thin" state. The ageing effect of a rendering with standard layer thickness could not be determined with the available material. Since it was a classic mineral rendering, which was only discovered in the course of the investigation, a significant ageing effect could not have been expected. This result would probably be different if it was an organically bound rendering.

The results of the study leaves the possibility open that a thickness effect or an effect of the reinforcement only occurs in the aged state. A further possibility is that the ageing effect only occurs when the layer structure is correctly applied, but not when it is too thin. An indication that the first possibility applies is the comparison of the façade examined here with the façade of the neighboring house. Both houses have the same design and are of the same age. Assuming that the façade of the neighboring house was correctly manufactured, the thickness effect in the aged condition could be assessed by comparing these two façades. The façade of the neighboring house had only a few impact damages, which could be repaired locally. This indicates that it was not the advanced age that caused the massive damage to the façade, but the poor workmanship. The repair was a complete rebuilding of the rendering.

7.2 Conclusions

The damage to the façade by the natural hail event of August 1st 2017 could be reproduced by bombardments with ice balls of 30 mm in diameter and a kinetic energy of at least 2.5 J. Artificial hail impact with the ice ball launcher onsite as well as with the air gun in the laboratory gave similar results. Energy threshold values for typical damages were determined for a typical mineral rendering system. In the course of the study it became apparent that the structure of the façade did not meet the current standards. Thus, it had to be assumed that the damage to the façade was not only influenced by the age (17 years old), but also by a too thin rendering base coat (1.5 mm instead of at least 2.0 mm). An ageing effect is weakly discernible in the data, while an influence of the coating thickness could not be found.

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