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Tracing hail stone impact on external thermal insulation composite systems (ETICS) – An evaluation of standard admission impact tests by means of high-speed-camera recordings

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ABSTRACT

Hail impact damage on External Thermal Insulation Systems (ETICS) is increasingly recognized by insurance companies owing to increased storm occurrence frequency and storm intensity. To develop hail resistant ETICS for houses and better understand existing admission tests, high-speed-camera recordings of ice ball impacts at an angle of 45° and steel ball impacts at angles of 90° and 45° were used to characterize the impact process and to derivate the damaging mechanisms of impacts on facades.

Recorded surface deformation is characterized by high indentation depth of the impactor and high flexural bending causing high surface parallel strain. Analyses of the impact process allowed the identification of the mechanisms and timing of fracture formation in different regions.

Additionally, differences in the impact process of the European steel ball impact test (90°, ETAG 004) and the Swiss ice ball impact test (45°, VKF P. No 8) are discussed in detail. Caused by the difference in impact angle, the 45° ice ball impacts lead to lower indentation depth and consequently to lower tensile strain and damage. However, surface parallel movement of the impactor caused the formation of an elongated damage pattern in the 45° impacts. To avoid the observed brittle failure behavior, the development of flexible materials with the ability to elastically accommodate impact strains is favorable to reduce hail stone impact damage.

1. Introduction

In recent years, damage caused by more frequent hailstorm occurrence is of economic importance for facade insulation systems, which are increasingly implemented for housings [1]. Using adequate facade insulation, transmission energy loss can significantly be reduced up to 80% [2]. Therefore, facade insulation is a key component for improving the energy performance of buildings. External Thermal Insulation Composite Systems (ETICS) are the most common measure used for the insulation of facades in Europe [3,4]. The system is popular because it provides thermal insulation at economic prizes as well as a long service life of up to 60 years [5]. Materials with a low thermal conductivity coefficient, like expanded polystyrene (EPS) or rock wool, are used to insulate buildings, as these materials reduce the heat transport and therefore optimize the costs for heating and cooling.

0.01pt?>As the insulation materials used in ETICS are soft and vulnerable, their surface is protected from weathering influences by a render system. The ETICS (Fig. 1) is composed of (1) an insulation plate fastened to the external house wall by adhesive and mechanical bolts, (2) a base coat (mortar), (3) a fibre glass mesh reinforcement embedded in the base coat and (4) a polymeric top coat (surface finish), sometimes being applied together with a primer for improved adherence to the base coat [6–8]. In this study we investigated cement based base coats, which are available as dry mortars.

ETICS play a key role in the struggle against climate change [9–11], as heating of houses makes up to about one third of the total energy consumption in countries on the northern hemisphere (e.g. 28% in Switzerland; [12]). However, severe damage to ETICS facades has been

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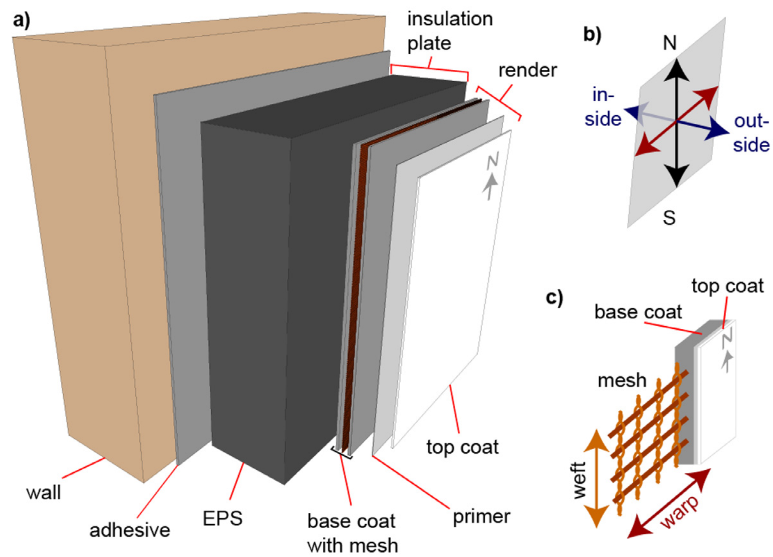

Fig. 1. (a) Design of External Thermal Insulation Composite Systems (ETICS) as used in this study, consisting (from wall to outside) of an adhesive layer (2 mm), an insulation plate (expanded polystyrene EPS, 80 mm), a base coat (4 mm) with reinforcement mesh and a top coat (layer thickness 1.5 mm). (b) Sample orientations used in this study: North direction toward the roof and inside toward the house wall. (c) Close up of the render showing the reinforcement mesh string orientation.

reported with the increasing frequency and intensity of heavy hailstorms in recent years [13–17]. Hail induced depressions and cracks are not only an optical degradation, but also a functional damage of the protective render system [18,19]. Resulting water intake may particularly lead to biodeterioration (like mould formation), which can ruin the entire facade [5,6,20]. The development of ETICS with an increased hail impact resistance is thus important in order to guarantee a long service life under the currently changing climatic conditions. Natural hail stones are described as spherical lumps with diameters of 0.5 to 10 cm (under extreme conditions even up to 18 cm) and weights of 0.1 to 500 g [21]. Final velocities of hail stones before impact are in the range of 10 to 50 m/s leading to impact energies of 0.01 up to 100 J (in extreme events even up to 1000 J, [21]). To test hail resistance of facades, two setups were established in the past:

According to the ETAG 004 [22], the impact resistance of ETICS is tested with a steel ball impactor indenting perpendicular to the surface. In this simple setup, experiments are conducted with steel balls of 0.5 kg at a fall height of 0.61 m or 1 kg from a height of 1.02 m corresponding to impact energies of 3 and 10 J, respectively. In Switzerland and Austria a more sophisticated approach is followed using ice balls with different diameters and speeds. They are shot at an angle of 45° onto the ETICS (VKF P. No. 8, [23]). A multi-step classification scheme with different ball sizes and speeds is applied to judge the suitability of facade products. In our study three different impact test setups (steel ball 90°, steel ball 45° and ice ball 45°) are implemented. [24] did a detailed comparison of the two admission test setups and provides a microstructural analysis of impact structures at the surface and within ETICS as a function of the impactor material (steel vs ice), its impact angle and energy. With increasing impact energy, first fractures are forming internally in the base coat below the impactor (central fractures below the mesh and spalling fractures) followed by circular ring fractures at the surface and mesh parallel fractures. The depression visible at the surface is caused by shortening in the upper part of the EPS.

This study complements these impact damage quantifications [24], by focusing on the dynamic evolution. A high-speed-camera was used to record the impact in order to gather detailed information on the process of indentation and to link these observations with the resulting fracture pattern allowing to unravel the processes of damage formation. In the first part of this paper the recorded impact process (3.1.) and the resulting surface deformation (3.2.) as well as measured values like the impact energy, contact area (3.3.) and impact force (3.4.) will be described in detail. In the second part the differences in the three test setups (4.1.) will be discussed and the surface damage formation processes (4.2.) and the damaging mechanisms derivated (4.3.).

The aims of this manuscript are twofold: First, the methodology allows for the first time to quantitatively evaluate and compare testing procedures used in the European Union (steel ball 90°, ETAG 004, [22]) and Switzerland (ice ball 45°, VKF P. No. 8, [23]) by directly tracing the impact process. Second, we particularly focus on the temporal dynamics of the impact and the resulting mechanical loads for the materials in order to identify optimization potential for hail resistance of the system.

2. Methods

2.1. Materials and sample preparation

ETICS are multi-layer composite materials consisting of i) an adhesion layer attaching the insulation to the house wall, ii) the insulation layer (in this study expanded polystyrene, EPS) and iii) the protective render system (Fig. 1). The render layer consists of a cementitious base coat with an embedded reinforcement mesh, a primer and a polymer based top coat. Materials and layer thicknesses as used in this study are presented in Table 1. Materials were chosen to resemble a typical ETICS as also used in comparable studies [7,24,25].

ETICS samples were produced in dimensions of 1 m x 0.5 m placed in a vertical frame for application of the render layers. Throughout all experiments, samples were oriented with the warp sting of the reinforcement mesh pinning toward the roof. This direction was indicated as “N” (North, also referred to as above) direction on the samples (Fig. 1) to ensure a reproducible orientation at the impact tests (45° impacts were shot from N direction). Sample preparation was carried out by a professional workman following a predefined procedure in analogy to the application on construction site. The base coat was first mixed (mixing of dry mix and water, 45 s propeller stirring, 5 min maturation period, 15 s re-stirring by hand). Then, the base coat was trowelled using a toothed trowel (type M1; [26]). After 3 minutes waiting, the reinforcement mesh was placed and incorporated in the base coat by a smoothing trowel. One week