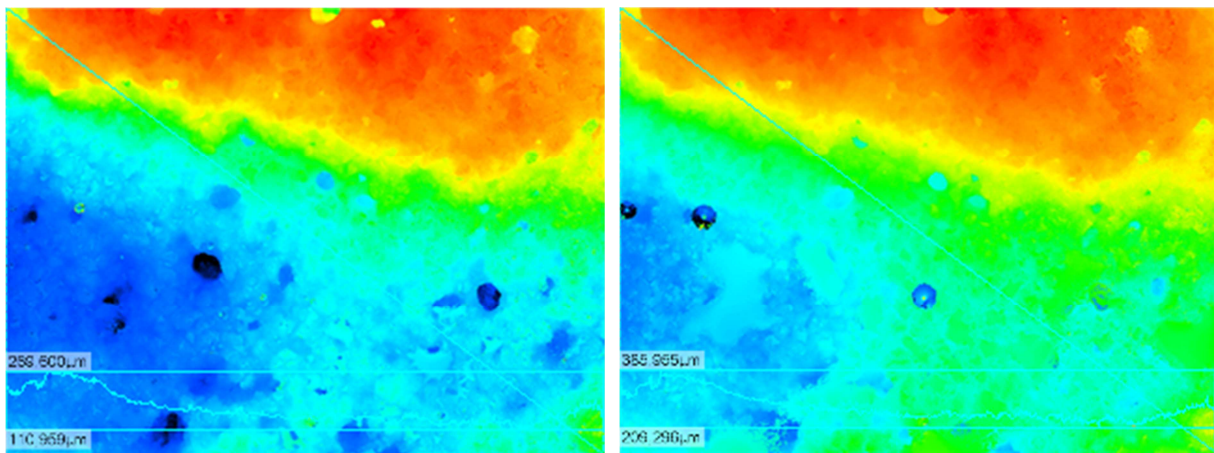


## Thesis Booklet

"New ways of demonstrating the condensation water behavior of mineral and organic plaster surfaces on façades"



**University Pécs, Breuer Marcell Doctoral School**

Faculty of Engineering and Information Technology

in cooperation with

**Hochschule Wismar**

University of Applied Science, Technology, Business and Design

Faculty of Engineering

**PHD in Architectural Engineering**

Torsten Steffgen M.Sc., B.A.

09. November 2018

## **Abstract:**

In recent years, both in new constructions as well as in renovation of building stock, more and more plastics have been used in façades, for example for thermal insulation to reduce energy loss. Thermal insulation of buildings is becoming increasingly important for the architect and energy designer in reducing greenhouse gas emissions.

The United Nations Environment Programme found that buildings consume about 40% of global energy. Many scientists who research on new building energy design are in favor of passive houses to reduce carbon dioxide emissions.

The trend is towards an increased use of synthetic material for the insulation as well as for plasters and paint coatings. Scientists have analyzed the complex range of problems of algae growth relating to the condensate load on façade. Further scientific research discovered that the condensation time is more than 10 times higher than the rainwater time.

This investigation allows the conclusion to be drawn that moisture films on the surface of the components are one of the main factors for the growth of algae. Today, scientists use static measurement methods to determine the actual amount of condensation directly on the surface by means of a fleece and a spring balance. In my own experiments, I also detected differences in various climate and location-dependent factors. A standardized recording method might help to make measurements more comparable.

Some manufacturers try to prevent algae growth on plaster and paint with targeted biocides (encapsulated or non-encapsulated). Biocides are chemical or biological substances used in Germany and Switzerland specifically to protect coatings and plasters against microbial degradation or algae growth. These agents do not remain in the façade but can be washed out by rain and enter the groundwater and drinking water. The leaching of active substances contained in biocides from plasters and paints have already been investigated and scientifically proven.

Biocides are only effective in the façade matrix and only in their aqueous phase, in which they reach the target organisms. These biocides are washed out of the plaster each time it rains or condensation occurs. They then enter the sewage system or groundwater.

The development of an exemplary representation for the future planning of moisture behavior of façades is a physical challenge. A model used to derive new and known

parameters for condensation protection on a façade should improve condensation protection in the future.

Materials science studies can offer further information to expand the capacity of different cleaning properties. A sustainable ecological design can yield additional findings regarding surface protection without biocides.

Physical protection measures are to be preferred, because, unlike biocides, they have no immediate impact on the environment.

# I. Content

|                                                                                           |           |
|-------------------------------------------------------------------------------------------|-----------|
| <b>1. Introduction and problem definition</b>                                             | <b>5</b>  |
| 1.1. Problems presented by façades made of plaster                                        | 5         |
| 1.2. Definition and façade protection theory                                              | 8         |
| 1.3. Questions and objectives for improving thawing behavior                              | 10        |
| <b>2. Current state of knowledge</b>                                                      | <b>10</b> |
| 2.1. Development of plaster and mortar past and present                                   | 10        |
| 2.2. Planning approaches for façade design without biocides and toxins                    | 11        |
| <b>3. Description of the test procedure</b>                                               | <b>12</b> |
| 3.1. The test specimens                                                                   | 12        |
| 3.2. The façade topcoats                                                                  | 13        |
| 3.3. Trial schedule                                                                       | 13        |
| 3.4. Water absorption coefficient (w-value) of the specimens                              | 14        |
| 3.5. Measurement of the amount of condensation water                                      | 15        |
| 3.5.1 <i>Measurement of the amount of condensation water with the laboratory balance</i>  | 15        |
| 3.5.2 <i>Measurement of the amount of condensation water by laser scanning microscope</i> | 16        |
| 3.6. Contact angle measurement                                                            | 17        |
| 3.7. Material analysis                                                                    | 19        |
| 3.7.1 <i>Material analysis by X-ray fluorescence spectroscopy (XRF)</i>                   | 19        |
| 3.7.2 <i>Material analysis by infrared spectroscopy</i>                                   | 20        |
| 3.8. Overview of the test results and thesis sentences                                    | 23        |
| <b>4. Conclusions</b>                                                                     | <b>24</b> |
| <b>5. Honorary declaration</b>                                                            | <b>26</b> |
| <b>6. Attachment</b>                                                                      | <b>26</b> |
| 6.1. Publications in the context of the thesis                                            | 26        |
| 6.2. Personal career                                                                      | 27        |



# 1. Introduction and problem definition

## 1.1. Problems presented by façades made of plaster

Plaster is the most commonly used construction material for façades [1]. It offers a wide variety of design options in terms of structure, shape and color. Since the beginning of civilization, plasters have been produced using manual processing methods in order to provide a structural-physical protection of the building or building envelope [1].

Surfaces of façades are increasingly prone to algae colonization. The effects of improving thermal protection of building envelopes as well as climate change and the reduction of air pollution reinforce this trend. The amount of condensation water accumulating plays a decisive role in this [2].

### Protective function for the façade

In recent years, the construction and refurbishment of existing buildings has increasingly focused on energy optimization. At the same time, more and more plastics are being used in thermal insulation to reduce energy loss [3]. The thermal insulation of buildings is an important factor in the reduction of harmful greenhouse gases [4], [5]. The United Nations Environment Programme has determined that buildings consume about 40% of the world's energy [6].

**VON WERDER** et al. have already dealt with this in their work and considered the condensate load more closely. They were the first to demonstrate the connection between condensation and algae colonization [7].

Furthermore, it was found that the monthly dewing time is up to 240 hours, while the rainfall per month is only about 22 hours per month [8]

### **H.-M. KÜNZEL and KRUS stated that:**

*"... the annual condensation in Holzkirchen is about ten times greater than the annual amount of driving rainfall on highly insulated façades. The moisture conditions on the façade depend crucially on the water retention or moisture retention properties of the façade surface layers" [9].*

A standardized test with different examination parameters should now lead to a better measure of the physical defrost protection of a façade. Significantly, the properties of the outer plasters are observed in depth with this approach.

Constructional and physical protection measures:

Structural protection measures have a high priority in reducing the condensation water and impact rainfall safety of a structure. Constructive protection measures include:

- Reasonable roof overhangs (adapted to the architectural style)
- Covers on cornice caps
- Overhangs on attics and masonry covers [10]

The physical protection factors are determined by the component's hygrothermal stress and storage mass [11]. The following consideration of the top plasters relates

primarily to the material characteristics, e.g. its water absorption. In this work, the outer plasters are considered first and foremost. In the author's opinion, the primer plaster should have water-repellent properties for every plaster system for façades, in order to avoid dampening of the masonry by driving rain. However, exceptions may be allowed for historical or listed buildings. Water uptake and release behavior plays a decisive role in the condensation resistance (hygrothermal load) in order to reduce algae colonization in the area of the top coat [11]. The water absorption and delivery of the top coat is determined primarily by the sorptive behavior of the building material. Filler, binder content, additives and auxiliaries play a further role.

Chemical protection measures:

In recent years, chemical protection measures have taken on an increasingly important role in plaster systems for façades. To provide chemical protection, cleaning biocides are added. These include a variety of products, e.g. disinfectants, pesticides and other biocides [12].

*"By definition, biocidal products are active substances and preparations whose purpose is to discourage, neutralize or destroy, by chemical or biological means, harmful organisms (such as bacteria, fungi, insects, rodents)" [13].*

In façade products (plasters and paints), the amount of active substances in an investigation ranged from 100mg/kg to 2000mg/kg [14].

*"Every rainfall event transports the biocides down the façade" [15].*

According to a study, about 25-40% of all professional products for façades (plasters and paints) in Switzerland are today equipped with encapsulated biocides [16]. Biocides will be included in the Water Framework Directive as suggested by the EU Commission and will be sampled more in waters [17]. In Germany, terbutryn has not been authorized as a plant protection product since 1997 [12]. In Hessian river systems, terbutryn concentrations above the value of the drinking water regulation of 0.1µg/l were found [18].

Here are some examples of façade discoloration caused by algae growth.



Fig. 01: Façade of an apartment building in Wismar.



Fig. 02: Apartment building in Pecs.

Plaster discoloration by algae growth is clearly visible. Exposure due to high building stock directly at the building.

## 1.2. Definition and façade protection theory

The aim of hydrophobically adjusted building materials is to make the mineral surface, such as of plaster, water repellent. This is done by lining the pore surfaces within the building material's internal structure, which prevents the formation of a water film on the walls of the pores and therefore water absorption inside the building material. The process of penetrating moisture through the capillary pores in the building material is interrupted [10].

In a hydrophilically adjusted building material, the mineral surface, such as plaster, is designed to be water absorbent. Water absorption in the interior of the building material structure can therefore take place. In hydrophilic building materials, absorption of water into the inner building material structure is desirable [10].

In Fig. 3 below, the various mechanisms of water absorption are shown using the example of a wall cross-section and described in more detail.

The mechanisms are:

*Liquid water absorption:*

1. Capillary absorbency
2. Leachate
3. Driving rain

*Gaseous water absorption:*

4. Condensation (condensation water)
5. Capillary condensation also by hygroscopicity



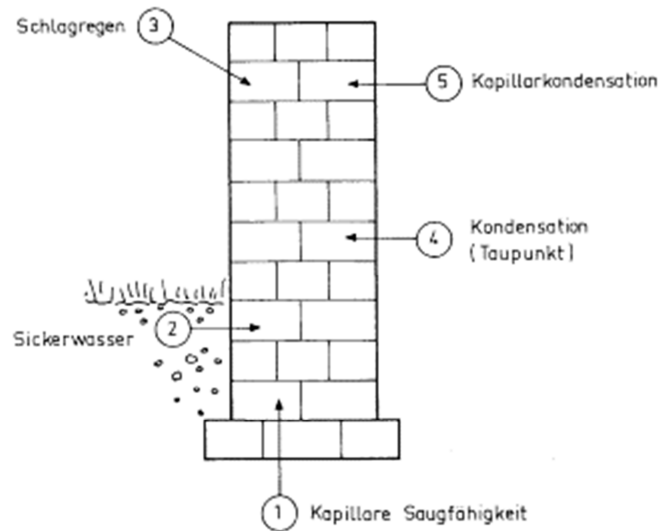


Fig. 03: Different mechanisms of water absorption [46]

The condensation, see Fig. 03 (4), is here regarded not in terms of the protection of the façade but rather for the inner surface. The defrost protection of a construction was sometimes completely neglected.

Heavily stressed façades or component surfaces can only withstand a sustained impact of driving rain if water absorption is low [19]. However, attention should also be paid to the drying and diffusion behavior. KÜNZEL took this as an opportunity in the sixties to determine this in the building physics parameters in the façade protection theory. These requirements were later adopted in standards DIN 4108-3 Thermal protection and energy economy in buildings, and DIN 18550 Design, preparation and application of external and internal plasters [20]. It should be noted, however, that the defrost protection for façades, which will invariably result in higher maintenance costs, is completely neglecting these considerations.

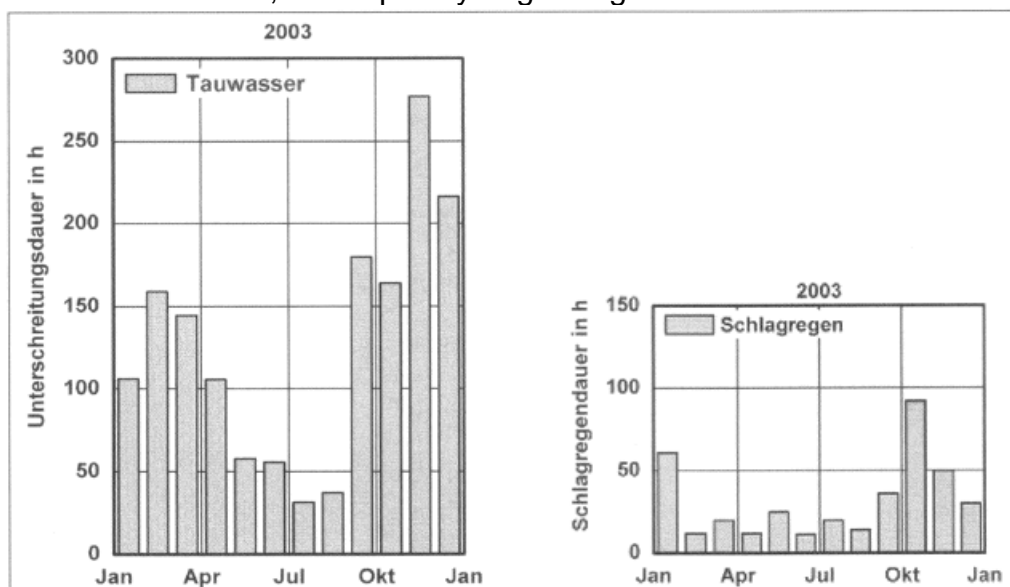


Fig. 04: Comparison of condensation formation – rain load [21].

Left chart: Duration of condensation formation in the months of January to January in hours. Right chart: Duration of rainfall load in the months of January to December in hours. Measured on a west-oriented experimental wall in Holzkirchen (Germany).

The surface consists of thin plaster with white coating on an external thermal insulation system. It clearly shows the much longer lasting condensation water load on the façade compared to the driving rain load. The condensation on the plaster surface is therefore responsible for algae colonization.

### **1.3. Questions and objectives for improving thawing behavior**

In this work, the relationship between the materials for plaster façades and their behavior in the event of condensation vulnerability is examined in more detail.

This research describes testing methods that are able to suggest pure building physics solutions without the use of environmentally harmful biocides. The following hypotheses are dealt with in more detail below:

#### Question I

*Are there (new) measuring methods to investigate the mode of action for a good condensation water protection?*

#### Question II

*With using various materials, is there a difference in the amount of condensation water that can ultimately influence algae colonization?*

#### Question III

*Are plastic-coated or modified plasters more susceptible to condensation?*

#### Question IV

*Has the exact composition of the mineral or organic plaster an influence on the absorbed condensation water? How can the composition of the plaster be determined?*

The experimental setup and the building materials used are described in more detail in section 3. The answers to these questions are given in section 3.8.

## **2. Current state of knowledge**

### **2.1. Development of plaster and mortar past and present**

#### Mineral-bound plasters and their development

In the past, the composition of aggregate differed considerably from today's aggregates. They had a much larger grain size as well as a high proportion of fine grain. Aggregates were not yet being extracted from open pits on an industrial scale, but often from streams and rivers on alluvial land. The oldest building materials therefore include natural stones, wood, and argillaceous bricks that were air-dried and later fired. In antiquity, the Greeks and Romans already knew that the properties of mortar and plasters could be adjusted by the addition of various aggregates and earths, such as lime and cement [22].

## Organic bound plasters and their development

In 1952, Swiss master painter Silvio Pietroboni experimented for the first time with plastic dispersions as a binder for plasters. In the 1960s, with polyvinyl acetate as a substitute for the usual binding agent lime or cement was introduced in the market. The organically bound synthetic resin plasters are today produced with a share of approx. 7% of polymer binder, approx. 75% of mineral aggregates to obtain the required grain structure, as well as water and approx. 2% additives [23]. Today, synthetic resin plasters are standardized in DIN 18550 (01.2018) together with the mineral plasters.

### Mineral binders

As mineral binders, the following are often used:

- Normal cement (EN 197-1)
- Building lime (EN 459-1)
- Hydraulic lime (EN 459-1)
- Plaster and masonry binder (EN 413-1) [24]

### Organic binders

As organic binders, the following are often used:

- Silicate emulsion
- Dispersing resin
- Silicone resin emulsion
- Polymer dispersion [25]

### Additives

Additives can significantly influence the material properties. They can, for example, improve machinability, hand processability or water repellency. Their addition is at the discretion of the manufacturer but should not produce harmful effects or impair the material's durability [24], [26].

Here, additives are used to improve the properties of the plasters. They also, however, allow various other binders to be substituted or their quantity to be reduced to save manufacturing costs [24], [26].

## **2.2. Planning approaches for façade design without biocides and toxins**

Every project has to be individually planned for the property in question. The procedural approach that is increasingly preferred by manufacturers is to be rejected.

For a biocide-free façade made of plaster, basic framework conditions must be observed. These are:

- Location
- Surroundings

- Alignment
- Design and construction
- Surface cooling
- Material or material selection [10]

Decision criteria for material selection can be:

- Wetting angle of contact
- Water absorption capacity
- Amount of condensation water on the surface
- Proportions of plastics when cleaning

Trials and preliminary investigations should not be dispensed with.

### **3. Description of the test procedure**

#### **3.1. The test specimens**

For the test series, mineral-bound topcoats (M) and organic (synthetic resin) bonded topcoats (O) were used. The specimens have a diameter of approx. 100mm\*10mm. The outer plasters were placed in a formwork made of PVC piping.



Fig. 05: Test specimen for the test procedure.

#### **3.2. The façade topcoats**

The individual products are described in more detail in section 3.2 below. The description refers to information provided by the manufacturer.

For technical data from the manufacturer, see the appendix in section 6.

### 3.3. Trial schedule

In order to plan a scientific experiment, it is necessary to create a trial plan with the necessary experiments. This allows the required number of specimens to be quickly determined. The following table shows the individual tests and the associated materials

| Item | Sample No. | Material            | Diameter [mm] | Thickness [mm] | Surface area [mm <sup>2</sup> ] | Binding agent | Grain size [mm] | w-value | Condensate volume | Wetting angle of contact | Material analysis | Laser scan microscope |
|------|------------|---------------------|---------------|----------------|---------------------------------|---------------|-----------------|---------|-------------------|--------------------------|-------------------|-----------------------|
| 1    | M 1.1      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 | X                        | X                 |                       |
| 2    | M 1.2      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 |                          | X                 |                       |
| 3    | M 1.3      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 |                          |                   | X                     |
| 4    | M 2.1      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 | X                        | X                 |                       |
| 5    | M 2.2      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 |                          | X                 |                       |
| 6    | M 2.3      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 |                          |                   | X                     |
| 7    | M 3.1      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 | X                        | X                 |                       |
| 8    | M 3.2      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 |                          | X                 |                       |
| 9    | M 3.3      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 |                          |                   | X                     |
| 10   | M 4.1      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 | X                        | X                 |                       |
| 11   | M 4.2      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 |                          | X                 |                       |
| 12   | M 4.3      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 |                          |                   | X                     |
| 13   | M 5.1      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 | X                        | X                 |                       |
| 14   | M 5.2      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 |                          | X                 |                       |
| 15   | M 5.3      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 |                          |                   | X                     |
| 16   | M 6.1      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 | X                        | X                 |                       |
| 17   | M 6.2      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 |                          | X                 |                       |
| 18   | M 6.3      | Fine finish plaster | 100           | 10             | 1000                            | M             | 2               | X       | X                 |                          |                   | X                     |
| 19   | O 1.1      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 | X                        | X                 |                       |
| 20   | O 1.2      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 |                          | X                 |                       |
| 21   | O 1.3      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 |                          |                   | X                     |
| 22   | O 2.1      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 | X                        | X                 |                       |
| 23   | O 2.2      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 |                          | X                 |                       |
| 24   | O 2.3      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 |                          |                   | X                     |
| 25   | O 3.1      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 | X                        | X                 |                       |
| 26   | O 3.2      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 |                          | X                 |                       |
| 27   | O 3.3      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 |                          |                   | X                     |
| 28   | O 4.1      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 | X                        | X                 |                       |
| 29   | O 4.2      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 |                          | X                 |                       |
| 30   | O 4.3      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 |                          |                   | X                     |
| 31   | O 5.1      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 | X                        | X                 |                       |
| 32   | O 5.2      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 |                          | X                 |                       |
| 33   | O 5.3      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 |                          |                   | X                     |
| 34   | O 6.1      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 | X                        | X                 |                       |
| 35   | O 6.2      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 |                          | X                 |                       |
| 36   | O 6.3      | Fine finish plaster | 100           | 10             | 1000                            | O             | 2               | X       | X                 |                          |                   | X                     |

Tab. 01: Test schedule, M = mineral plaster, O = organic plaster

### 3.4. Water absorption coefficient (w-value) of the specimens

The water absorption coefficient describes according to EN ISO 15148, hygrothermal performance of building materials and products. With this method, the water

absorption due to the capillary forces can be assessed by partial immersion in a water bath. These are in a complex correlation with the temperature and humidity gradients and the properties of the respective building materials [27].

The following water absorption coefficients were determined for the test specimens:

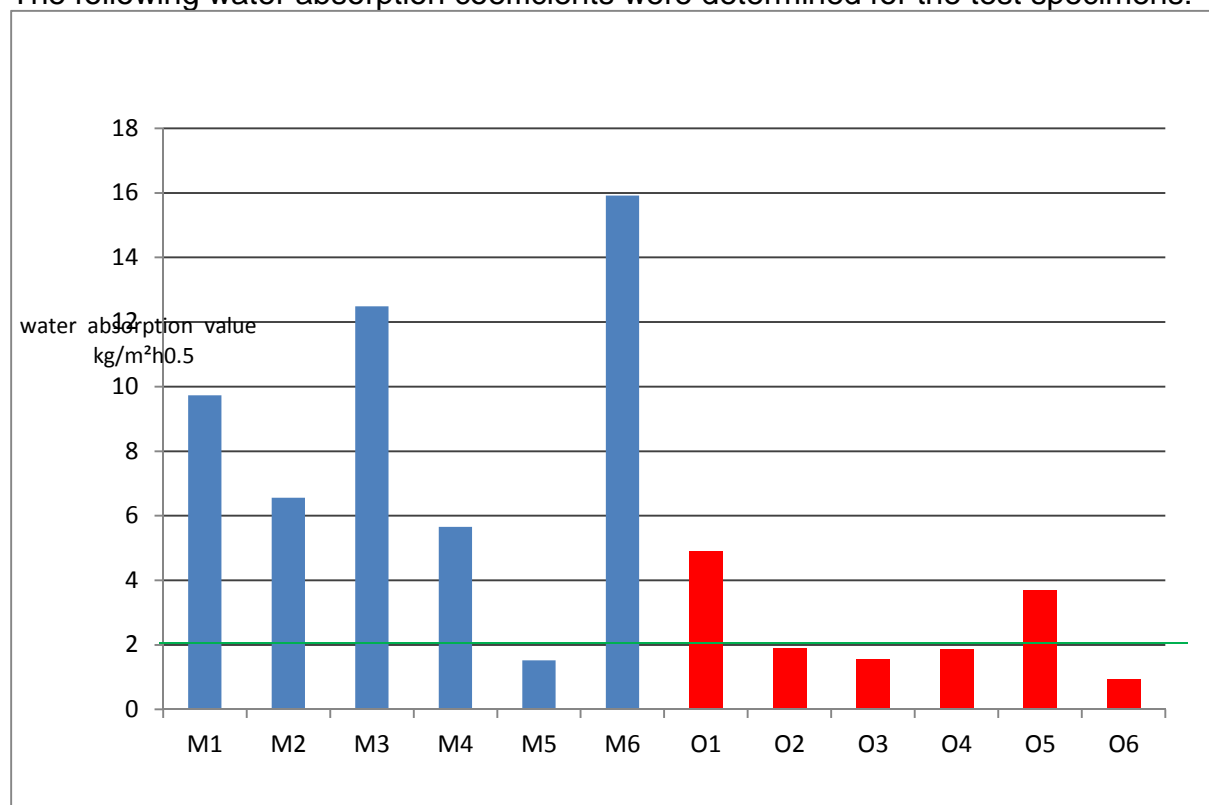


Fig. 06: Comparison of the water absorption coefficient  $w$   $\text{kg/m}^2\text{h}^{0.5}$  of samples M1 to O6.

Limit for strongly sucking  $w > 2,0\text{kg/m}^2\text{h}^{0.5}$  see green line.

It can be assumed that mineral-bonded topcoats absorb condensation water more quickly and strongly than organically bound topcoats.

### 3.5. Measurement of the amount of condensation water

Dew or condensation water is free water vapor that precipitates on cool surfaces of objects. As soon as vapor containing air is cooled below the dew point, the airborne water vapor changes from its gaseous to its liquid state [94]. It condensates on adjacent surfaces and forms a film.

#### 3.5.1 Measurement of the amount of condensation water with the laboratory balance

A good static measurement method is to record the condensation on the test specimens in field tests or in the laboratory. The static measurement is carried out by means of absorbent fleece and weighing with a laboratory balance, here Kern 572. The samples are dabbed with the fleece, which is weighed before and after dabbing to determine the amount of water transferred from the specimen.

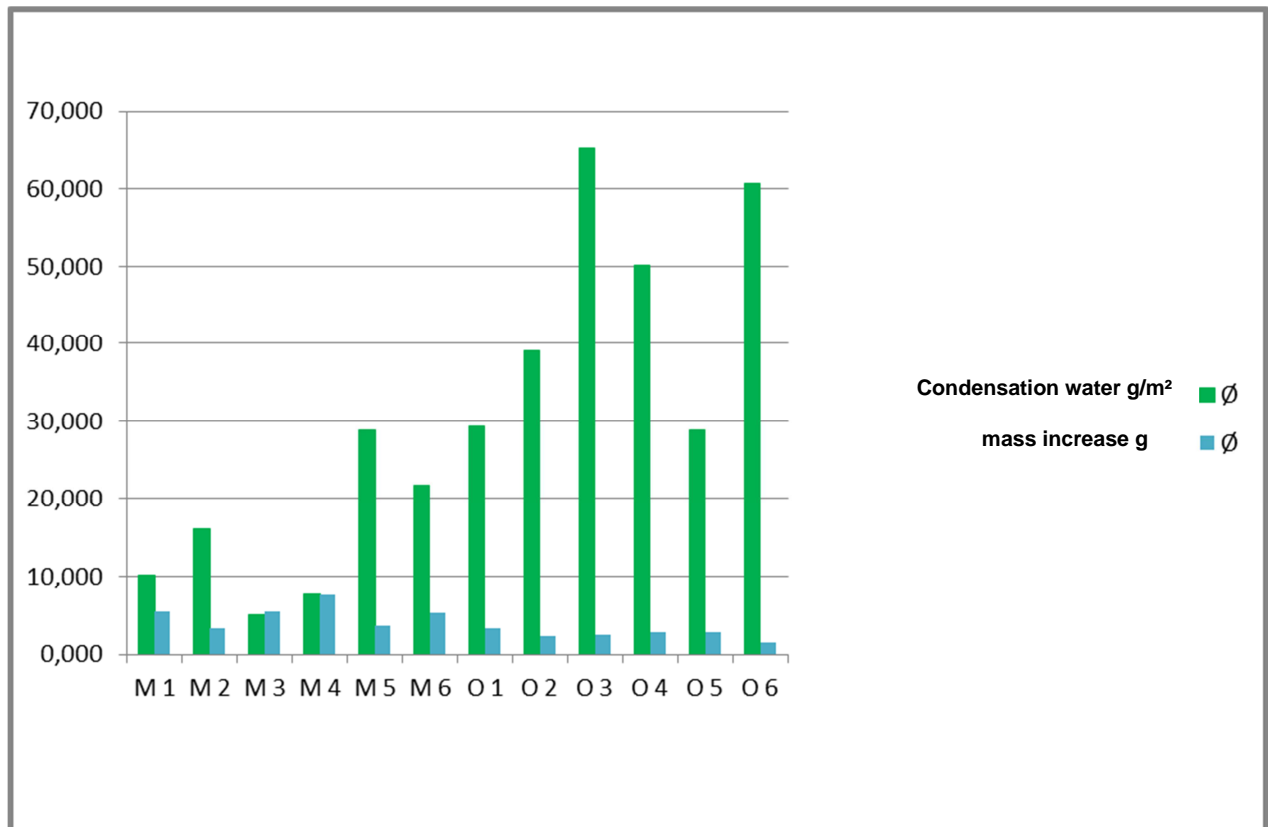


Fig. 07: Amount of condensation water and mass increase of samples M1 to O6.

The graph shows the amount of condensation water and the mass increase of the samples during a dewatering cycle of 2 h of samples M1 to O6.

Fig. 07 clearly shows the difference between the mineral-bound building materials and the organically bound samples. The amount of dew water is greater in the organically bound plasters than in the mineral bound plasters. The purple line is the arithmetic mean of about 30 g/m<sup>2</sup> of all samples.

### 3.5.2 Measurement of the amount of condensation water by laser scanning microscope

Laser scanning allows a quantitative analysis of various characteristics such as surface condition, and the film thickness measurement of condensation water. The laser scanning microscope uses two beam paths with two light sources and two detectors. The white light source and the CCD camera chip produce a high-resolution microscope image as an optical image [28]. This is necessary, for example, to measure the height and length of peaks and valleys on a surface. The peaks and valleys are visualized with different color thresholds on a scale; see Fig. 09.

A three-dimensional measurement in the X-, Y- and Z-axes takes place automatically and is displayed by the processing program with a different color threshold. The machining program can additionally generate and display a 3D model. The profile curves can also be compared and the increase in average height at the measuring point can be determined [28].



Fig. 08: Experimental set-up with Keyence VK 9700 laser scanning microscope and cooling plate.

Example of a laser scan measurement of mineral bonded surface plaster M5

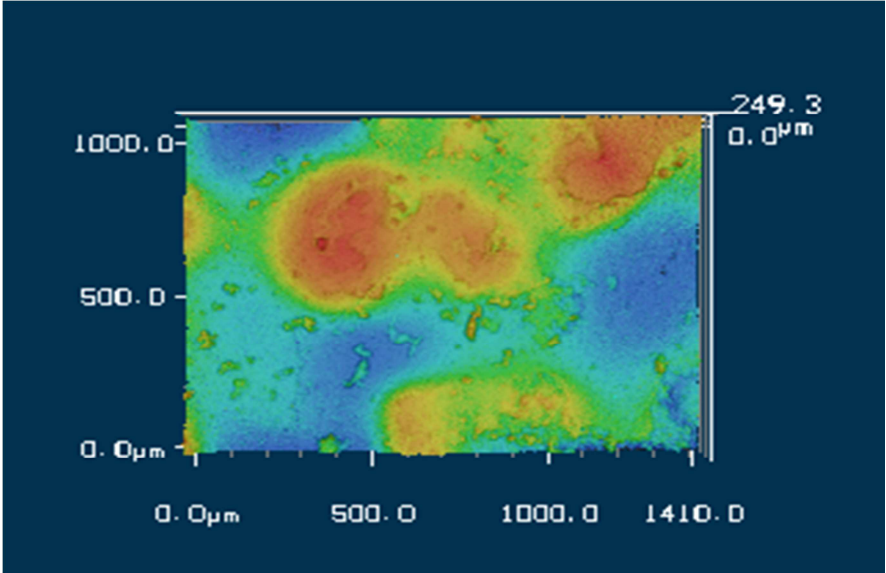


Fig. 09: Measurement in 3D before condensation (t = 0min.), sample M5.

The coloring of the Z-axis (dark blue corresponds to a low contour, red to a high contour). This makes it possible to visualize high and low contours. All height values in  $\mu\text{m}$ .



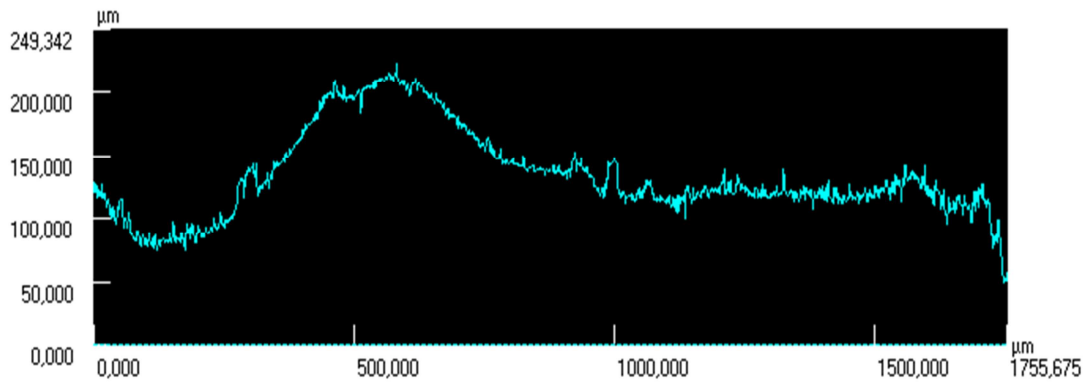


Fig. 10: Roughness depth measurement before condensation ( $t = 0\text{min.}$ ), sample M5.

The course line (Z-axis, shown in light blue) shows the surface roughness of the sample. Lowest point at approx.  $50\mu\text{m}$ , highest point at approx.  $232\mu\text{m}$ , average height at  $133.725\mu\text{m}$ .

### 3.6. Contact angle measurement

The test specimens are now subjected to a wetting angle measurement in the next step. The measurement of the contact (wetting) angle allows the surface of a building material to be characterized as hydrophobic (water-repellent) or hydrophilic (water-absorbent). Wetting means the propagation of a liquid phase on a surface.

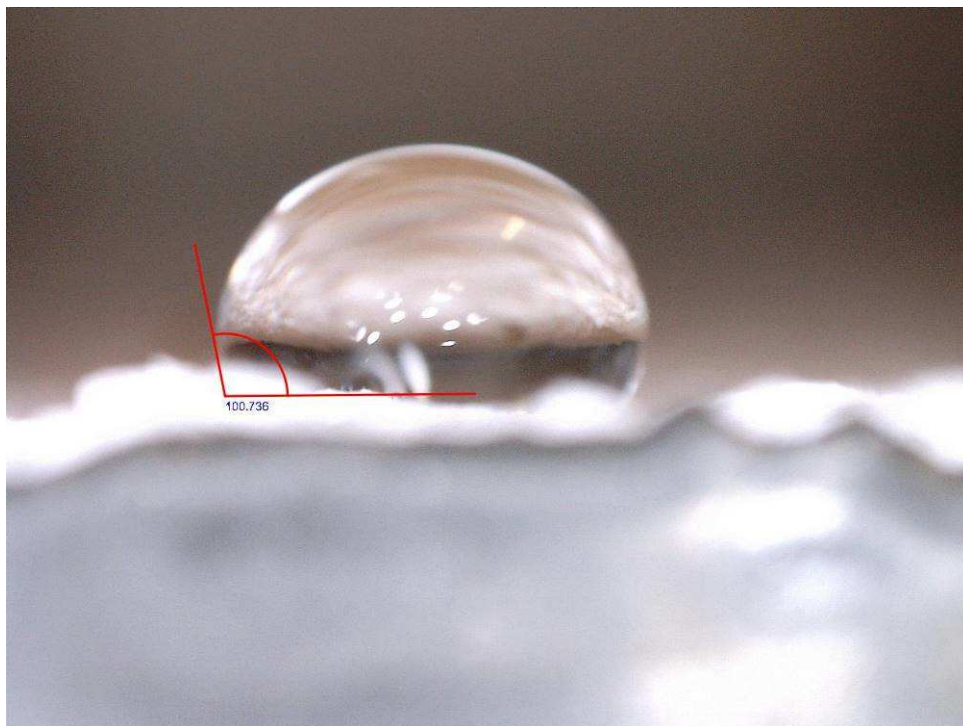


Fig. 11: Wetting angle measurement of sample O 2, here  $100.736^\circ$ .

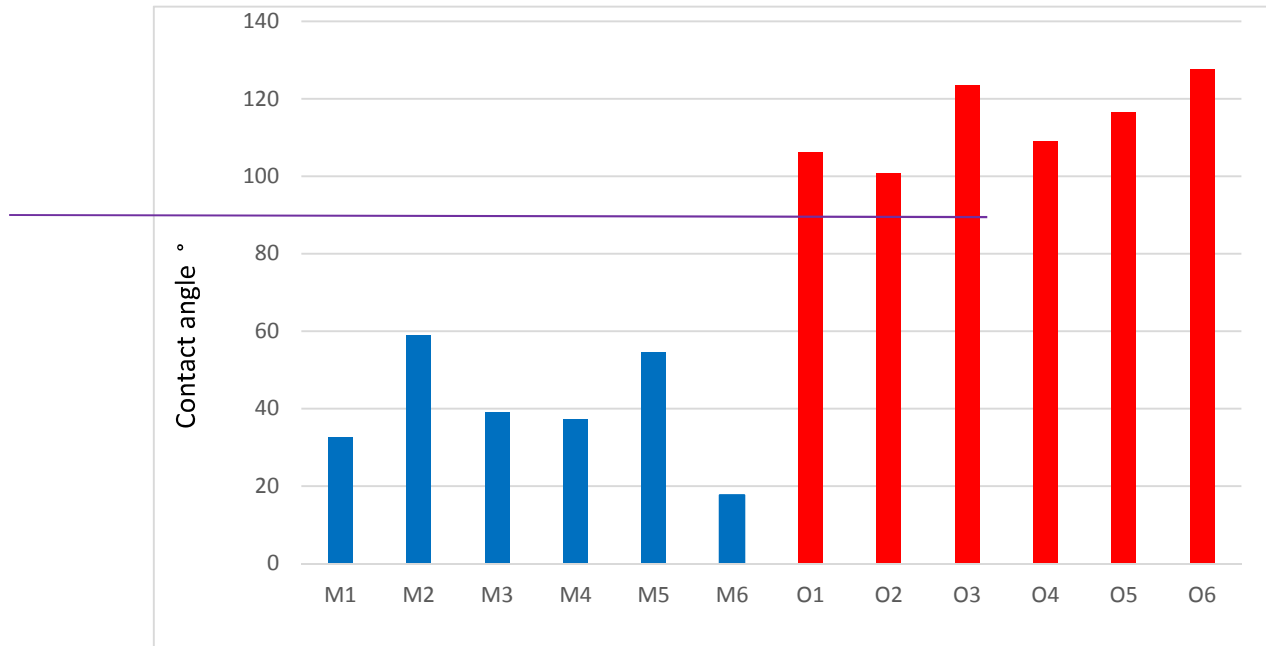


Fig. 12: Graph of measured wetting angles of samples M1 to O6.

Comparing the mineral (M1 to M6) and the organic (O1 to O6) samples, a clear difference in wetting angle can be seen. Purple line represents the 90° contact angle.

Intermediate result of the wetting angle measurement:

At a contact angle of more than 90°, it can generally be assumed that moisture absorption through driving rain is hardly possible. Absorbency is, in effect, zero. This is called capillary depression [29].

For all organic plaster samples, an wetting angle of more than 90° was measured. These samples thus all have hydrophobic properties.

### 3.7. Material analysis

#### 3.7.1 Material analysis by X-ray fluorescence spectroscopy (XRF)

X-ray fluorescence spectroscopy is a method developed for the field of material analysis. It allows a qualitative and quantitative determination of elements in ceramics, glass, metal and building materials. The sample is excited by X-rays [30].

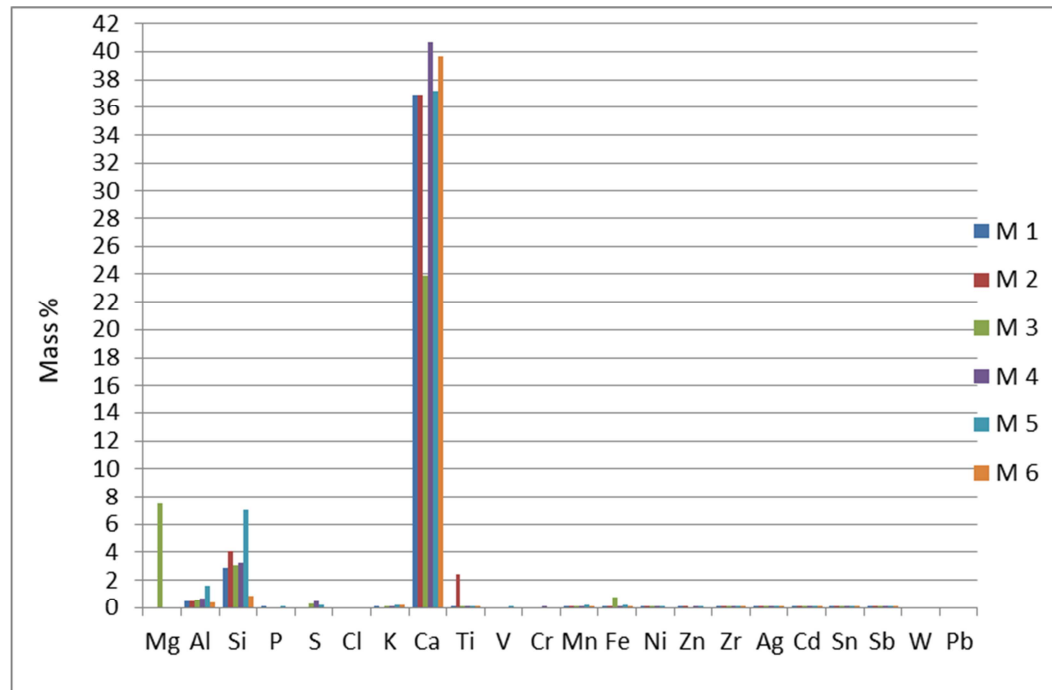


Fig. 13: Material analysis by XRF, compilation of the ingredients of samples M1 to M6.

Some ingredients were below the detection limit and could not be determined. Clearly visible, however, are silicon and calcium.

Amazing is the detectable content of thallium – a very soft metal – in one plaster sample. Thallium can also be used as a poison or disinfectant [31], [32]. The possibility that it originates in the cement cannot be excluded, although it is but unusually high [32].

The amount of calcium in sample M3 is lower than in the other samples. This is due to the self-mixing according to conventional recipe. Otherwise, the calcium levels are not very different. The plaster samples can be classified as mineral plasters, since their calcium content is between about 36 and 40% by weight. The silicon in samples M1 to M4 and M6 is a natural constituent of the aggregates used. Sample M5, however, is conspicuous in its much higher silicon content. This would indicate that this may not only be naturally occurring silicon but also crosslinked silicon residues of hydrophobing agents, e.g. silicone or siloxane [33]. This correlates with sample M5, which has a low w-value and a high wetting angle.

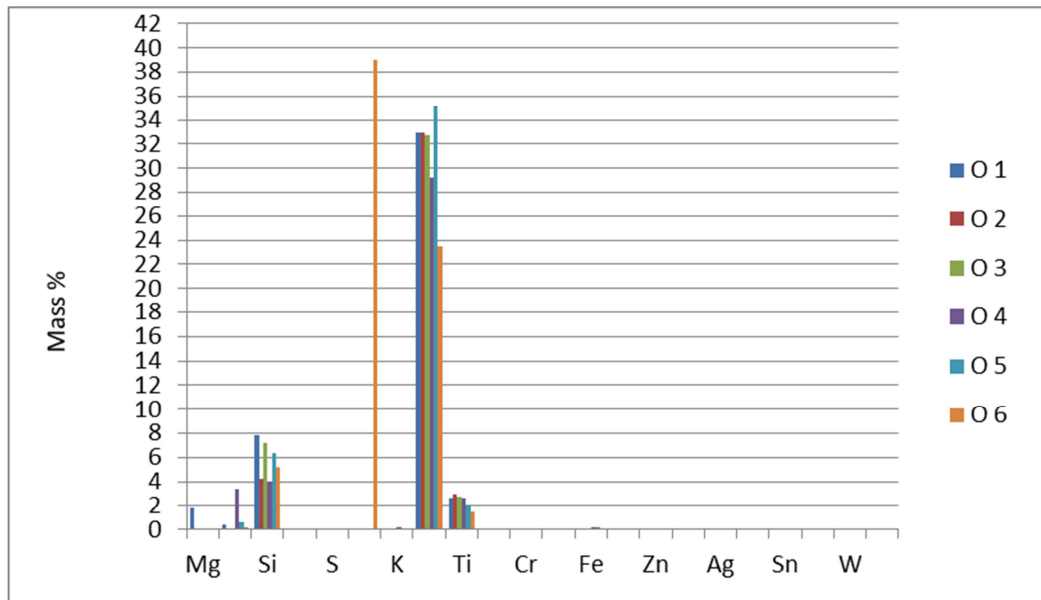


Fig. 14: Material analysis per XRF, compilation of the ingredients of samples O1 to O6.

Some ingredients were below the detection limit and could not be determined. Clearly evident, however, is the higher proportion of silicon and thallium compared to the mineral-bound plaster. A remarkable fact is the amount of thallium – a very soft metal – that could be detected in the plaster samples. Thallium can also be used as a poison or disinfectant (biocide) [31], [32].

The calcium content is lower than in the samples of mineral-bound topcoats. The calcium content lies between 23 and 35% by weight and is significantly lower than in the mineral and samples.

The content of silicon, which acts as a binder, is significantly higher than in the mineral bound top coat. The thallium content is also significantly higher than in the mineral bound top coat.

In the case of samples O1 to O6, the silicon content is clearly silicon in occurring naturally in the aggregates and binders. This would indicate that this may not be just naturally occurring silicon, but rather crosslinked silicon residues of hydrophobing agents, e.g. silicone or siloxane [34]

### 3.7.2 Material analysis by infrared spectroscopy

Infrared spectroscopy, also known as IR spectroscopy, is a physical analysis method that investigates the interaction of electromagnetic radiation from the infrared spectral region with a sample. IR spectroscopy is used for the quantitative determination of substances, which are identified by the wavelengths they emit within the reference spectrum [35].

#### Mineral samples

In sample M1, significant wave numbers of calcium carbonate, as main constituent, as well as silicates are found. During the extraction of toluene, components of methyl chains (CH<sub>2</sub>) could be detected in mineral sample M1. Paraffin wax or fatty acids are found at 720cm<sup>-1</sup> [36], [37].

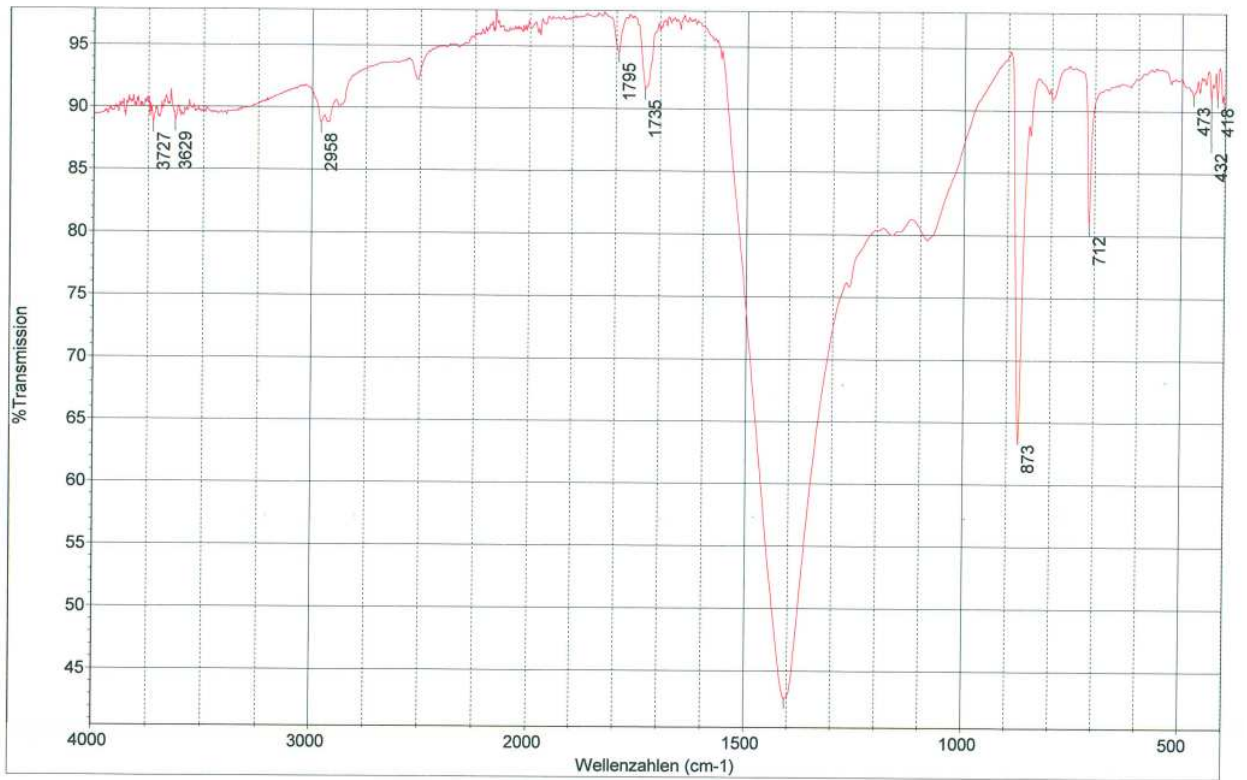
Sample M3 was found to consist of mixtures of inorganic silicates (main constituent) and significant amounts of calcium carbonate (lime) at  $179\text{ cm}^{-1}$ ,  $1428\text{ cm}^{-1}$ ,  $875\text{ cm}^{-1}$ ,  $857\text{ cm}^{-1}$  and  $713\text{ cm}^{-1}$ ; organic compounds are undetectable [36], [37].

The plot of sample M5 shows clear wave numbers of calcium carbonate as the main constituent as well as silicates. The pyrolysis products contain aromatic structures, and these are significantly higher in M5 than in M1 and M3. In mineral sample M5, components of methylene chains ( $\text{CH}_2$ ), e.g. paraffin wax or fatty acids, are detected at  $720\text{ cm}^{-1}$  and silicones (silicone oils) based on polydimethyl siloxane at  $1260\text{ cm}^{-1}$  and  $802\text{ cm}^{-1}$  [36], [37]. Thus it is very likely a modified mineral finish with organic components. Mortars and plasters are referred to as modified if they contain 0.1 parts by weight of synthetic material per one part by weight of cement [38].

### Organic samples

Sample O1 consists of a mixture of calcium carbonate as the main constituent and a silicate found at approx.  $1080\text{ cm}^{-1}$  and small amounts of carboxylic acid ester (acrylate) at  $1735\text{ cm}^{-1}$  [36], [37].

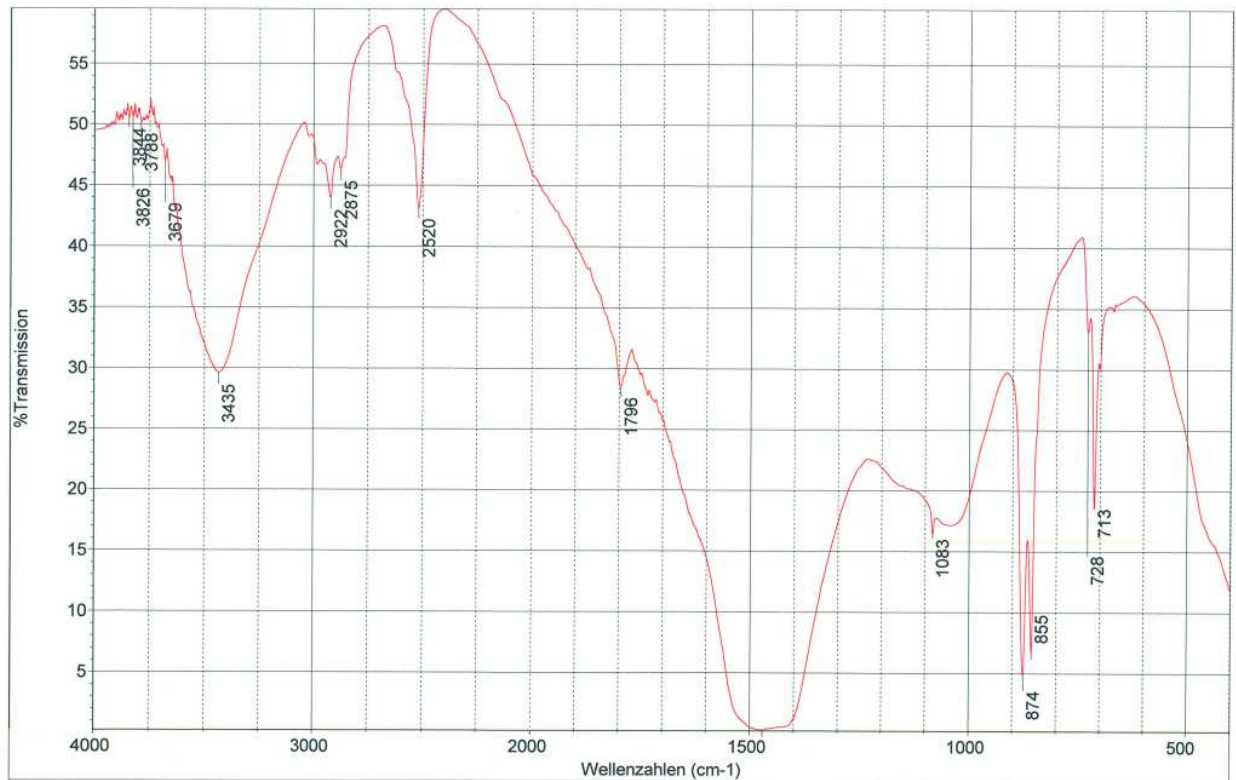
Sample O6 revealed distinct wave numbers of inorganic silicates as the main constituent at  $1080\text{ cm}^{-1}$  and calcium carbonate [36], [37]. Shown below are examples of the spectra of several specimens.



0948\_1 Muster O1, ATR

Mo Sep 03 09:47:49 2018 (GMT+02:00)

Fig. 15: Example of an IR spectroscopy with wave numbers of sample O1 [36].



0811\_1 M1 Original in KBr

Do Mai 17 13:32:58 2018 (GMT+02:00)

Fig. 16: Example of an IR spectroscopy with wave numbers of sample M1 [37].

Thus, the difference between organic and mineral samples can be clearly distinguished with the help of IR spectroscopy. In addition, it is also possible to detect organic constituents in mineral samples.

The IR spectroscopy of all experiments is included in the appendix in section 6.

### **3.8. Overview of the test results and thesis sentences**

The following remarks provide an overview of the investigations carried out.

A set of rules describing standardized condensation resistance can be drawn up based on the following basic findings:

Organically or mineral bound topcoats with added plastic offer a poorer thawing behavior. The condensation water measurement with cloud chamber and balance as well as with the laser scanning microscope shows good results for comparing the samples. The material analysis by X-ray fluorescence analysis (XRF) and IR spectroscopy can, for example, be used to analyze the material composition of plaster on existing buildings. They allow the type of binding – mineral, modified or organic – to be identified. Material analysis based on XRF and IR can also detect intentional or unwanted admixtures. Thus, it should also be possible to detect toxic substances that are not covered by the Biocidal Products Regulation.

#### Answers to the theses of the work

##### Thesis I

So far, there was no way to measure the condensation film dynamically at periodic intervals. Only static methods were used.

Through my method – modified laser microscope with a cooling plate – it became possible to measure the condensation film dynamically [39].

With the help of dynamic measurements, I have shown that the condensation water behavior basically differs between mineral and organic plaster [39]:

The tendency of the organic plaster to absorb the condensation water is lower than that of the mineral plaster [39].

##### Thesis II

With the aid of dynamic measurements, I have demonstrated that the condensation water behavior fundamentally differs between mineral and organic plaster. Organic plaster accumulates condensation water more quickly and at a higher mass than mineral plaster [39].

##### Thesis III

Performing measurements by different methods (contact angle, water absorption value, laser scanning microscope with cooling plate, and cloud chamber) I found the following [40], [42]:

- The plastic-modified and organic plasters adsorb more condensation water than mineral plaster.
- The amount of the condensation water on the surface of the organic plasters and plastic-modified plasters is 3 to 10 times higher than on mineral plaster.

#### Thesis IV

After the search to find material differences of the plasters material-specific analysis methods had to be used.

Regarding identification of the binder and the additives in the plaster, I showed that X-ray fluorescence analysis (XRF) and infrared spectroscopy allow an identification of ingredients in organic plaster, mineral plaster, or even plastic-modified mineral plaster [41].

#### Thesis V

The selected methods of investigation can be used to provide basic building physics recommendations for improved condensation water behavior on plaster surfaces. Through my basic research, the statement can be made that organic and plastic-modified plasters lead to a worsening of the condensation behavior. If possible, plastics should not be used on the upper layer of plaster to ensure improved condensation protection [40], [41].

The complete evaluation of all experiments can be found in the attachment in section 6. or in the attachment of the PHD Thesis.

## 4. Conclusions

Surfaces on façades are increasingly prone to algae colonization. Effects of increasing better heat protection of building envelopes, building construction measures and climate change reinforce this [41].

The accumulating amount of condensation water plays a decisive role, which was often neglected in the past. The differences can be highlighted in various systems and materials by the analysis methods:

- Contact angle measurement
- Condensate quantity
- Water absorption value
- Material Analysis



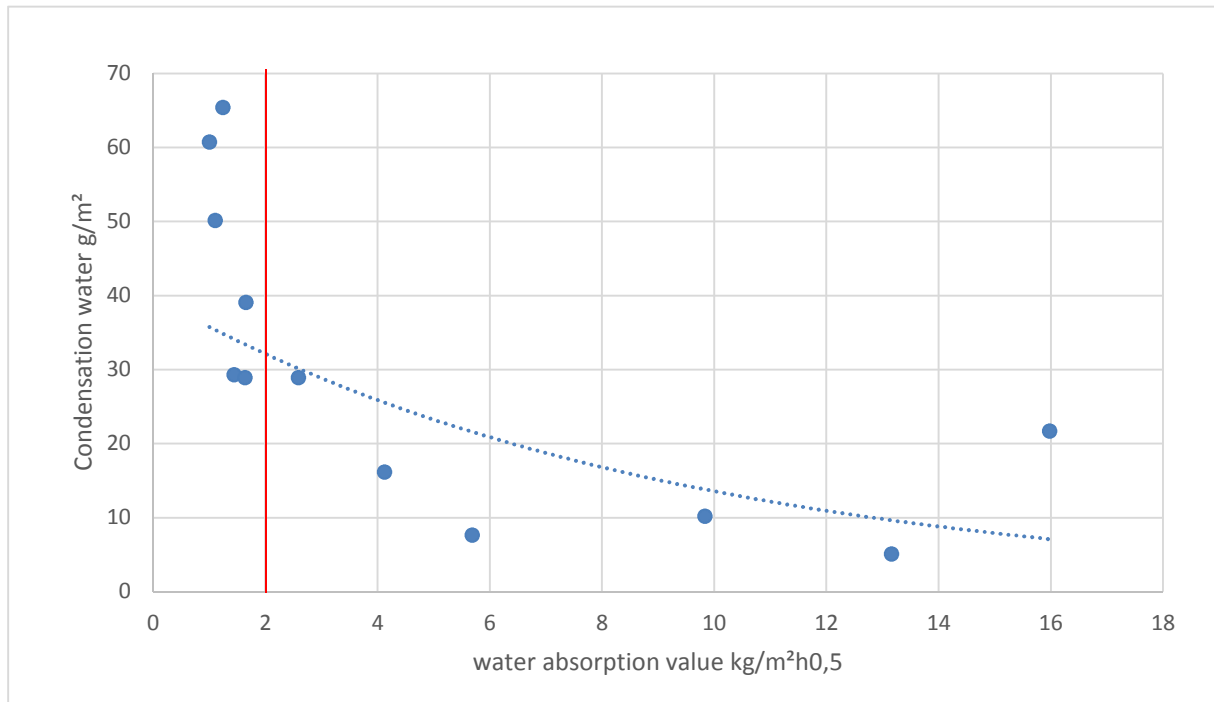


Fig. 17: Representation of the amount of condensation water in connection with the water absorption coefficient of the samples M1 to O6.

The lower the water absorption value, the larger the amount of condensation water.

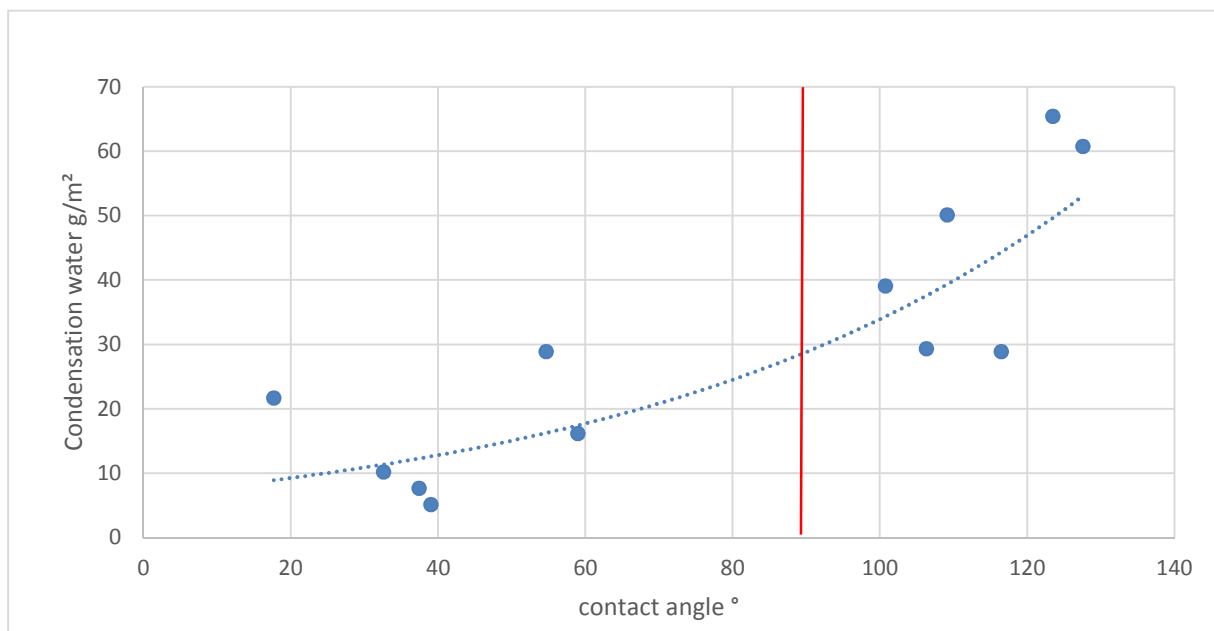


Fig.18: Representation of the amount of condensation water in connection with the contact angle of the samples M1 to O6.

The higher the contact angle, the higher the amount of condensation water.

For example, an outer surface layer which can store condensation and let it evaporate quickly again, and a second layer of plaster, which serves to protect against rain.

Physics protection measures on buildings are to be preferred, as these avoid environmental pollution from biocides and other toxins.

## 5. Honorary declaration

I hereby declare on my honor that I have prepared the present work independently. The thoughts taken directly or indirectly from external sources are identified as such. No sources other than the ones indicated were used. The present work has not been submitted to any other examination authority and has not yet been published.

Dreis, \_\_\_\_\_

\_\_\_\_\_

Signature

## 6. Attachment

### 6.1. Publications in the context of the thesis

- I. Title: Condensation water profilography with the help of laser scanning microscopy  
Author: Torsten Steffgen  
Coauthor: Helmut Venzmer  
Book: Energielieferant Altbau, pages 55 to 62  
Publisher: Beuth Verlag, Deutschland, Österreich, Schweiz, Berlin, Wien, Zürich  
Year of publication: 2017
- II: Title: Plastic-modified plasters are prone to condensation  
Author: Torsten Steffgen  
Coauthor: Helmut Venzmer  
E- Book: Bautenschutz Nachweismethoden und Anwendungen,  
chapter 4, pages 1 to 20  
Publisher: Edition Bautenschutz, Poel, Germany  
Year of publication: 2018
- III: Title: Experimental studies - Building physics investigations in condensation water on plaster surfaces  
Author: Torsten Steffgen  
Book: Pollack Periodica, Vol. 14xx  
Publisher: Pollack Periodica, Pecs, Hungary  
Year of publication: 2019

## 6.2. Personal career

### Personal data

Name: Steffgen

First name: Torsten

Date of birth: 01.11.1977

Place of birth: Wittlich

Nationality: German

Contact: tsteffgen@gmx.de

### Professional training

1998: Degree: skilled worker training as a road warder

### Secondary education / Studies

2001: Degree: State-certified construction technician at Balthasar-Neumann-Technikum in Trier

2003: Degree: State-certified technical Business Administration at Balthasar-Neumann-Technikum in Trier

2011: Degree: Bachelor of Arts (Business Administration) at the Euro FH in Hamburg

2014: Degree: Master of Science (Building Protection) at the University of Applied Sciences of Wismar

2014-: PhD degree program and doctoral college at the University of Applied Sciences of Wismar as well as University of Pecs

### 6.3. List of Illustrations

|                                                                                                                                               |    |
|-----------------------------------------------------------------------------------------------------------------------------------------------|----|
| Fig. 01: Façade of an apartment building in Wismar .....                                                                                      | 7  |
| Fig. 02: Apartment building in Pecs. ....                                                                                                     | 8  |
| Fig. 03: Different mechanisms of water absorption [46] .....                                                                                  | 9  |
| Fig. 04: Comparison of condensation formation – rain load [21]. ....                                                                          | 9  |
| Fig. 05: Test specimen for the test procedure.....                                                                                            | 12 |
| Fig. 06: Comparison of the water absorption coefficient $w$ $\text{kg/m}^2\text{h}^{0.5}$ of samples M1 to O6. ....                           | 14 |
| Fig. 07: Amount of condensation water and mass increase of samples M1 to O6. ....                                                             | 15 |
| Fig. 08: Experimental set-up with Keyence VK 9700 laser scanning microscope and cooling plate.....                                            | 16 |
| Fig. 09: Measurement in 3D before condensation ( $t = 0\text{min.}$ ), sample M5. ....                                                        | 16 |
| Fig. 10: Roughness depth measurement before condensation ( $t = 0\text{min.}$ ), sample M5. ....                                              | 17 |
| Fig. 11: Wetting angle measurement of sample O 2, here $100.736^\circ$ .....                                                                  | 17 |
| Fig. 12: Graph of measured wetting angles of samples M1 to O6.....                                                                            | 18 |
| Fig. 13: Material analysis by XRF, compilation of the ingredients of samples M1 to M6.....                                                    | 19 |
| Fig. 14: Material analysis per XRF, compilation of the ingredients of samples O1 to O6.....                                                   | 20 |
| Fig. 15: Example of an IR spectroscopy with wave numbers plot of sample O1 [36].....                                                          | 22 |
| Fig. 16: Example of an IR spectroscopy with wave numbers plot of sample M1 [37]. ....                                                         | 22 |
| Fig. 17: Representation of the amount of condensation water in connection with the water absorption coefficient of the samples M1 to O6. .... | 25 |
| Fig.18: Representation of the amount of condensation water in connection with the contact angle of the samples M1 to O6. ....                 | 25 |

### 6.4. List of Tables

|                                                                        |    |
|------------------------------------------------------------------------|----|
| Tab. 01: Test schedule, M = mineral plaster, O = organic plaster ..... | 13 |
|------------------------------------------------------------------------|----|

## 6.5. References

- [1] Weißert M. and 9 Coauthors: Technical Manual Putz Stuck Drywall Thermal Insulation 3 Edition. Stuttgart, self-publisher of the trade association, 2010. Page 544
- [2] Krus M., Thiel A., Born A., Höfener S.: Energy supplier Altbau, Berlin, Vienna, Zurich, Beuth Verlag, 2017, page 159-160
- [3] Szodrai F., Lakatos A. Effect of the air motion on the heat transport behavior of wall structures, Pollack Periodica, Vol. 8, No. 1, 2017, S. 67– 73.
- [4] Porhincak M., Estokava A., Vilcekova S. Comparison of environmental impact of building materials of three residential buildings, Pollack Periodica, Vol. 6, No. 3, 2011, S. 53– 62.
- [5] Donnelly K., Mahle M., Chamberlain heights redevelopment: A large scale, cold climate study of affordable housing retrofits, Build America, US Department of Energy, 2012,  
[https://www1.eere.energy.gov/buildings/publications/pdfs/building\\_america/chamberlain\\_hgths\\_redev.pdf](https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/chamberlain_hgths_redev.pdf), visited on 01.04. 2018.
- [6] Buildings and climate change: status, challenges and opportunities, United Nation Environment Programme, <https://www.unenvironment.org/resources/report/buildings-and-climate-change-status-challenges-and-opportunities>, visited on 10.02.2018.
- [7] Venzmer H., von Werder J., Kogan D.: Surface technologies and building protection; Beuth Verlag Berlin-Vienna-Zurich, 2010. Page 225
- [8] Venzmer H., von Werder J., Kogan D.: Surface technologies and building protection; Beuth Verlag Berlin-Vienna-Zurich, 2010. Page 233
- [9] Künzel H.M. H., Fitz C., Krus M.: Facade renovation; Beuth Verlag, Berlin-Wien-Zurich, 2010. Page 34
- [10] Resch M.: Practice manual building protection; Rudolf Müller Verlag, Cologne, 2012. Page 158-165
- [11] Von Werder J., Kogan D. Venzmer H.: Surface technologies and building protection; Beuth Verlag Berlin-Vienna-Zurich, 2010. Page 225- 227
- [12] Kahle M., Nöh I., Federal Environment Department: Biocides in Waters: Pathways and Information on Exposure and their Effects, Dessau- Roslau (Germany) 2009, page 3
- [13] Kahle M., Nöh I., Federal Environment Department: Biocides in Waters: Pathways and Information on Exposure and their Effects, Dessau- Roslau (Germany) 2009, page 6
- [14] Burkhardt M., Vonbank R., Schwitzer Federal Environmental Agency, Leaching of encapsulated biocides from facades, Bern, (Switzerland), 2011, page 41
- [15] Burkhardt M., Vonbank R., Schwitzer Federal Environmental Agency, Leaching of encapsulated biocides from facades, Bern, (Switzerland), 2011, page 44
- [16] Burkhardt M., Vonbank R., Schwitzer Federal Environmental Agency, Leaching of encapsulated biocides from facades, Bern, (Switzerland), 2011, page 3
- [17] Kahle M., Nöh I., Federal Environment Department: Biocides in Waters: Pathways and Information on Exposure and their Effects, Dessau- Roslau (Germany) 2009, page 38ff
- [18] Kahle M., Nöh I., Federal Environment Department: Biocides in Waters: Pathways and Information on Exposure and their Effects, Dessau- Roslau (Germany) 2009, page 4
- [19] Schneider, K.-J.: Construction tables for engineers. 13th edition. -Düsseldorf: Werner Verlag, 1998. page 10.37
- [20] Venzmer H., von Werder J., Kogan D. : Surface technologies and building protection; Beuth Verlag Berlin-Vienna-Zurich, 2010. Page 236
- [21] Künzel H., Fitz C., Krus M., Façade renovation Practical examples, product properties, protective functions, Beuth Verlag Berlin, Munich, Zurich. 1st edition 2011, page 35

- [22] Künzel H., Fitz C., Krus M., Façade renovation Practical examples, product properties, protective functions, Beuth Verlag Berlin, Munich, Zurich. 1st edition 2011, page 25- 27
- [23] <https://www.igrodry.com/de/cocciopesto-antica-innovazione/>, visited on 20.09.2018
- [24] Steinlechner U.: Standards manual; Planning, preparation and execution of interior and exterior plasters. Beuth Verlag, Berlin, Vienna, Zurich, 2016, page 13
- [25] Steinlechner U.: Standards manual; Planning, preparation and execution of interior and exterior plasters. Beuth Verlag, Berlin, Vienna, Zurich, 2016, page 15
- [26] <https://www.beton.org/fileadmin/beton-org/media/Dokumente/PDF/Service/Zementmerkb%C3%A4tter/B3.pdf>, visited on 10.06.2018
- [27] EN ISO 15148:2002, Determination of the water absorption coefficient with partial immersion. Heat and Moisture Behavior of Building Materials and Construction Products, Beuth Verlag, Berlin, (Germany) 2002. page 4
- [28] Keyence Corporation, Osaka, Japan, 3D- Color Laser Microscopy, VK-9700K Special Image Composition Software VK-H1J1E, page 1-1 through 6-6
- [29] Weber, H; und 16 Coauthors: Façade protection and renovation. Renningen: Expert Verlag, 1994. Pages 407-409
- [30] <https://de.wikipedia.org/wiki/R%C3%B6ntgenfluoreszenzanalyse>, visited on 10.08.2018
- [31] <http://www.chemie.de/lexikon/Thallium.html>, visited on 30.09.2018
- [32] <http://www.gesundheits-lexikon.com/Labormedizin-Labordiagnostik/Schwermetalle/Thallium.html>, visited on 29.09.2018
- [33] WTA Leaflet 4-11-02 / D: Hydrophobic impregnation of mineral building materials. -Stuttgart: Fraunhofer IRB Verlag, 2010. page 4-5
- [34] WTA Leaflet 4-11-02 / D: Hydrophobic impregnation of mineral building materials. -Stuttgart: Fraunhofer IRB Verlag, 2010. page 4
- [35] <https://www.spektrum.de/lexikon/chemie/infrarotspektroskopie/4458>, besucht am 13.09.2018
- [36] Lüdemann W. E., Laboratory for Instrumental Analysis, Report 0948, Ratzeburg 2018
- [37] Lüdemann W. E., Laboratory for Instrumental Analysis, Report 0811, Ratzeburg 2018
- [38] Weber, H; und 16 Coauthors: Façade protection and renovation. Renningen: Expert Verlag, 1994. Page 55
- [39] Steffgen T., Venzmer H., Energy supplier Altbau, Berlin, Vienna, Zurich, Beuth Verlag, 2017, page 58 –
- [40] Steffgen T., Plastic-modified plasters are prone to condensation, Wismar, Edition Bautenschutz 2018, Chapter
- [41] Steffgen T., Venzmer H., Energy supplier Altbau, Berlin, Vienna, Zurich, Beuth Verlag, 2017, page 55
- [42] Steffgen T., Experimental studies - Building physics investigations in condensation water on plaster surfaces. Pollack Periodica Vol. 14, 2019