COMPARISON OF THE CRACK-BRIDGING ABILITY (CBA) OF COATING SYSTEMS WITH THE CRACK FORMATION IN A BUILDING

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The maintenance of a building is an important requirement to guarantee its functionality. An essential part of this maintenance is the restoration of cracks, which can represent both aesthetic and technical faults. In interiors, a long-term and inexpensive solution to these problems can be found in the use of elastic coating systems that can successfully bridge static noncritical cracks. In this study, the crack-bridging ability (CBA) of selected coating systems is evaluated and compared with the crack formation in an actual building. For the evaluation of the CBA an innovative strain measurement test and an optical deformation analysis are used. The crack formation in the building was initiated by artificial dehydration and was recorded for nearly 2.5 years of continuous monitoring. On the basis of the obtained data from the monitoring and the test results, the application of elastic coating systems as a remediation method for crack-afflicted buildings is reviewed and discussed.

Keywords: *crack-bridging ability (CBA), strain, coating system, interior, bending beam strain measurement test, building monitoring, crack formation*

1. Introduction

Whether a crack constitutes a defect, is generally determined through its conspicuousness according to the viewer's perception. Above all, this is defined through the width of the crack and the structural nature of the surface being viewed [1]. According to the definition in DIN 18555-1 [2], cracks can be termed optical or technical defects starting at a width of 0.2 mm. Crack formation can impair both the usability and durability of a building [1, 3]. In office and residential buildings, due to the higher aesthetic requirements placed on the interior of such types of buildings, cracks often present a conspicuous impairment to the usability, which in many cases leads to high repair costs [1, 4].

The use of elastic coating systems can represent a long-lasting and easily applicable solution for repairing cracks in the interior. These systems should be able to successfully bridge cracks that are harmless from a static point of view, but visually disturbing. Such cracks are e.g. shrinkage cracks that occur by natural curing of concrete and cement based materials [5] or cracks in the board joints in drywall constructions as a result of hygric or thermal dimensional change [6]. However, the CBA of the used coating system should only allow crack bridging to a certain level so that critical structural failures can still be announced by cracking [7, 8].

In order to select the right coating system corresponding to the actual crack formation, it is crucial to be familiar with the CBA of the coating system in question. The test methods in accordance with DIN EN 1062-7 [9] and DIN EN 15812 [10] proved to be unsuitable for the evaluation of this value, as they provide only a categorization of the CBA and the setups of these methods are too rough and heavy for the application on the fine coating systems used in interior spaces [11]. For this reason, an innovative strain measurement test was applied in this study, which was already used in [11] to determine the strain of interior coatings. With the help of this test, but in a modified test setup, the maximal strain up to a hairline crack (0.2 mm) as well as the responding crack opening in the carrier material were determined for selected coating systems under laboratory conditions. The determination was carried out with the aid of an optical deformation analysis. In the second part of the study, the crack opening in the interior of a building, which was constructed using a stay-in-place (SIP) formwork system with prefabricated elements made of cement bonded particle boards (CBPB), was observed and recorded. In order to initiate a crack formation in the interior of the building a dehumidification was carried out after finishing of the construction work. The drying process continued until the cracks in the interior showed no further crack growth. By comparing the crack opening recorded in the interior of the building with the CBA of the tested coating systems, the use of such coating systems as a preventive measure in buildings with a tendency to crack formation was investigated.

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2.Experimental

2.1.Program and materials

By combining 2 plastering systems with 5 interior coatings, 10 coating systems (*complete system*) were prepared. For this purpose, the plastering systems were performed with the Quality Level 2 (Q2) and therefore consists of a basic filling (Q1) and a finishing (*"in order to achieve a continuous transition to the board surface, including sanding the jointed areas if necessary"*) in accordance with the classification of the European Union of contractors of plastering, dry lining, stucco and related activities (UEEP) and European federation of national associations of gypsum product manufacturers – EUROGYPSUM [12, 13]. The application of the basic filling was carried out by inserting a joint tape of glass mat with the width of 5 cm. Figure 1 shows schematically the structure and the components of these 10 coating systems.

In addition to the above said coating systems two more variants of a coating system for each plastering system were prepared, where either the joint tape (*var. 1*) or the interior coating (*var. 2*) were left out, in order to examine the impact of these two components on the CBA of the complete system.

In total, the laboratory tests include 14 different coating systems, from each of which 10 samples were prepared and tested.

The two selected plastering systems differ from one another regarding the used binder as well as regarding the processing. While System 1 was a powder and uses Calcium sulphate (Gypsum) as binder, in System 2, which was a ready-to-use mixture, a Copolymer is used in order to create a binding action. The composition of these two

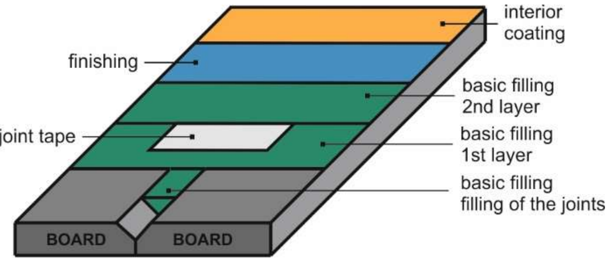

Fig. 1 - Schematic Illustration of the layers of the tested complete coating systems.

systems is listed in Table 1. For System 1, the quantity of the solvent is indicated in the table as an addition based on the weight of the powder.

The five interior coatings used in this study were selected from the interior coatings, the maximal strain of which was already examined in [11]. The selected coatings are all water-based polymer dispersions, from which four are emulsion paints and one is a latex paint according to the definition given by Rusam [14]. The composition of these five coatings is shown in Table 2.

2.2.Test method

For the quantitative evaluation of the strain and the crack-bridging ability (CBA) of the prepared coating systems an innovative measurement test was applied, the setup of which was based on the 3-point bending test in accordance with DIN EN ISO 178 [15]. This test is called "*Biegebalken-Dehnmessverfahren"* (*"bending beam strain measurement test"*) and was patented in 2018 under the patent number AT 521308 B1 [16] at the Austrian Patent Office.

In this measurement test the tested coating (coating system) is applied on a prismatic bending beams made of 24 mm thick CBPB that undergoes

Table 1

Ingredients of the selected plastering systems according to the manufacturer

Plastering system		Binder		Fillers		Solvent	
System 1	basic filling	50 – 70%	calcium sulphate (gypsum)	n/a		+50%	water
	finishing	50 – 70%	calcium sulphate (gypsum)	n/a		+56.25%	water
System 2	basic filling	2.5 – 10%	styrene acrylate copolymer	10 – 25% 25 – 50%	dolomite perlite	25 – 50%	water
	finishing	2.5 – 10%	styrene acrylate copolymer	50 – 75%	dolomite	25 – 50%	water

Table 2

Ingredients of the selected interior coatings according to the manufacturer

Coating	Binder	Fillers	Pigments	Preservatives
A	(-) copolymer	dolomite talc	kaolin titanium dioxide	benzisothiazolinone (BIT) methylisothiazolinone (MIT)
B	polyvinyl acetate copolymer	calcium carbonate silicate	titanium dioxide	benzisothiazolinone (BIT) methylisothiazolinone (MIT)
C	styrene acrylate copolymer	calcium carbonate silicate	inorg./org. colored pigments titanium dioxide	benzisothiazolinone (BIT) methylisothiazolinone (MIT)
D-Latex	vinyl acetate copolymer	n/a	n/a	benzisothiazolinone (BIT) methylchloroisothiazolinone (MCI) methylisothiazolinone (MIT)
E-Standard	acrylate copolymer vinyl acetate copolymer	carbonate silicate	titanium dioxide	benzisothiazolinone (BIT) methylchloroisothiazolinone (MCI) methylisothiazolinone (MIT)

a 3-point bending test. During the test, the applied coating is located on that side of the bending beam, on which tensile stresses and further extension deformations are generated by the bending process. Due to the bond between the applied coating and the bending beam, these deformations are transferred to the coating and recorded by an optical deformation analysis for the time of the test. The testing lasts as long as cracks with a crack opening of more than 0.2 mm (hairline crack) occurred on the coating surface. This condition is considered as the one at which the maximal strain of the tested coating has been reached.

For the purpose of the test, the bending beams are provided with a notch that was approx. 12 mm deep and 3 mm wide and was situated in the middle of the beam and perpendicular to its longitudinal axis (Figure 3a). Since in this study not only the strain, but also the crack-bridging ability (CBA) of coating systems has been evaluated, the tested coating systems were applied in contrast to [11] on that side of the bending beams on which the notch was located. In this manner, the notch simulated a kind of a board joint. By recording the notch opening by the optical deformation analysis during the test, the evaluation of the crack-bridging ability (CBA) of the tested coating system as an absolute value was enabled. Figure 2 shows schematically the used setup for the bending beam strain measurement test in this study.

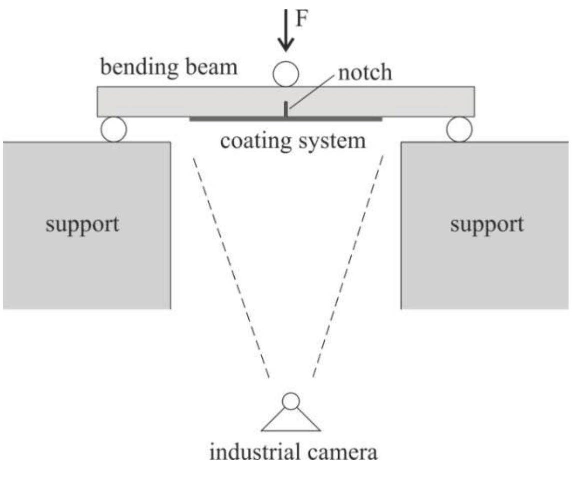

Fig. 2 - Schematic illustration of the setup of the used test method for strain and CBA measurements of coating systems acc. to patent [16].

2.3. Test specimen and procedure

As in [11], CBPB of the type BASIC manufactured by CETRIS® with a thickness of 24 mm and a weight per unit area of 32.4 kg/m² were used for the preparation of the bending beams. These boards consist of 63 vol% wood fibers, 25 vol% cement, 10 vol% water and 2 vol% hydration additives and have an absorbent behavior that can be compared to that of a mineral plaster [17].

In the first step of the preparation, rectangular beams with the full board thickness of 24 mm and dimensions of 300x73 mm (Figure 3a) were cut out of these boards. Next, the beams were provided with the notch specified by the used test method and conditioned in a climate chamber at 21°C and 50±3% relative humidity until constant material moisture of about 14±1% by all bending beams were reached.

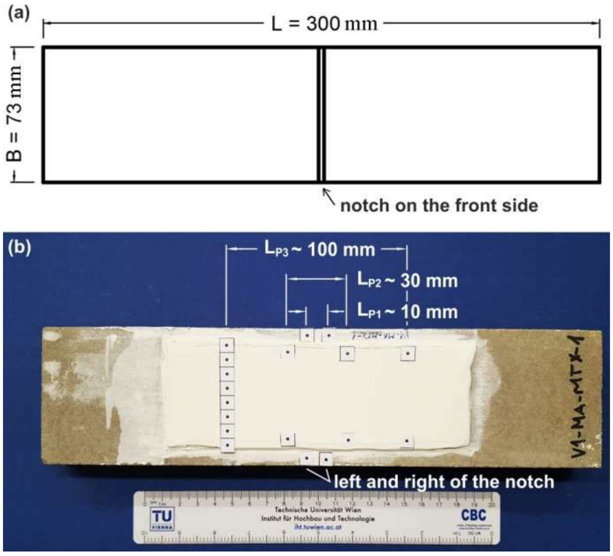

Fig. 3 - Shape and dimensions of the bending beams (a) and a bending beam ready for testing with point pattern (b) acc. to patent [16].

After the conditioning, the coating systems were applied on the bending beams. The application was carried out for all test variations in a particular order with defined thickness and drying time for each layer of the coating systems (see Table 3 and Figure 1). In order to obtain a uniform thickness of the layers in all samples (dimensional deviation: <3%), a template was used. The drying process took place in a climate chamber at 21 °C and 50±3% relative humidity according to the regulations of DIN EN 23270 [18] (23±2 °C and 50±5% RH).

Table 3

Order, thickness and drying time of the layers of the prepared coating systems in acc. with Figure 1

No.	Layer	Thickness	Drying time
0	basic filling filling of the joints	plane	24 h
1	basic filling 1st layer	0.6 mm	none
-	joint tape (where required)	embedded	none
2	basic filling 2nd layer	1.0 mm	24 h
3	finishing	0.5 mm	24 h
4	interior coating (where required)	0.4 mm	24 h

After the application of the coating systems, a point pattern was applied as a last step of the sample preparation. This pattern was used for the optical deformation analysis and was placed in a special arrangement (Figure 3b) on the coating system as well as on the bending beam (left and right of the notch). This enabled by the recording both the extension deformations of the coating system and the notch opening during the test the determination not only of the strain, but also of the CBA of the tested coating system.

In line with [11], the tests were performed displacement controlled with a rate of 0.3 mm/min (crosshead) on a universal tensile and compression testing machine made by INSTRON, model 4206, with a load capacity of 150 kN. Due to the quasi-brittle material behavior, which all components of the tested coating systems showed after the drying process, it could be assumed that the displacement control did not lead to any significant impairment of the measurement results.

During the test, the observed area of the sample (the area with the applied point pattern) was recorded by industrial camera made by IDS Imaging Development Systems GmbH, model uEye® UI-1220LE-M-GL. The recordings were taken at a frame rate of 2 fps and processed by measurement software based on Digital Image Correlation (DIC) [19]. This software was specifically developed by the Vienna University of Technology for optical deformation analysis and enables the determination of dimensional changes of a test specimen based on applied point pattern. With the aid of this software, the strain was determined according to Eq. (1) and the CBA according to Eq. (2). In each case, l_1 is the distance between two measuring points at the time of a crack opening of approx. 0.2 mm (hairline crack) in the interior coating and l_0 is the distance between the same two measuring points before the beginning of the test.

$$\varepsilon = \frac{l_1 - l_0}{l_0} \cdot 1000 \quad [‰] \quad (1)$$

$$CBA = l_1 - l_0 \quad [mm] \quad (2)$$

For the calculation of the CBA of the tested coating systems, the distance L_{P1} was used, whereas for the calculation of the strain the distance L_{P2} was used (Figure 3). The distance L_{P3} was only used in case that the crack formation occurs outside the distance L_{P2}. However, this case did not appear in any of the tested specimens.

2.4.Results

After completion of all tests, the recorded data of the optical deformation analysis was evaluated and the measured values of the strain in ‰ and the CBA in mm for all tested coating systems were displayed in a bar chart, Figure 4. In this chart, the values are shown in three groups. The main group represents the "*complete system*" as a combination of the two plastering systems with the five interior coatings fully applied according to Figure 1 and Table 3. The other two groups in the chart represent the two variations of the complete system where either the joint tape (*var. 1*) or the interior coating (*var. 2*) was not applied. In the chart, each bar shows the mean and error bars indicated the standard deviation of all 10 samples of a coating system tested.

Considering the test results in Figure 4 with regard to the plastering system used, it is becoming apparent that System 2 which uses a copolymer as a binder has a significantly higher strain and CBA then System 1, which is based on gypsum. Comparing the results of the coating systems without joint tape (*var. 1*) with these of the complete system (“A”) , it is evident that the joint tape contributed only in combination with System 2

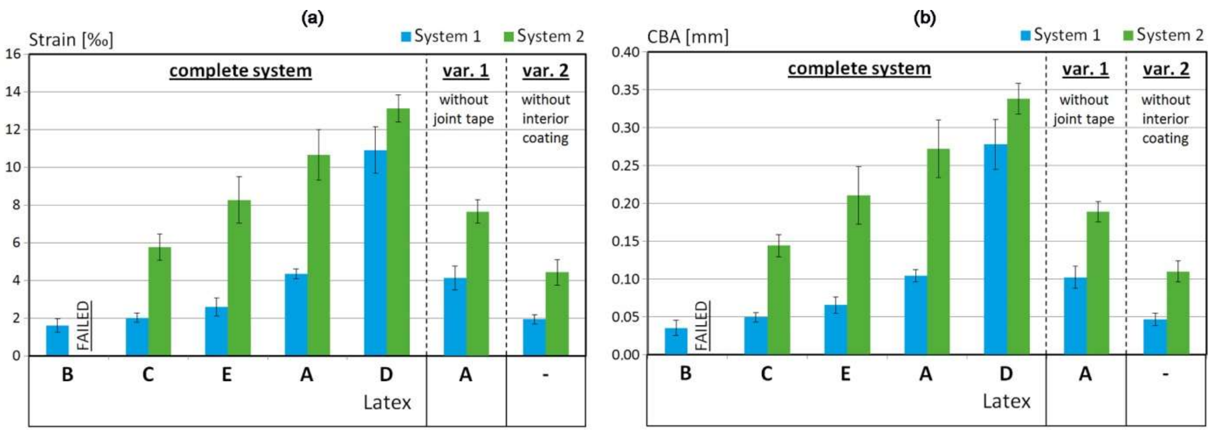

Fig. 4 - Strain (a) and crack-bridging ability (CBA) (b) of the tested coating systems.

to an improvement in the crack-bridging properties of the complete coating system (approx. 50%). The influence of the interior coating on the crack-bridging properties of the complete system is shown by comparing the test results of the coating systems without interior coating (*var. 2*) with these of the complete system. It is evident that the use of elastic interior coatings can lead to a considerable increase in the strain and the CBA of the complete coating system (up to approx. 200% in System 2 and approx. 450% in System 1 in combination with "D-latex"). Nevertheless, the application of an interior coating leads not automatically to better results. The use of the interior coating "B" led in combination with System 1 to decrease of the crack-bridging properties of the complete coating system and in combination with System 2 even to failure of the coating system due to crack formation in all samples during the drying process. It can be assumed that, the reason for this crack formation was an incompatibility between the plastering system and the interior coating.

Also interesting is the comparison of the strain of the complete system with that of the interior coatings tested with the first setup of the used measurement test in [11]. It shows a complete correlation of the measured values of both studies, which offers a first, at least own validation of the obtained test results.

3.Building monitoring

3.1.The building

For the purposes of this study, a single-storey building with a rectangular ground plan with dimensions of 6.44 x 5.44 m (Figure 5) and a ridge height of about 3 m was erected. This building consisted of a reinforced monolithic concrete construction (strip foundations, floor slab, exterior and interior walls and ceiling) insulated with an expanded polystyrene (EPS) external thermal insulation composite system (ETICS) and covered by a low-slope metal roof installed over a wooden substructure. For the erection of the concrete construction, a SIP formwork system was used, the elements of which were factory-made of the same 24 mm thick CBPB of CETRIS® like the bending beams for the laboratory tests. Since these boards are produced with basic dimensions of 3.35 x 1.25 m [1717], the formwork elements had a board joint every 1.25 m. These joints were performed with polyurethane adhesive and were situated for all wall elements in the vertical direction (Figure 6). As a concrete for the construction, a ready-mixed concrete with a strength class of C25/30 and a consistency class of F6 (spread: 630 – 690 mm) for the walls and F3 for all other elements acc. to DIN EN 206 [20] was used. In order to increase the observation area, the interior of the building, which had a ceiling height of 2.50 m, was divided by 6 interior walls into 8 chambers and a corridor. To enter the building an exterior door (100 x 210 cm, U_d = 0.7 W/m²K) in the corridor and to provide sufficient daylight a window (60 x 60 cm, U_w = 0.8 W/m²K) in each chamber was installed. In order to achieve a uniform climate in all chambers by ensuring sufficient air circulation, each interior wall was provided with one rectangular (30 x 60 cm) and two round (DN 150 mm) openings at different heights. The construction work lasted from May to June 2014.

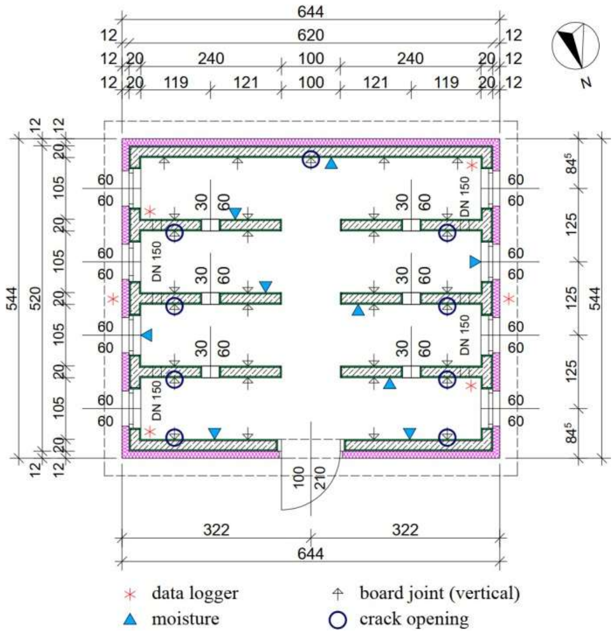

Fig. 5 - Ground plan of the building (dimensions in cm) with north arrow and position of the monitoring points.

Fig. 6 - Wall formwork elements installed on the construction site with indication of the factory-made board joints.

3.2. Monitoring and crack initiation

The monitoring started during the construction of the building and covered a period of about 29 months (May 2014 – October 2016). The first measurement as part of the monitoring took place on 21 Mai 2014, right before the prefabricated wall elements of the formwork system were filled with fresh concrete (Figure 6). The measurements were carried out at regular intervals and generally included the following three parameters:

- *Indoor and outdoor climate:* The air temperature and humidity was measured and recorded with the help of professional climate data loggers at 15-minute intervals both inside and outside the building. Four of these data loggers were installed in the corner areas of the interior and another two on the eastern and western façades of the building (Figure 5). Special care was taken to ensure that none of these climate loggers were exposed to direct sunlight. The activation of the climate loggers took place on 27 Mai 2014, right after the concrete construction was completed and the door and windows were installed.
- *Moisture of the CBPB:* Since the geometry of the CBPB, which covers the wall and ceiling surface of the building, is moisture-dependent [21] (length change at 1% change in moisture content: 0.03% [22, 23]) due to its relatively high wood content of 63 vol% [17], the moisture content of the wall formwork elements was continuously measured and recorded. This was carried out every 2 to 6 weeks (depending on the drying progress) at 9 measuring points inside the building (Figure 5) using a moisture meter made by BES Bollmann, model Combo 200KB, set for hard particle boards. The board moisture was measured at three different depths (1.0 and 2.0 cm from 21 Mai 2014, 0.5 cm from 23 April 2015,) on each measuring point. On the basis of the recordings, the correlation between the moisture content in the boards and the crack opening is shown.
- *Crack opening*: For the recording of the crack opening, the board joints of the formwork system were taken into account. Since the joints had a tensile strength that was at least 30% lower than that of the board they were most affected by crack formation. The measurement was carried out on 9 board joints of the wall formwork elements inside the building (Figure 5), where the joint width Δ_L was determined at three different heights above the ground – 0.30, 1.20 and 2.10 m. For the purpose of the measurement, two metal pins, each on every side of the board joint, were installed in a distance of about 40 mm of each other and in a line perpendicular to the board joint (Figure 7). Using a digital micrometer screw gauge made by Mitutoyo, model 293-112, with a measuring range of 25 to 50 mm and a measuring accuracy of ±1 µm, the distance L between these pins was determined. The crack opening at the time of each measurement $\Delta_{L,i}$ was calculated according to Eq. (3), where L_0 is the distance between the pins taken on the first measurement on 21 Mai 2014.

$$\Delta_{L,i} = L_i - L_0 \qquad \text{[mm]} \qquad (3)$$

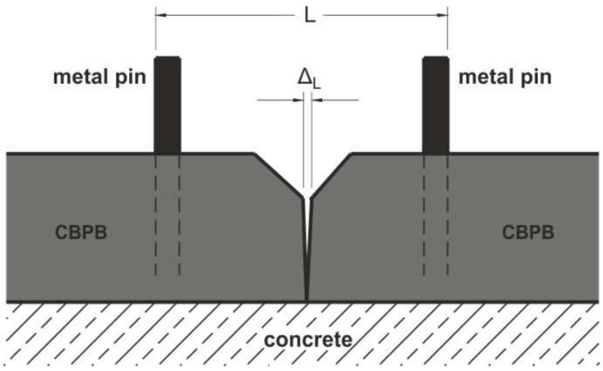

Fig. 7 - Setup for the measuring of the crack opening in the board joints.

In order to initiate a crack formation in the interior of the building, the moisture of the CBPB was reduced in two stages for the time of the monitoring. The decrease in moisture caused shrinking of the boards, which led directly to the intended crack opening in the board joints. In each of the two stages, the board moisture was reduced by heating and dehumidifying the interior. A space heater with a power of 3 kW was used for heating and a construction dryer made by Einhell, model LEF 10 M with a power of 260 W and an air flow rate of 100 m³/h was used for dehumidification. In addition, a fan was also installed to ensure sufficient air circulation between the chambers. The stages were carried out in two consecutive years as follows:

- *Stage 1:*

Heating and dehumidification 23/03/2015 – 17/06/2015

- *Stage 2:*

Heating 05/02/2016 – 01/06/2016
Dehumidification 15/06/2016 – 09/09/2016

The end criteria for the first stage was to achieve a moisture content on the board surface of around 14±1%, since this moisture content is a requirement for the start of the painting according to experts. For the end of the second stage, the reaching of the maximum crack opening was set. The monitoring ended about 1.5 months after the end of the second stage with the last measurement on 28 October 2016.

3.3.Measured data

Once the monitoring was completed, the collected data was processed and presented in the form of line graphs over the entire 29-month period of the monitoring. For the better analysis of the

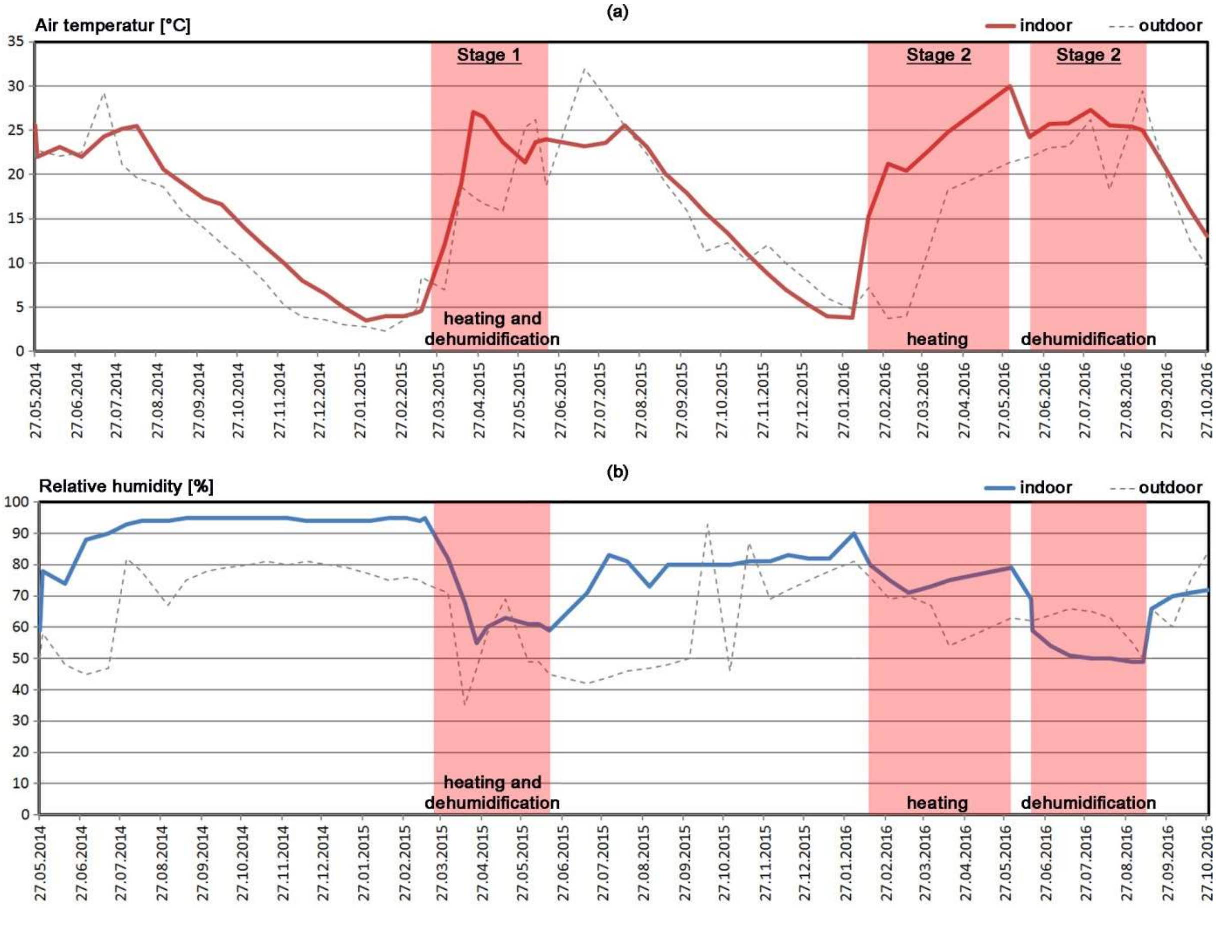

Fig. 8 - Air temperature (a) and relative humidity (b) during the monitoring of the building.

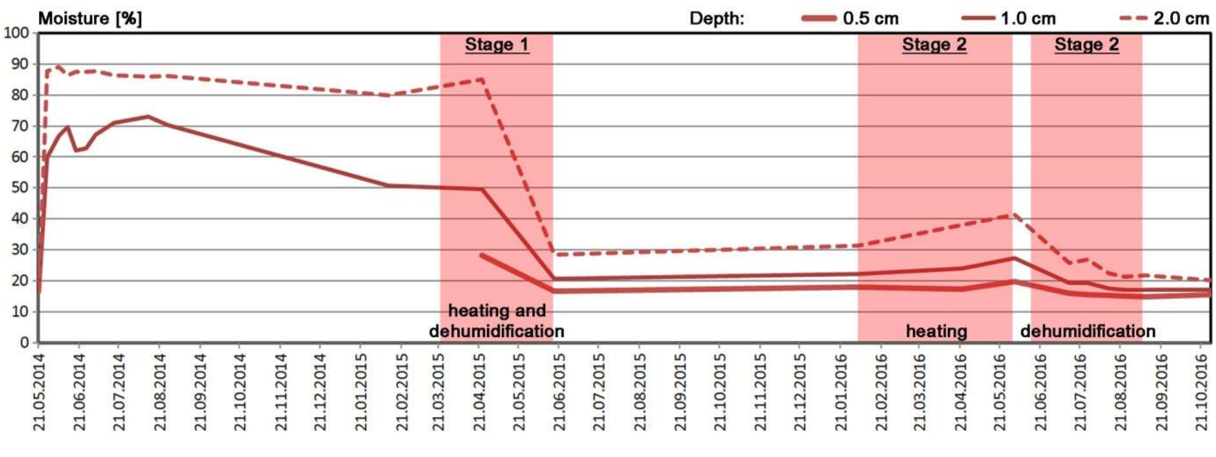

Fig. 9 - Moisture of the CBPB at various depths during the monitoring of the building.

data, the duration of the heating and dehumidification periods are also indicated in the graphs. Based on the recordings of the climate loggers, the air temperature (Figure 8a) and the relative humidity (Figure 8b) is shown both indoors and outdoors as a mean of all related loggers. The moisture of the CBPB is shown in Figure 9 as a mean of all measuring points (Figure 5) at three different depths. Figure 10 shows the crack opening in the board joints. In addition to the mean of all 27 measuring points (9 board joints with 3 measuring points each), the standard deviation (SD) as well as the maximum and minimum values per measurement are also shown in this graph. The determined values of the crack opening at each measurement had a normal distribution.

As the curves plotted in Figure 9 and 10 show, the crack opening in the joints is directly related to the reduction of the board moisture. The only exception is the increase of the crack opening at the beginning of the monitoring. However, this was not caused by the moisture, but by the hydrostatic pressure of the fresh concrete during the construction work. After the CBPB getting

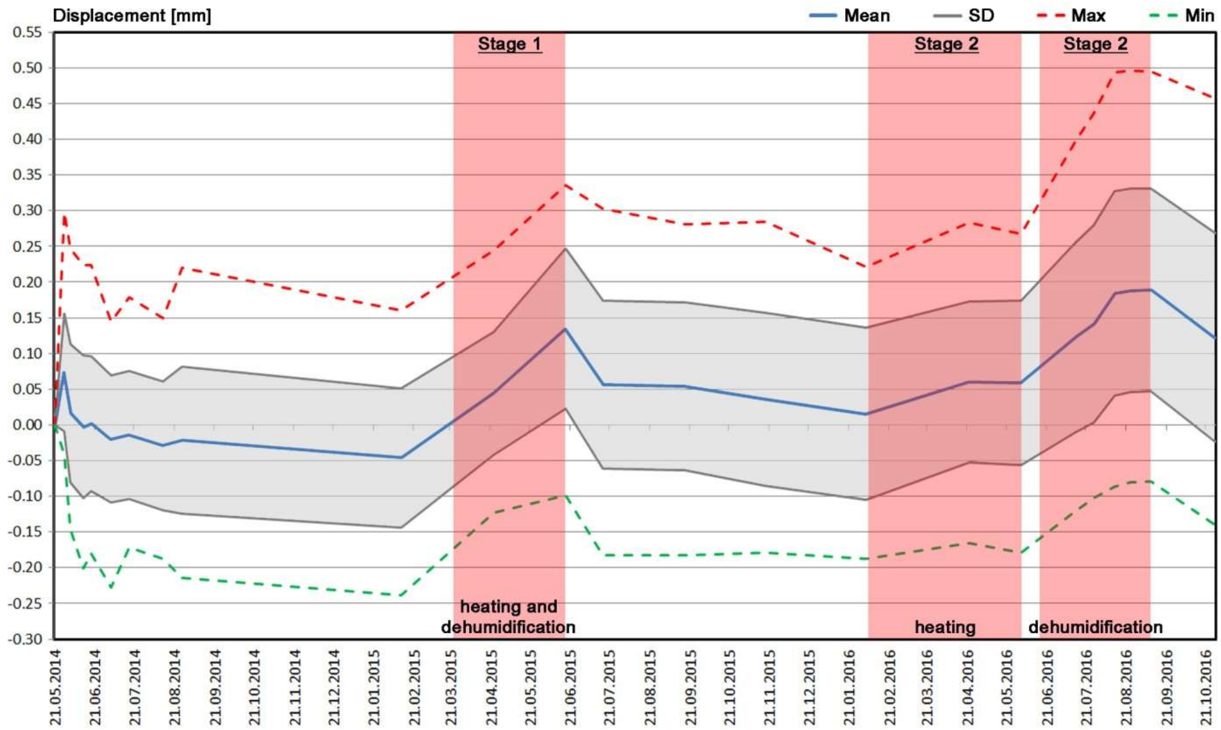

Fig. 10 - Crack opening in the board joints during the monitoring of the building.

moistened and the fresh concrete had hardened, the crack opening decreased again. The first, significant expansion of the board joints occurred during the heating and dehumidification in Stage 1 and reached a mean of about 0.14 mm. During this period, the CBPB lost most of the moisture accumulated during the concreting. A further expansion of the board joints took place during Stage 2. A small increase in the crack opening was registered in the heating period, but this was reduced again due to the increased diffusion of moisture from the concrete wall core to the boards and the interior of the building (Figure 8b and 9) as a result of the increased temperature (Figure 8a). The maximum crack opening was achieved by the followed dehumidification of the interior. Due to the dehumidification, the mean of the crack opening reached a maximum of about 0.19 mm with a standard deviation of about 0.14 mm and a maximum value of about 0.50 mm.

4. Conclusions

The recorded crack opening in the building shows that certain coating systems are able to bridge cracks in the interior. Considering the most elastic coating system tested in this study (System 2 with "D Latex"), it can be expected that this coating system with a CBA of about 0.33 mm could bridge about 84% of all cracks appeared in the observed building. As this system cannot provide the bridging of all cracks, a prior announcement of critical structural failures on the basis of the crack formation that has occurred is in this case also possible. However, this assessment is only valid in the on-site application is equal with the sample preparation in the laboratory. Since the quality of the works on the construction site often does not by far match that in the laboratory, such assessments should be treated with caution. It is also important to note that the determination of the CBA of the selected coating systems was based on short-term tests. As the recorded crack opening in the building has occurred over a relatively long period, ageing effects on the CBA must also be taken into account in such an assessment. Nevertheless, the results of this study provide a brief overview of the potential of using elastic coating systems to repair and prevent cracks in the interior and should serve as a basis for further research.

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