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Moistening of Walls Caused by Damage to Terraces - Research Studies and Numerical Simulations

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Abstract. The aim of the article is to determine the impact of terrace damage on the moisture of adjacent external walls. Changes in moisture of wall structures can be diagnosed based on different measurement methods. In the building being the subject of the research, the damage to the terrace was caused by the moisture of adjacent external walls, made of solid ceramic bricks. On the basis of macroscopic studies, the causes of irregularities were determined. Conducted measurements of water content of individual parts of the external wall made of solid ceramic bricks were made by non-invasive method and destructive method. Measurements of water content by non-destructive method were carried out using a measuring instrument with a probe to measure material moisture. The research showed differentiation of the water content of walls depending on the location in relation to the source of moisture. During the non-destructive tests carried out inside the building, the surface moisture of the solid ceramic brick, constituting the construction of external walls and lime plaster, was measured. Measurements of water content of plaster and brickwork, qualifying them as wet walls. In places outside the area of moisture, the water content of plaster and solid bricks were several times lower. The destructive tests were carried out using the drying-weight method. In order to obtain the results of water content in the area of moisture and outside the moisture area, 3 samples of solid bricks were collected. The average water content of the ceramic brick wall in the places of occurring moisture, they were three times higher than the water content of the brick outside the moisture area. The obtained test results indicate significant differences between the moisture of the brick examined in the near-surface area and water content inside the wall. On the basis of obtained results of laboratory tests, numerical calculations were carried out using WUFI 2D software. Numerical simulations made it possible to present changes in water content of a solid brick over a period of three years. Based on the carried out tests and numerical calculations, it can be concluded that despite relatively large differences in the initial water content of wall parts in moist and non-moist areas, after a period of 3 years, the moisture status for both analysed cases is similar and occurring water content differences are practically negligible.

1. Introduction

The accumulated building engineering experience bears out those terraces belong to a group of building elements whereof construction and maintenance in a good technical condition can be quite troublesome. Their location in the external environment and exposure to constant impacts of changing weather conditions necessitates the adoption of a thorough design project and implementation diligence as well as constant technical inspection during their service life. Contemporary terrace solutions are based on a large extend on the latest technical, technological and material achievements, both in terms of structural elements, layering and flashings patterns, drainage systems and installation

of railing. Not infrequently, coherent system solutions are applied. The issues involving technical condition of terraces can be addressed both to historic buildings and newly erected ones [1, 2, 3]. The material and structural solutions of terraces are to a great extent connected with combined heat and mass transfer through building envelopes. At the designing stage of such elements, the issues of thermal bridges and thermal accumulation capacity should be given a lot of consideration [4, 5, 6, 7]. Inappropriate design solutions may lead to a higher heat demand [8, 9] and build-up of moisture in the walls [2, 3, 8, 10]. Other problems may also arise during the construction works and related to its hygrothermal phenomena [11, 12, 13]. The changes in moisture content of wall structures can be diagnosed and investigated on the basis of non-destructive and destructive methods. Non-destructive methods are based on the measurement of moisture content of materials in external layers. Destructive tests, where samples of building materials are collected for laboratory tests, allow us to determine the content of water inside the tested elements. Most analyses aiming to determine the influence of terrace solutions on moisture content in the envelope are based on numerical calculations [14]. There is no factual data regarding the humidity condition of building envelopes based on measurements. In view of the authors' experience, the results of laboratory tests can constitute a basis to adopt initial conditions for the drying process of building envelopes. The objective of the work is to determine the drying process of the external wall, moistened as a result of damage to the neighbouring terrace, depending on the accepted mass humidity of the building envelope components. Basing on the diversified measurement results obtained from the tests on an exemplary building with the use of destructive and non-destructive methods, we could determine the course of the drying process of the components in time domain and identify the discovered differences.

2. Factors affecting the durability of balconies and terraces

The essential material from which a large number of terraces are made is concrete. This material has a capillary-porous structure. The pores are partially filled with water and partly with moist air [1-3]. The structure of concrete is exposed to harmful environmental impact, in particular the hygrothermal one [3]. To ensure the durability of the employed solutions, it is necessary to satisfy relevant requirements, such as: total tightness, which prevents the penetration of rainwater into the structure, regardless of the nature, type of thermal load and efficiency of rainwater drainage, which was included among others in the works [1, 15, 16].

The technical condition of terraces is the resultant of the adopted design solutions, applied construction materials as well as the way they are utilized and maintained. In the case of historic buildings, damage to individual building elements is associated in most cases with the progressive destruction of building materials and the lack of renovation works or their improper execution. The occurring irregularities may result in structure safety hazards, threat to usage and damage to the adjacent building elements. The professional practice of the authors shows that the problems involving incorrect technical condition of terraces, often result from improper execution (also as part of repairs or renovations) of flashing works, faulty anchoring depth of the flashings under the top layers of the balcony or terrace, also from the unsuitable shape and distance of the drip from the surface of the wall. The way they have been installed often raises doubts in terms of design or work execution. The issues involving the installation of flashings in balconies and terraces have been discussed in numerous publications in this field [9, 17, 18]. However, these requirements do not contain detailed guidelines and assembly solutions. The fabricating and fixing methods of the flashings depend among others on the substrate, the type of applied insulation, solutions of surface elements or the method of water drainage (e.g. balconies with surface drainage, with composite sub-floor sealing or with drainage methods of water discharge). In most cases, the guidelines apply only to material solutions, or to the need to provide water outflow, or to ensure proper expansion joints. At the same time, the provisions of the regulation on the detailed scope and form of a construction design define the designer's responsibilities, in terms of which the descriptive part of the project should include, among others, "Data resulting from the specificity, character and complexity of a building object or construction works", and he graphic part "Structural and material solutions of internal and external building

envelopes". The drawings should be provided with necessary graphic sign references and descriptive explanations that enable unambiguous understanding of the construction project. The designer should decide on the type of flashings for terraces and how they should be installed so that it is consistent with the dehydration method adopted in the project and with material solutions as well as with the specificity of performance of particular construction elements when subjected to the impact of the external environment. As indicated by the professional examples of the authors, improper solutions or poor work execution of terraces lead to the deterioration of technical conditions inside buildings (moisture, technical damage to materials) and negative impact on the usage conditions of the rooms (favourable conditions for the development of moulds).

3. Results and discussions

In the public utility building located in Gliwice, built before World War II as a residential object, the renovation of rooms and facades was carried out in the years 2013-14. The works comprised the renovation of three terraces, including new floor surfaces and the installation of flashings. In 2017, due to visible moisture on the internal surfaces of the external walls and on the internal surfaces of upper floors, as well as due to evident surface salt blooming, plaster damage and damage to external coatings, visual inspection and macroscopic examinations were performed to identify the reason for their occurrence. In addition, the research included the measurements of mass humidity of the external wall elements, using non-destructive methods as well as sampling for laboratory tests. As part of the non-destructive tests carried out inside the building, the surface moisture of solid ceramic brick with lime plaster used for the construction of external wall structures was measured. Mass humidity measurements were carried out using the Testo 635-2 measuring instrument with a probe to measure humidity level of the material (Figure 1). The instrument is used for the measurement of temperature, air humidity and humidity balance of the material. In the places where the symptoms of moisture were identified, on a section of the external brick wall of the utility room, a fragment of the wall was exposed and made available (plaster rubble). Humidity measurements were made on the surface of visible bricks, on two levels, i.e. 20cm and 50cm from the floor level. Similar measurements were made in another room within the area of the adjoining terrace, in which the users had removed the moistened internal plaster, replacing it with the repair plaster. On its surface, surface salt blooming was visible in some places as well as traces of strong moisture around it.

Figure 1. Measurement of mass humidity of the brick (a) and (b)

The moistening of external walls located in the immediate vicinity of the presented terraces was caused principally by irregularities involving the surface of bay window. Damage to ceramic tiles, lack of effective waterproofing and inaccurate work execution of flashings, and also leaks in the walls at the contact places with gres plate flooring or with flashings resulted in rainwater penetration into the

interior of the building, bringing about progressive moistening of external walls and the destruction of finishing elements. Additionally, floor surface slopes of the terrace were improper, causing water stagnation (Figure 2,3,4).
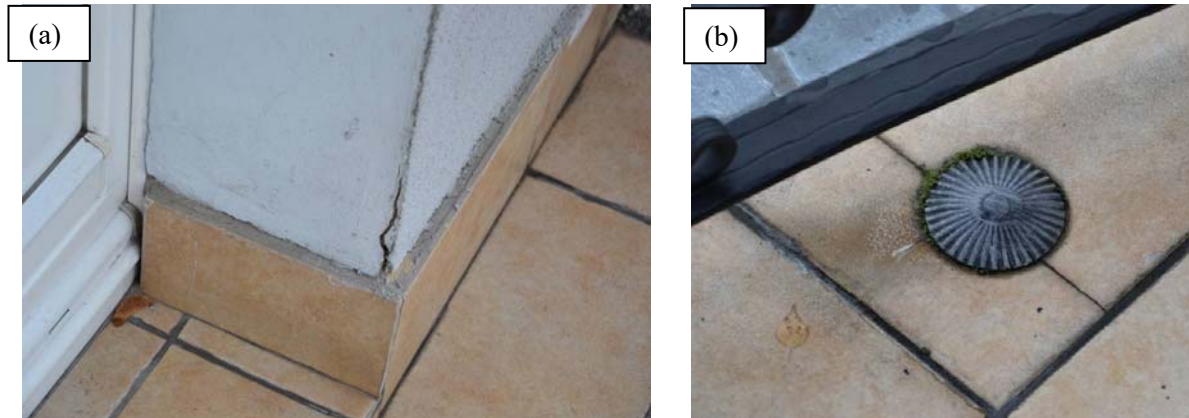

Figure 2. Damage within the terrace area above the bay window: (a) Damage to the plaster in the corner, (b) Cracking of the terrace tile
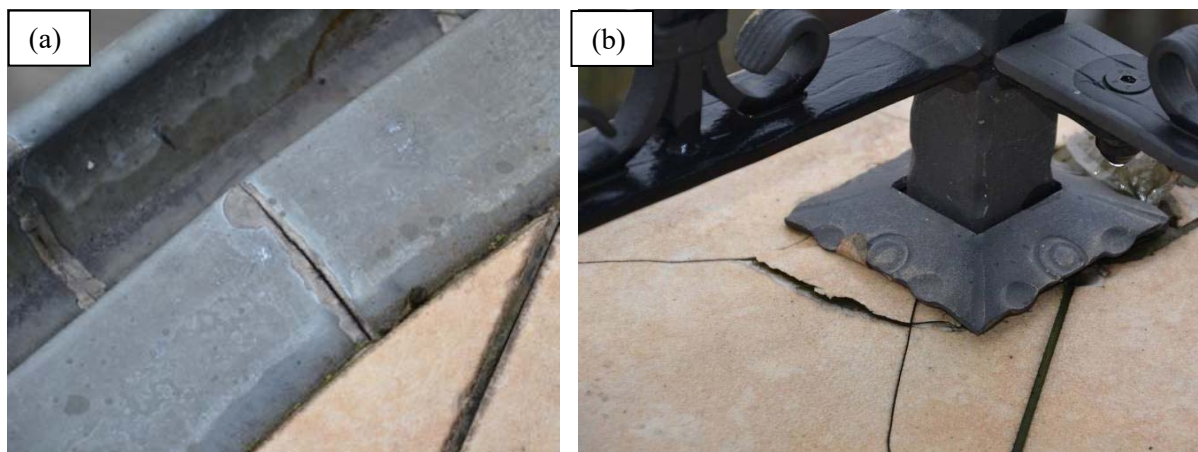

Figure 3. Damage within the terrace area above the bay window: (a) Leaks in flashings, (b) Crack in the terrace tile – mounting place of the balustrade
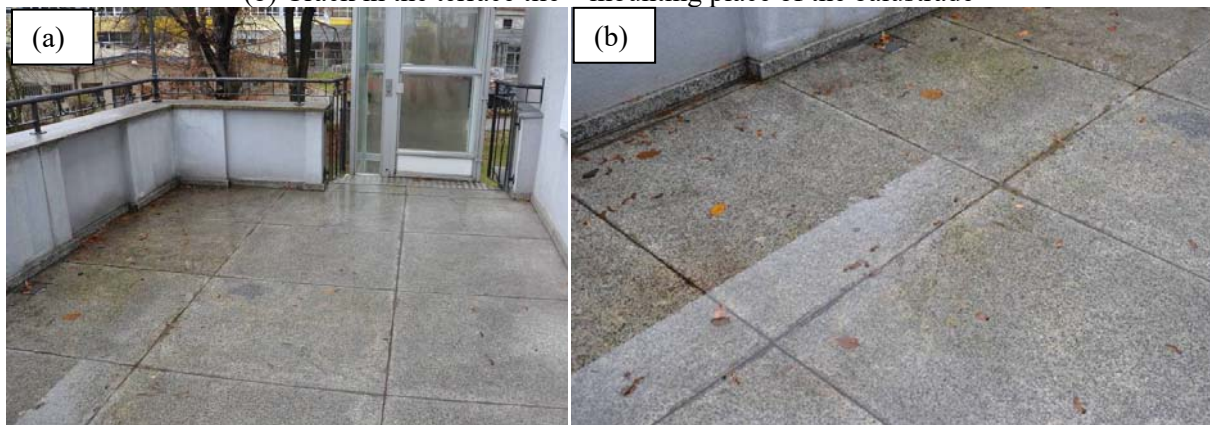

Figure 4. Ground floor terrace: (a) Lack of required floor slopes, (b) Water stagnation

The measurements of mass humidity of the plaster done in the place of strong discoloration and humidity of the external wall yielded the values ranging from 14.3% to 18.6%. After the removal the plaster layer, the measurements of mass humidity of the brick wall were made, yielding the results ranging from 13.9% to 17.5%. Further non-destructive control measurements were made in places located about 1.5 m from the fragment of the moistened wall. Mass humidity of the plaster ranged from 3.1% to 3.9% and mass humidity of the solid brick wall on lime mortar ranged from 4.3 to 5.2%. Mass humidity measurements with the Testo 635-2 measuring instrument with the probe for material moisture measurements yielded the following mean values (from six measurements) in the places of identified moisture:

- ceramic brick wall - 15,8%
- lime plaster - 14.7%.

In the places outside the area of increased moisture, the average mass humidity was:

- ceramic brick wall - 4.9%
- lime plaster - 3.4%.

Invasive tests were carried out using the dry oven method. The method consists in taking out a small sample from the material to be tested, weighing it, then drying it up at the temperature of about 105°C until the mass is constant and re-weighing it. In order to collect samples from the inside of the wall, holes are drilled with a 100mm-diameter core drill bit. During the sampling process, special attention was paid to avoid drying the sample with the heat generated during the drilling process. Therefore, a slow-speed impact drill was used. The collected samples were put into sealed containers and delivered to the laboratory. The pictures below present a fragment of the sample of solid ceramic brick collected from the depth of about 20 cm from the surface of the internal plaster along with the applied moisture analyser. In order to obtain the results of mass humidity from the place of identified moisture and from the place outside the moist area, 3 samples of solid brick were collected (Figure 5). The average mass humidity values of the ceramic brick wall in the places of identified moisture amounted to 9.9%. At the distance of about 1.5 m from the moistened fragment, the mass humidity was 3.4%.

Figure 5. Testing of the sample in the moisture analyser (a) and (b)

In order to determine the impact of initial conditions of the humidity of individual components of the external wall on the process of its drying, simulation calculations were made using the WUFI 2D

program. The said program is an acknowledged tool for assessing the moisture content of envelopes and it is the upgraded version of the program WUFI Pro for calculating flat envelopes in 1D elements. The program WUFI 2D is based on a system of non-linear partial differential equations describing non-stationary coupled heat and moisture transport in building materials. The moistening of individual envelope layers is determined taking into account the diffusive flow of water vapour, sorptive accumulation of moisture and capillary action. In the program WUFI 2D, the diffusions of vapour flux are described with the ordinary transport equation in the Cartesian coordinate system X, Y, as follows:

$$\frac{\partial u}{\partial \tau} = \frac{1}{\partial x}(D_w(u)\frac{\partial u}{\partial x}) + \frac{1}{\partial y}(D_w(u)\frac{\partial u}{\partial y}) \qquad (1)$$

where D_w - liquid transport coefficient depends on the type of material and hygrothermal conditions.

To calculate the changes in moisture, a 38cm thick masonry external wall made of solid bricks was applied along with two-sided lime plaster. In the analysis, practically only materials available from the program's database were applied. In the hygrothermal calculations, the dependence of thermal conductivity of the material and that of the capillary transport coefficient on its moisture was taken into account. This was particularly important in the case of materials used for external envelopes, for which thermal resistance constitutes a significant part of the overall thermal resistance of the envelope. It happens so in the case of an exemplary single-layer solid brick wall. Before the simulation, the data needed for the calculations was defined. The initial mass humidity of a solid brick wall was defined at X% and Y%. The extremely high initial moisture content in the material brings about the increase of its thermal conductivity. It depends on the amount of moisture and structure type of the material. Other material data including porosity, density, specific heat was based on the data contained in the WUFI 2D database. The outdoor climate was simulated based on the climate data for the city of Warsaw. The calculation was made for the envelope located on the west side of the building, due to the large unfavourable amount of precipitation (Figure 6). With respect to the indoor climate, the calculation variants were limited to dry rooms utilized in a regular way with conditions similar to those of typical calculation conditions, i.e. it was assumed that for normal conditions, the temperature was changing in a sinusoidal manner from 18°C in winter to 24°C in summer and relative humidity of the air changing from 55% in winter to 65% in summer.
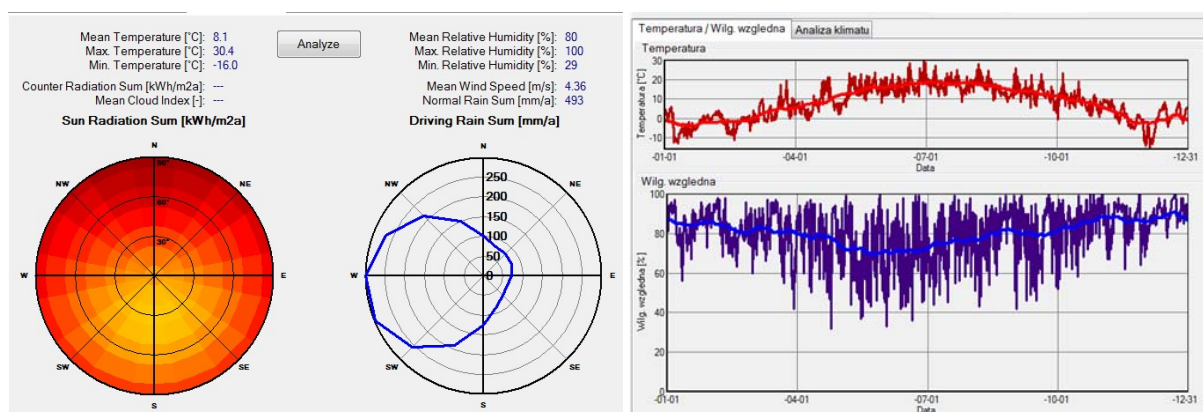

Figure 6. External climate for the city of Warsaw, based on the WUFI 2D program: (a) and (b)

The changes of moisture were tested for two variants. The first calculations were carried out for the wall at the place of the identified moisture. The next calculations were carried out as comparative ones, for the wall, which was not moistened. In each of the variants, the values of average mass humidity from the dry oven tests were used as the initial conditions. The program WUFI 2D offers a

wide range of options involving the analysis of the obtained results. In the article, the presentation of the obtained results is limited to the presentation of moisture changes in the structural layer, i.e. the wall made of solid ceramic brick for two assumed variants. All calculations were carried out for the envelope exploitation period of three years, i.e. 26280 h, for the following initial conditions: start of calculations on 01/10/2018, climate for Warsaw, initial microclimate t_i = +20 0C, φ_i = 55%. The mass humidity of the brick for the moistened wall was assumed at the level of 188.1 kg/m^3, i.e. m = 9.9%. The mass humidity of the brick for dry wall was assumed at the level of 64.6 kg /m^3, i.e. m = 3.4%.

The results of the one-dimensional modelling calculations obtained in the WUFI program are presented in the graphical form. The content of moisture in the present model for the moistened wall over the period of 3 years is presented in Figure 7. The mass humidity of the brick in the analysed period decreased from 188.1 kg/m^3 to 34.4 kg/m^3. The largest decrease to the value of approx. 3.6% (the decrease of humidity by approx. 6.3%) was recorded in the first 365 days. In the following year, we could observe a decrease in humidity by another 1.3% to the level of 2.3%. In the third year, the drop in brick moisture did not exceed 0.5%. The mass humidity was 1.8%.
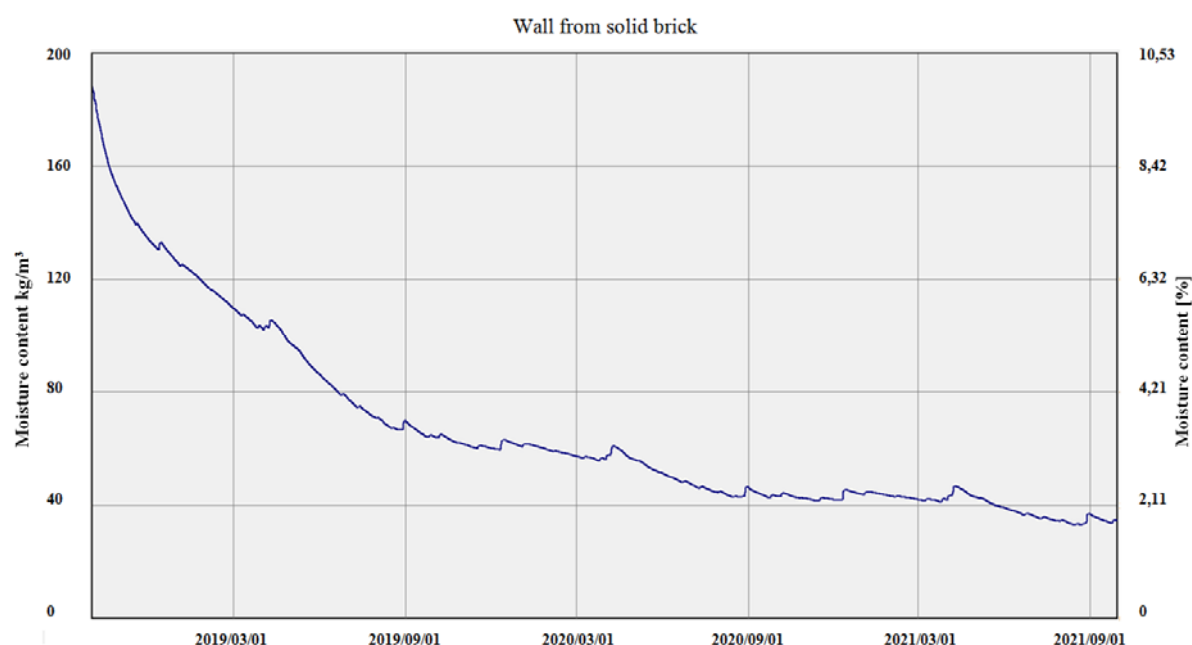

Figure 7. Changes in mass humidity of the solid brick of the initial humidity of 9.9% over the 3-year period, based on the WUFI program

The calculation results involving the change in water content for the solid brick located outside the moisture zone of the external wall are presented in Figure 8. The mass humidity of the brick in the analyzed period decreased from the initial value of 64.6 kg/m^3 to 30.1 kg/m^3. The largest decrease, the same as for the moistened wall, by about 1.0%, to the value of 2.4%, was recorded in the first 365 days. In the following year, we can observe a decrease in humidity by another 0.5% to the mass humidity of 1.9%. Over the last, third year, the drop in brick humidity did not exceed 0.3%, to the value of 1.68%.
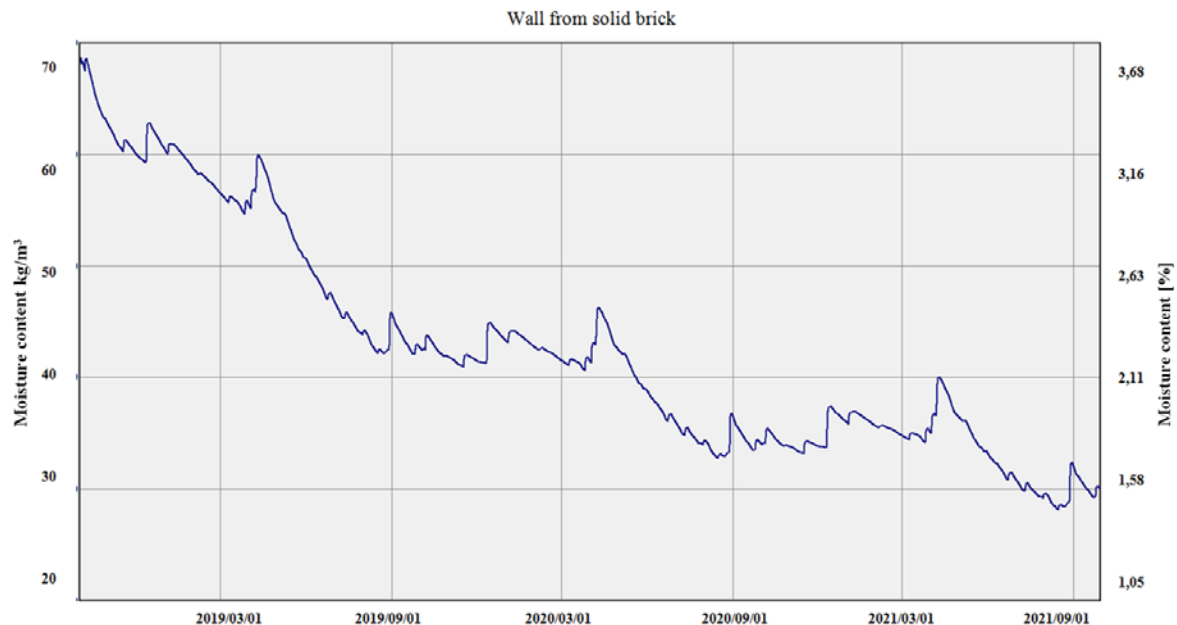
Figure 8. Changes in mass humidity of the solid brick of the initial humidity of 3.4% over the 3-year period, based on the WUFI program

4. Conclusions

The research results presented in this study demonstrate that the measurement results of moistened and non-moistened wall fragments using non-destructive methods and destructive methods are diverse. The tests on the solid brick carried out by means of the instrument with a probe measuring surface moisture yielded the average mass humidity of 15.8%. The measurement of a part of the non-moistened wall yielded the value of mass humidity at the level of 4.9%. The laboratory measurements on the brick samples collected for testing made it possible to determine its actual mass humidity of 9.9% for the moistened wall and 3.4% for the wall in the area not subjected to the impact of water effected by terrace damage. The obtained test results demonstrate significant differences between the moisture tested in the near-surface area and the moisture of the material inside the wall. The identified difference in the measurements of up to 6% is also caused by the accuracy of individual measuring methods. The numerical calculations carried out in the WUFI 2D program made it possible to present the changes in humidity of a solid brick over the period of three years. The laboratory results obtained by the dry-oven method were used as initial data. After the period of one year, the difference in mass humidity between the moistened and non-moistened fragment of the external wall was only 1.2%. In the following year, the difference was only 0.4% and virtually disappeared after 3 years. Based on the carried out tests and numerical calculations, we can conclude that despite relatively large differences in mass humidity of the wall fragments in moistened and non-moistened areas, after the period of 3 years, the humidity level of both analyzed fragments is similar, and the observed differences of 0.12% are practically negligible.

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