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DIAGNOSTICS AND MULTI-CRITERIA ANALYSIS OF METHODS FOR DRYING BUILDINGS AFTER FLOODING. CASE STUDY

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A b s t r a c t

This article presents guidelines for moisture and mycological diagnosis procedures for buildings after flooding. This paper proposes a division of the diagnostic procedure according to the medium of action and collects and presents methods for drying building elements. 54 companies dealing with drying were analyzed. The task of dehumidification is to use various methods to reduce the moisture level of building partitions to the equilibrium moisture level. An analysis of dehumidification methods in terms of ease of application, duration of the dehumidification process and level of structural interference is presented. In Poland, there are no guidelines formulated in legal acts or instructions regarding the procedure for moisture diagnostics and nor drying. It was noted that in situ studies cannot always lead to determining the actual values of mass moisture and thus to creating a real model of partition drying.

Keywords: moisture diagnosis, mycological diagnosis, drying methods, restoration work, flooding

1. INTRODUCTION

Moisture in a building poses a significant threat to its durability, it negatively affects both the technical condition of the structure, i.e. it affects the deterioration of the physical, mechanical and chemical characteristics of building materials and also increased moisture content in a partition affects energy consumption, which results in increased carbon dioxide emissions [10-12,38,39]. In materials of organic as well as inorganic origin, increased moisture promotes the development of biological corrosion. Additional factors that have a damaging effect on building components are water-soluble salts and, in the case of water penetrating from the ground (fields), microbial contamination. The requirement for protection against damp and biological corrosion of buildings arises from legal provisions and guidelines.

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Building partitions designed in accordance with the law, the applicable standards and technical conditions to which the buildings should conform, and the principles of technical knowledge applied in the construction industry, are also exposed to the effects of suddenly occurring water. Suddenly appearing water in a building associated with failures, flooding, floods, storms e.g. a retreating sea wave carries destructive factors affecting both historic and modern materials [3,13,14,17,42,44]. Also dangerous is the large amount of water suddenly appearing in the building elements during a firefighting operation by the fire brigade [6]. Before starting to deal with the consequences caused by flooding of the building, diagnostic tests must be carried out, an important part of which is the recognition of the structure (layers) and the actual condition of the building partitions. A survey of the actual condition of the masonry, floors or roof is then carried out. An important element of the diagnostic analysis is the measurement of water content, aggressive salts in the partition, as well as a mycological examination [22-25,28]. The purpose of diagnostics is to examine and appropriately assess the existing condition of a building element, as well as to correctly determine the actual parameters of the building materials and thus select appropriate methods for drying and revitalising flooded buildings. The water absorption capacity of brick masonry immersed in water can be 23-25%t (the moisture content of dry masonry does not usually exceed 3-5%), this means that there can be up to 250-350 litres of water in a cubic metre of masonry [29-32]. In the case of timber structures, the change in weight is largely dependent on the species of timber. That is to say, the load-bearing capacity of building elements that have been fused changes significantly, increasing the weight. Another issue is the emerging biodeterioration especially on fibrous materials can lead to building disasters. The development of mycotoxins significantly affects the condition of the occupants in the rooms where flooding has occurred [14,16]. It is not only the building elements that are affected by flooding, but also the building equipment. The destructive effect of fungi in fabrics becomes apparent mainly in the form of morphological changes such as superficial mycelial growth, which is usually accompanied by multicoloured stains [20,21,34,35,40,45]. The correct management algorithm is a moisture-mycological diagnosis together with the performance of drying works and works related to the neutralisation of myco-organisms and bacteria [4,15,19,21,26,43].

2. BUILDING MATERIALS AND MOISTURE TRANSPORT

Most building materials have a porous structure [7,9,48]. In porous building materials, moisture transport is very complex. In materials of mineral origin, the increase in volume with changes in state of aggregation damages the structure, and especially with repeated freeze-thaw cycles they degrade completely. Wood is also classified as a porous material and, being composed of macromolecular organic compounds, also degrades when exposed to moisture. Some components of wood, especially polysaccharides, have the ability to adsorb water vapour from the air and condense it on their inner surface until it condenses. The absorption and binding of water vapour molecules by the components of the cell membrane is based on the phenomena of adsorption and capillary condensation. Wood that is periodically moistened and dries out repeatedly passes through the range of optimum conditions for the growth of myco-organisms and is easily decomposed [20].

2.1. Physical models of moisture transmission

The initial scientific analysis of moisture transport processes in the pores of building materials was based on two phenomena, the so-called diffusion, i.e. the flow of water vapour, and the so-called capillary conductivity, which describes the transport process of liquid water in the pores [41,48]. Rose's research, revealed three mechanisms of moisture transport in porous materials. He described two types of diffusion in addition to capillary flux: surface diffusion and water vapour diffusion. In contrast, Gertis and Werner, with regard to molecular transport phenomena, gave a division into three forms:

- diffusion,
- laminar flow,
- and Knudsen molecular transport.

Referring to the given mechanisms of water transport in a porous medium, it should be stated that they can only occur with a specific pore geometry. The coefficient of moisture transport depends on the form of moisture and the size of the pores in the porous material [5,8,18,37,48]. In all these cases, the mass flux is described by an equation of type (2.1):

$$\text{mass flux} = \text{transport coefficient} \times \text{pressure gradient} \tag{2.1}$$

The calculation model for the transport of moisture through partitions used in numerical programmes [9,37] (the WUFI -Wärme- und Feuchtetransport Instationär programme dedicated to historic partitions) uses the method developed by Künzel, which is based on the differential equation (2.2):

$$\rho_w \frac{\partial\theta}{\partial\varphi}\frac{\partial\varphi}{\partial t} = \frac{\partial}{\partial x}\left(\rho_w D_w \frac{\partial\theta}{\partial\varphi}\frac{\partial\varphi}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial p}{\partial x}\right) \tag{2.2}$$

where:
D_w – capillary conductance coefficient,
p – partial pressure of water vapour,
θ – moisture content,
δ – diffusion coefficient of water vapour in air,
μ – diffusion resistance coefficient of dry material,
ρ_w – water density,
φ – relative humidity.

2.2. Drying

The drying of porous materials depends on:

- material properties (moisture storage and transport);
- climatic conditions (temperature and relative humidity);
- heat and vapour exchange conditions (air flow conditions).

Two phases of drying of building materials can be distinguished (Fig.1). The maximum moisture content of the material is assumed in the chart as volumetric moisture content. The first is characterised by a rectilinear decrease in the mass of the sample over a given time. In the A-B section, moisture is removed from the partition very quickly. In the first phase, transport of moisture to the evaporation surface takes place in the partition, this process is rapid (diagram A-C). When the critical moisture content W_{kr} (diagram C) is reached, dry patches appear on the surface of the material being dried and the drying process ceases to be uniform. Further drying effects become slower and slower. When the moisture is completely removed from the surface, i.e. when the second critical point on the graph-point D-is reached, the drying curve approaches the equilibrium moisture value W_r [14,46]. In the second phase of drying, the opposite physical phenomenon occurs. Moisture transport is slow and the boundary conditions allow moisture to move towards the surrounding air faster than it reaches the surface. During the second phase, drying is limited by the properties of the materials [5,47]. The moisture content of the material w_r due to the sorption of water from the surrounding air stabilizes at a certain level at a constant relative air humidity - this value is referred to as equilibrium moisture content.

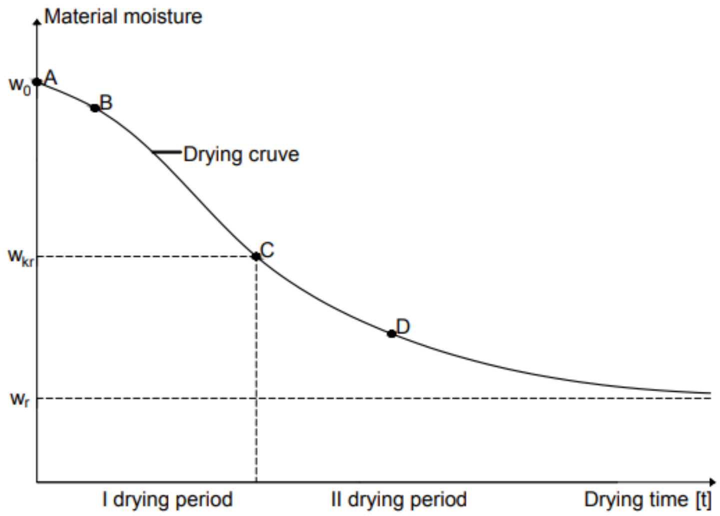

Fig.1. Drying curve [46]

3. METHODS OF DRYING BUILDINGS AFTER FLOODING

Having analysed [1,2,22] the occurrence of moisture transport mechanisms in desiccation, we can formulate a definition of dehumidification. We can call drying drying the transport of moisture leading to the mixing of the moisture (water) level in the element subjected to this process. In the case of damp building partitions, one of the restoration tasks is to select secondary waterproofing methods, and the other is to select dehumidification methods in order to get rid of the problem of dampness in the structure.

After an analysis of the available literature [27,33,41] among the secondary waterproofing methods, a division of methods for drying the building envelope was proposed:

a. natural drying (without the use of additional facilities),
b. artificial drying (with the use of devices),
- invasive methods (interfering with the wall structure),
- non-invasive methods (without interfering with the masonry structure),

c. methods involving constant reduction of humidity,
d. Bi methods (first stage drying, second stage secondary waterproofing),
e. methods lowering water source (drainage).

Methods a and b are dedicated to buildings after flooding, as the other methods are used to dry the building envelope from capillary moisture. Although capillary transport of moisture in a partition can take place from any source, e.g. stagnant water on the roof, methods c,d,e are most frequently applied to partitions adjacent to the ground. Selected drying methods are characterised below.

3.1. Natural drying

The method involves the natural, unforced drainage of water from damp masonry. It is a complex process and depends on the microclimate around the partition. The initial stage involves the elimination of moisture from the surface of the partition and lasts the shortest of all the dehumidification stages, about 20 – 30 days. The rate of this process depends on the difference in the magnitude of the vapour pressure between the water vapour on the surface of the wall and the water vapour in the area away from it.

The rate of drying of soggy masonry increases when:

- the rate of air movement increases along the masonry surface,
- the temperature of the masonry surface increases in comparison to the ambient temperature,
- the value of relative air humidity in the surroundings of the partition decreases.

The second stage of natural drying is the diffusion-convection transport mechanism, immediately followed by diffusion taking place in the capillaries. The effectiveness of natural drying depends primarily on the environmental conditions of the partition. The diffusion resistance of the material also has an influence on the effectiveness of the drying process of the wall - the lower the resistance, the faster the drying of the partition. This technique is time-consuming and does not eliminate the development of biological corrosion, which often accompanies the problem of damp building partitions. This method is dedicated to partitions with low levels of moisture and a small thickness. The advantage of the method is that it requires no financial outlay and does not interfere with the structure.

3.2. Hot-air drying

This method is a derivative of natural dehumidification, and is one of the more popular techniques of non-invasive dehumidification is to force air movement together with a simultaneous increase in the temperature of the partition or the room in which the partition is located. The basic equipment in this technique is oil or electric heaters and mechanical fans. The temperature of the air inside the room should not exceed 37°C. Temperatures in excess of this can contribute to excessive, unfavourable vapour pressure present in the masonry. Acting on the masonry with hot air without using adequate ventilation causes water to drain into the surface areas of the masonry. A significant amount of moisture from the near-surface internal layers is then transported deep into the masonry. In the case of floors, the method involves local degradation of the floor layers, i.e. drilling. The method is expensive and lengthy.

3.3. Condensation drying

A technique categorised as artificially non-invasive. The method is based on cooling the air below the dew point, which results in condensation, i.e. the condensation of moisture contained in the air. As a result of the humidity gradient, moisture is transported from a place of higher humidity to a lower one. In this way, the moisture present in the masonry is evaporated into the air inside the room, the capillary action disappears and the moisture is released through the wall by vapour diffusion. Devices dedicated to this method work best in a temperature range from 10 to +35°C, with the best results at temperatures of approx. 20 to 25°C and high relative humidity. The method is not suitable for drying areas that are difficult to access, as it can cause soiling on the masonry surface.

3.4. Absorption drying

The technique is classified as artificially non-invasive. Its essence is to extract moisture from the air by absorbing it thanks to highly hygroscopic materials. In this method, the most effective way of dehumidification is to carry out the above process in rooms that are tightly closed, where the relative humidity falls below the value of 30%. The advantage of this technique is the ability of dehumidifiers to work at low air temperature (which, however, impairs efficiency). The method may result in the formation of pits on the surface of the masonry. In this technique, as the surface layer of the building envelope dries, the moisture gradient is shifted deep into the dehumidified element.

3.5. Microwave drying

This technique is known internationally as Fast Drying. The system, belongs to artificial, non-invasive methods. The essence of this system is the use of the phenomenon of converting the energy created in an electromagnetic field into thermal energy. Moisture in the partition is transformed under the influence of heat into water vapour and enters the room, from where it is transported outside through the ventilation system. As a result of the emission of electromagnetic waves, all biological life such as mould and fungi is eliminated through thermal destruction. The maximum wall heating temperature is 80°C. A time-consuming method requiring supervision and the use of special nets to prevent electromagnetic waves from penetrating walls and ceilings not subjected to the drying process; in addition, the device must be moved. The method does not result in the formation of soiling on the masonry surface. Metals cannot be heated by microwaves. Their high electrical conductivity means that the electromagnetic field cannot penetrate deep into the metal material, but leads to currents on the surface of the metals, which can be reflected.

3.6. Infrared drying

The technique is classified as artificially non-invasive. The masonry is heated by infrared radiation directly through reflector technology, thus avoiding heat loss and reducing power consumption. The temperature of the masonry is heated to no more than 55°C. The panel method requires no supervision. It is a localised method; the heating panel must be moved.

3.7. The heating pacer method

The method belongs to the invasive techniques for drying building partitions. It uses a set of heaters, e.g. 70 or 50 cm long (Clean company). The idea behind this method is to introduce electrically powered heaters into the wall through drilled holes and heat it to a temperature of approx. 30°C. The heaters raise the temperature inside the wall, which in turn raises the temperature of the wall. The heaters raise the temperature inside the partition, resulting in the evaporation of the liquid contained in the masonry. A process of vapour diffusion into the surroundings takes place. It is therefore important to use dehumidifiers in this technique, which can absorb the water vapour that appears in the room as a result of the dehumidification process. The method requires supervision, timers and protection against excessive heating of the partition.

4. COMPARISON OF DRYING METHODS

A database of 54 companies carrying out dehumidification processes was selected for validation. The dehumidification time for the various methods is strongly influenced by the ambient conditions and the performance of the equipment used in the process. The most time-consuming method is the natural method. As the decrease in wall humidity is about 1.5 % per month in summer, and the natural drying process practically ceases in autumn and winter, it can be assumed that it takes about 1,000 days to bring a two-brick thick ceramic partition to an air-dry state.

In the case of artificially non-invasive methods, the drying time lasts up to a maximum of several months and depends on the power of the equipment involved. The more power-consuming the equipment, the more expensive the dehumidification. The heating pacer method, which is used under standard conditions for walls up to 25 cm and when the wall is heated to 30°C, can take 10 – 20 days. The fastest and most effective method of drying buildings is the microwave method; drying can be carried out from the outside and inside, and is carried out locally. The method makes it possible to reduce the humidity by 5-8% on the first day, and the whole process can take from a few days to two weeks. In the case of dehumidification by non-invasive methods, the degrading effect on the structure can be neglected. When heaters are used, rapidly raising the air temperature to a very high value can lead to the occurrence of cracks on both the plaster and floor layers. When using the microwave method, which raises the temperature of the masonry, not the air, there is a direct temperature impact on the masonry. If the temperature is applied too rapidly, the mortar is damaged by thermal stresses and the strength of the masonry is reduced. Direct effects on the structure also occur with infrared drying. With this method, there is no excessive thermal stress as the temperature of the masonry reaches a maximum of 55°C, so there is little impact on the structure with this technique. The most intrusive method is the heating pack technique, as this method involves drilling holes into the object and placing heaters in them. A method that is also invasive is the method of infusing pressurised 'dry' air into the layers of the envelope. The Pl market has the largest number of companies offering non-invasive methods of dehumidification. The diagram (Fig. 2) shows a database of companies that dry buildings using various methods: drying with heaters, condensation dehumidification, absorption drying, microwave drying, infrared dehumidification:

Fig. 2. Availability on the market of companies offering various methods of dehumidification (drying with heaters (7pos), condensation dehumidification (22pos), absorption drying (12pos), microwave drying (12pos), infrared drying (11pos)

In the case of system failures and tap water affecting the building, we can consider the contamination of the medium to be the least intense. The most contaminated medium is water, which transports mycotoxins from septic tanks, the sewage system or fields. Firefighters use a variety of sources to use fire extinguishing agents to extinguish a fire. The most common is water but also foaming agents, extinguishing powders, extinguishing gases. [6] many times firefighters make direct use of natural bodies of water such as lakes and rivers. An object does not always have to be on fire to be flooded. Water is not only used for direct firefighting by firefighters, but also to cool objects in immediate danger. The test procedure, i.e. Carrying out a damp-moisture diagnosis of buildings after flooding, should consist of the following steps:

- a preliminary survey carried out at the time of the site visit;
- analysis of available documentation;
- basic research, including both moisture and mycological research;
- analysis of the results obtained from the report of the mycological examination of samples carried out in the laboratory and the dampness tests carried out in situ or in the laboratory and, in selected cases, from the analysis of data obtained from the report of the general geotechnical investigation of soil and water conditions.

In Poland, there are no guidelines formulated in legal acts or instructions, e.g. by the ITB (Institute of Building Technology) on how to proceed with moisture diagnosis. The WTA (German Scientific and Technical Working Group for the Protection of Historic Buildings and Renovation of Old Buildings) discusses the diagnosis of damp masonry. However, the WTA does not describe or specify as a "hard" condition to be fulfilled specialist examinations, such as mycological and geotechnical examinations, in the event of flooding. The procedure for analysing the moisture condition of a building is also given in ÖNORM B 3355 "Trockenlegung von feuchtem Mauerwerk - Bauwerksdiagnostik und Planungsgrundlage", published by the Austrian Institute for Standardisation.

The standard includes a scheme of diagnostic procedures, viz: presenting the main objectives aimed at getting rid of dampness (water) from the building, technical methods of drying masonry (mechanical, chemical, electrophysical methods, functions and modes of action of drying plasters). In the paths of the diagnostic procedure, the authors of the standard did not mention mycological examinations focusing on salt analysis and moisture characteristics of the masonry.

Moisture diagnostics can be carried out in a number of different ways: non-contact (using thermal imaging to map moisture), and by taking measurements using invasive or non-invasive methods. " Meters used in the indirect method, measure moisture at a shallow depth, down to a few centimetres. Only the microwave meter, measures moisture at a depth of 30 cm. It should be noted, however, that the measurement may prove to be incorrect, as in the case of hygroscopic and capillary moisture, the distribution of moisture may be different in a wall section. Testing with a microwave meter, does not show the distribution of moisture in the tested element, but gives an average value measured at a depth of 30 cm" [21].

In the case of the hydrophobic paints used, non-invasive meters do not give the actual moisture level in the partition. It should also be noted that in the later stages of natural, absorption and convection drying, as the moisture content of the wall surface decreases, the boundary of the dampness area shifts deeper into the wall and, in the case of using moisture meters, performing control tests using non-invasive methods does not show the actual dampness of the wall.

Direct methods must be used to verify and create calibrations for the non-invasive devices. However, even information obtained by invasive testing may be subject to errors. In order to avoid inaccuracies, surveys must be carried out under a strict regime, both with regard to sampling and when carrying out laboratory transport tests.

5. CASE STUDY

The study presents buildings constructed in 1930 and 2008 that were flooded as a result of an internal installation failure and a water main failure. Both buildings were constructed in traditional technology, using clay bricks with a timber roof structure. In the case of the 1930 building, the flat (Fig.4) was flooded as a result of a failure of the internal water supply system and was not diagnosed; the choice of drying method was decided by the owner. Degraded surfaces, drying cas 2 years. Traces of mycological changes and damaged finish layers visible. The wood was heavily degraded. Symptoms of severe brown or white decay of the wood were observed on most of the samples provided for testing. Numerous structures of Poria vaporaria - the white house fungus - and Serpula lachrymans - the teardrop beetle - were found in all samples. In addition, structures of 11 mould species were found in the wood samples. Alternaria alternata, Penicillium and C. cladosporioides were predominant. Fungi of the genus Aspergillus were relatively numerous. In the case of Poria vaporaia, even one colony obtained indicates a high risk of this species developing in the wood. Regardless of the level of colonisation obtained, the wood was exposed to decay in the cases analysed.

Fig. 3. Moisture measurements of a flooded structure 2 years after failure

Fig. 4. View of contaminated surfaces after application of the natural drainage method

The second object of analysis is a building from 2008 that was involved in a water main failure and was flooded by water flowing from a damaged 1m diameter pipe. As the surrounding septic tanks were flushed out, the water flooding the building was mycologically and bacteriologically contaminated. To define the technical condition, the degree of dampness and the degree of microbiological contamination of the building and to select a drying method, a full diagnostic was carried out and the following steps were taken:

- preliminary survey,
- moisture mapping of walls,
- open excavations in the floors with preliminary moisture measurement,
- basic research (laboratory measurements of mass dampness of masonry and floor layers on the ground),
- measurements of climatic parameters,
- mycological tests were carried out,
- geotechnical investigations were carried out.

A diagnostic of the building took place two weeks after the bus failure. During the flooding of the building, the level of contaminated water reached between 0.20 m and 0.30 m. This is evidenced by deposits of applied silt (Fig.5).

Fig. 5. Level of ground contamination

Fig. 6. Level of water ingress inside the building

The flooding with contaminated water caused considerable dampness in the lower zones of the building's walls (Fig.6), at the same time causing damage to the gypsum plaster and degradation of the paint finishes. The floor screeds were made damp and microbiologically contaminated water was found in the eps polystyrene layer. Contaminated water was located in the adhesive layer under the tiles and under the floorboards. The floor panels and floorboards had become damp and microbiologically contaminated. The level of contamination based on the test results is determined to be high. Cracking of the ceramic floor tiles occurred as a result of water exposure. The floor screed was found to be cracked after excavation. Tests of the mass moisture content of the masonry material (Fig.7) carried out at the points selected by the preliminary tests, using the laboratory weighing and drying method, showed moisture content ranging from 9.88% to 13.91%. The moisture content of the floor screed material was between 8.12% and 9.27%. From the samples taken from the selected representative sites (Fig.7), a total of 12 species of fungi and six species of bacteria were obtained, including typical faecal bacteria, the genera enterococcus and escherichia. Bacteria predominated in the material collected. Most of them are considered pathogenic and the number of their structures was high enough to pose a risk of food poisoning. The presence of organisms capable of causing allergies was identified. In particular: alternata, cladosporioides and chrysogenum. In particular: Alternata, Cladosporioides and Chrysogenum. Among the fungi obtained were taxa described in the medical literature as causative agents of diseases of the human internal organs and opportunistic skin or eye diseases. Geotechnical investigations showed no change in the soil structure under the building.

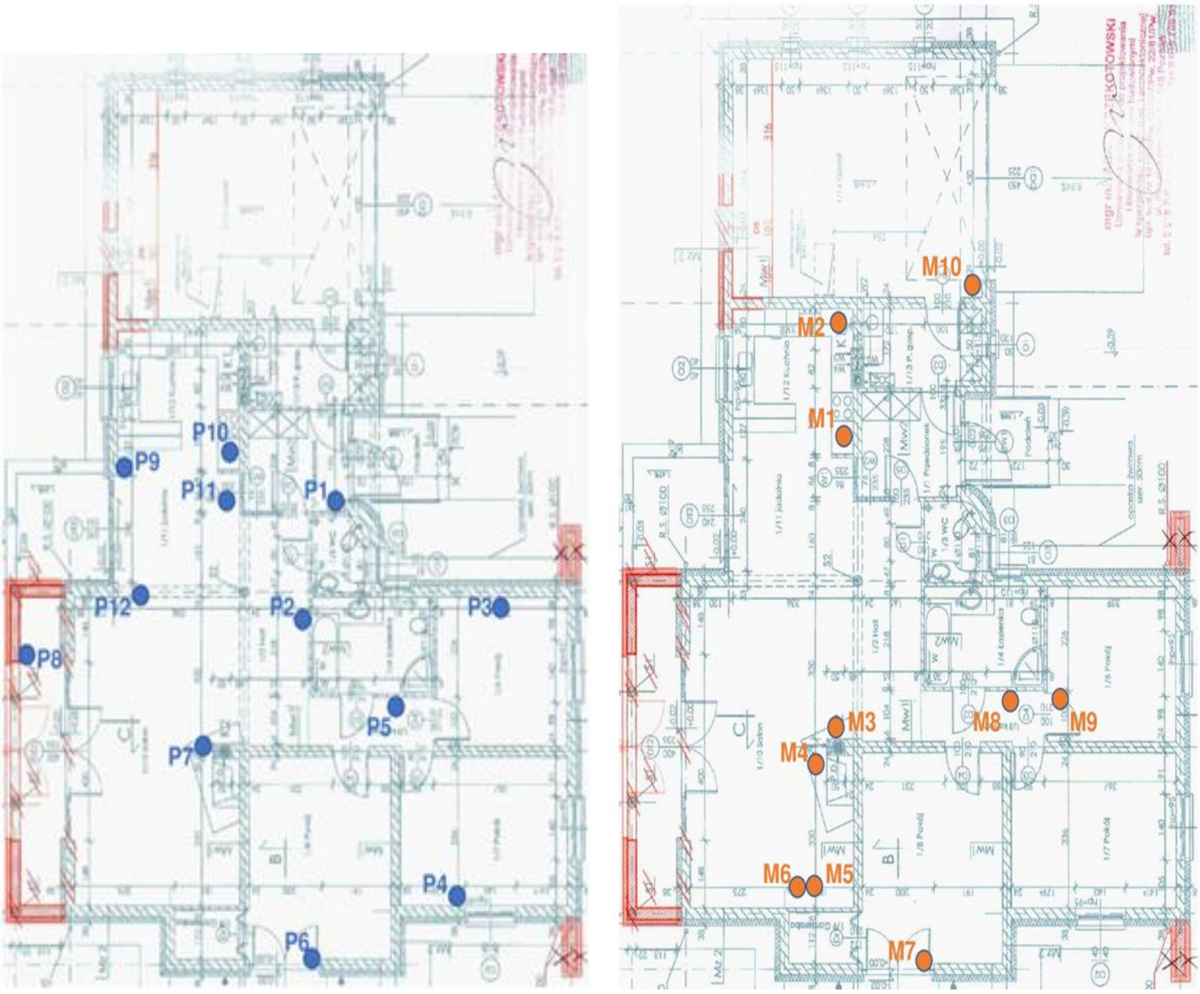

Fig. 7. Example of masonry moisture test plan (P) and sampling sites for mycological tests

Based on the diagnostics performed, it was recommended that the building be disinfected by spraying with biocides that neutralise myco-organisms and bacteria before any work was carried out. Due to the lack of effective decontamination technology for the inner layers of the floors, it was ordered that the bacteriologically contaminated screeds be dismantled and removed, and that the contaminated polystyrene be removed and disposed of. No structural breach or damage to the waterproofing was found. Due to the significant area of flooding, two techniques were indicated as the method of dehumidification: microwave and absorption with moisture control of the walls after dehumidification.

6. CONCLUSIONS

Before starting renovation works in buildings flooded with contaminated water or with wooden elements, moisture and mycological diagnostics should be performed. If mycological contamination is detected, it is recommended to neutralize mycotoxins and proceed with drying works. Resigning from mycological tests, especially when choosing condensation and absorption drying methods (most often used in the case of flooded objects), may result in structural and health problems. As the review of drying techniques showed, an important aspect informing about the effectiveness of the treatments performed is the performance of actual humidity tests. Correct measurement of partition humidity depends on many factors, which should be carried out by specialists. As the analysis showed, an important element influencing the correctness of the work carried out is the "human factor".

Improper drying method or incorrectly carried out work carries the risk of cracking and plaster falling off, which in the case of historic buildings leads to the loss of cultural treasures. Before drying begins, the condition of the waterproofing should be assessed, as its incorrect operation or lack thereof requires the performance of appropriate repair works. If building partitions made of materials with holes, e.g. hollow core slabs, are flooded, the accumulated water should be allowed to flow out. This is because the process of water evaporation in these elements may not occur or, under favorable conditions, it may last from several to several months. Especially in the case of flooding of wooden elements, an incorrect drying method may result in the degradation of the wood structure. Each of the drying methods presented has its advantages and disadvantages, which are described in points 3.1-3.7. As demonstrated in available numerical programs, it is possible to create a computational algorithm determining the amount of moisture and the time of water elimination from the partition. However, the absolute conditions for creating a computer simulation are real data obtained using in situ methods.

The selection of the appropriate diagnostic and drying method, especially for an extremely valuable building that is a testimony to culture, enables further conservation work to be carried out and, once completed, will ensure the appropriate durability of the flooded object.

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