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REVIEW

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Assessment of the effectiveness of secondary anti-damp insulation in heritage buildings made of historic brick: the current state of knowledge, research gaps and perspectives

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Abstract

Destruction caused by excessive moisture is a common problem in heritage buildings made of brick. Historic buildings usually have walls that of different constructions, i.e. walls with all joints filled, walls without filled vertical joints, and walls with a layered arrangement. Excessive moisture causes brick cavities, reduces the load-bearing capacity of walls, is unsightly, and can lead to the destruction of walls or the failure of a building. Secondary anti-damp insulation is used to protect the brick walls of historic buildings. However, there has not been enough research to confirm the effectiveness of secondary anti-damp insulation. This type of insulation is performed with the use of the injection method, with various factors (such as soils, the type of injection material, etc.) that affect the effectiveness of the insulation being taken into account. There is also insufficient research on how injection material penetrates brick. This article presents the current state of knowledge, research gaps, and research regarding anti-damp insulation in historic buildings made of brick, and also the perspectives of future research. The authors propose the use of non-destructive and destructive methods to assess the effectiveness of anti-damp insulation in brick walls.

Keywords Moisture, Heritage buildings, Anti-damp insulation, Brick

Introduction

The rising level of moisture in brick walls is a common problem that causes the degradation of materials. It contributes to poor thermal performance and adversely affects the aesthetic qualities of buildings. In addition, this phenomenon negatively affects the comfort of people in a building and threatens the health of its users [1]. Excessive moisture in buildings leads to increased mechanical, biological and chemical corrosion, and also deteriorates the physical and mechanical properties of building materials [2]. It causes mortar to separate from joints between bricks and increases the susceptibility of masonry components to frost destruction [3]. The problem of excessive dampness in walls occurs primarily in heritage buildings [4, 5], especially in those that do not have horizontal insulation (damp insulation began to be used at the beginning of the twentieth century), or when there is incorrect positioning of insulating materials [6]. Excessive moisture is a global problem that particularly affects legally protected and cultural heritage objects, high historical value objects [7], and more generally -old buildings [8].

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As a result of the lack of anti-damp insulation, moisture penetrates from the ground into a wall and, due to capillary rise, it then moves higher (Fig. 1) and can reach up to even 4 m in height [9, 10]. It is a common phenomenon that occurs when porous material, such as brick, stone or concrete, is in free contact with moisture [11–13]. It lasts until the levels of pulled up water and water evaporated by the surface of the materials equalize [14]. In the case of capillary rise, there is the continuous transport of water through the capillary pores in the direction opposite to that of gravity. The water evaporates on the surface of a masonry wall, and is then transported through active capillaries. At the boundary between the dry and wet zones in the masonry, the evaporation process is the most intense. If moisture penetrating into the walls is not stopped, it is transported through capillaries to higher parts of the structure. Building materials, in this case brick and mortar, have a porous structure, which results in micro-voids. The forces that cause water to rise in a material, known as capillary forces, depend on the size and structure of the pores (capillaries) [15]. The capillaries present in brick and mortar cause water to be pulled up into the internal structures of these materials when they come into contact with a moist substrate. The porosity of a building material, or the ratio of the volume of free spaces per unit volume of the material, affects the rate of water uptake. In materials with big capillaries, the rate of capillary rise is higher than in materials with small capillaries. In contrast, in materials with small capillaries, the level of rise is much higher. In the case of the very small or very large radii of pores, capillary transport does not occur. Therefore, the more open pores there are (and the smaller their diameter is), the greater the capillary rise. Moreover, the capillary rise of water in brick walls depends on the width of these walls, the sorption of the material, and the properties of the masonry mortar [16].

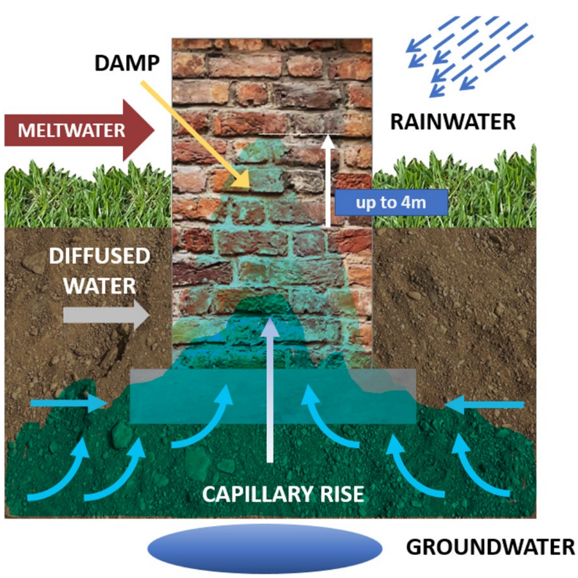

Fig. 1 The process of the capillary rise of water and the main causes of moisture in a brick wall

A high groundwater level is primarily responsible for capillary rise in a building [17]. However, this is not the only factor. Rainwater and meltwater flows down a wall and penetrates into building materials (Fig. 1), which in turn causes their slow deterioration. Excessive moisture in brick walls causes plaster to peel off, and also reduces the strength of structural materials. This leads to the crumbling and detachment of brick and mortar fragments.

Figure 1 presents the process of the capillary rise of water, and shows the main causes of moisture in a brick wall.

Water that penetrates building partitions usually has harmful salts in it [18]. This causes destructive processes to take place as a result of the crystallization and expansion of salt crystals. These salts, together with their solution, move from deeper capillaries to surface ones, and then form a deposit on the surface (or in the surface pores) of the historic building [19]. The largest salt clusters are formed in the parts of walls that are exposed to the most intense water evaporation i.e. the near-surface zone [20].

As a result of crystallization in pores, crystallization nuclei are formed, which significantly increase in size over time. If the pores are completely filled, the further growth of crystals will put pressure on the surrounding walls, which in turn will lead to the bursting of the material structure, i.e. its destruction [21]. The crystallization pressure that occurs in this process is so high that during the drying of porous materials (during repeated cycles of salt dissolution and crystallization) their mechanical strength is reduced and, as a result, fragments of mortar and bricks crumble and fall off [22, 23]. The salts that cause the greatest damage to materials are those that crystallize when there is a temperature difference in the environment, i.e. sodium and magnesium sulfates, and sodium carbonate [24]. An increase in the degree of the hydration process that is caused by the above-mentioned salts, and during which water molecules attach to salt crystals, usually causes the crystals to grow significantly. The increase of their volume then exceeds 300%. The enormous pressure exerted on the walls of the capillaries (as a consequence of repeated hydration and dehydration) can destroy a construction material [25].

Figure 2 shows typical plaster, brick and mortar damage caused by excessive moisture and salinity in a brick wall from a heritage building. Figure 2a, b show the Church of the Holy Spirit in Warsaw, Poland. The

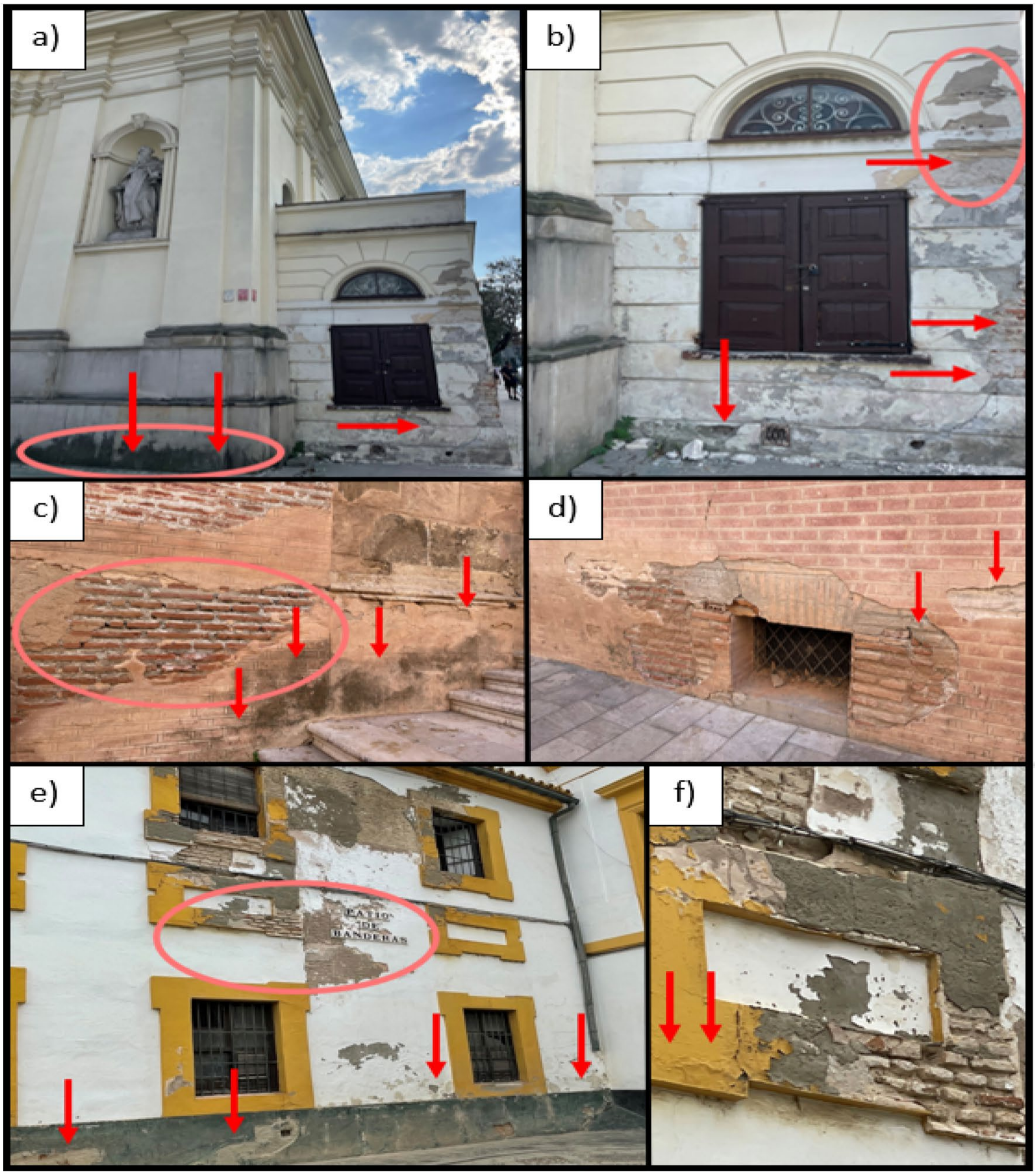

Fig. 2 Exemplary damage caused by excessive moisture in heritage buildings: **a**, **b** The Church of the Holy Spirit (XIV c.), Warsaw, Poland; **c**, **d** Cathedral (XVI c.), Malaga, Spain; **e**, **f** Patio de Banderas (X-XVIII c.), Seville, Spain

lower part of the building is excessively damp due to the capillary rise of water from the ground. In this case, the durability of the brick wall decreased, which in turn led to the flaking of the plaster and damage to the bricks, mortar and facade (which began to crumble and then fall off in fragments). Figure 2c, d show the back part of the brick cathedral in Malaga, Spain. As a result of the capillary rise of water, the strength of the bricks and mortar reduced, leading to their crumbling and their partial disintegration. Biological corrosion is also visible in the lower part of the wall. Excessive moisture adversely affected the plaster, which peeled off in some parts of the walls. Figure 2e, f show the Patio de Banderas in Seville, Spain. Extensive peeling of the plaster is visible on the entire facade of the building. In addition to the flaking of the plaster, excessive moisture led to damage to the facade and bricks, which is particularly evident in Fig. 2f. In this case, capillary rise reached a height of several meters and led to damage to the structure of structural materials, as well as to the deterioration of the building's appearance and its technical condition. As can be seen in Fig. 2, excessive moisture, in addition to being an unsightly phenomenon, is also destructive to walls and buildings. It causes defects in bricks [26], reduces the load-bearing capacity of walls [27], and may lead to the failure of a building [28]. Therefore, in order to prevent damage to buildings caused by excessive moisture, it is important to cut off the flow of moisture in walls by making secondary anti-damp insulation.

In the paper, the authors aim to focus on the evaluation of the effectiveness of anti-damp insulation made using the injection method. Future research will cover the method of implementing the injection material into brick, and the investigation of the interphase between the injection material and the brick. The authors evaluate the effectiveness of anti-damp insulation by considering the factors that affect the effectiveness of the injection process. The following factors are considered by the authors:

- The type (porosity, structure) and age (ancient, old, new) of the brick,
- The structure of the brick wall: a brick wall with all joints filled, a brick wall with unfilled vertical joints, and a layered wall (opus emplectum),
- The type of used mortar,
- The moisture level in the brick wall,
- The penetration of the injection material into the masonry,
- The interphase between the injection material and the brick,
- The effect of salts (sodium and magnesium sulfates and sodium carbonate),
- The possible chemical reactions of the injection material with the salts in the brick wall,
- The method of application (gravity, pressure),
- The type of used injection material.

Current state of knowledge

Literature review

Taking information contained in the introduction into account, it can be said that knowledge concerning the effectiveness of secondary anti-damp insulation is particularly important with regards to historic buildings, the good condition of which is of public interest [29, 30]. In turn, experimenting on a historic building is impossible. In such buildings, the possibility of taking samples (e.g. to check the distribution of injections), drilling, or performing other actions is only possible to a very limited extent, and only with the permission of conservation services. However, a review of the available literature shows that this problem has not yet been sufficiently studied [31, 32].

Cultural heritage is considered valuable to the community and the nation. The principle of sustainable development is to allow the people of the next era to learn about the achievements of their ancestors. Therefore, it is important to protect and preserve heritage buildings in order to allow the next generation to learn about them. There are many heritage buildings around the world, and more than 900 of them are listed on the UNESCO World

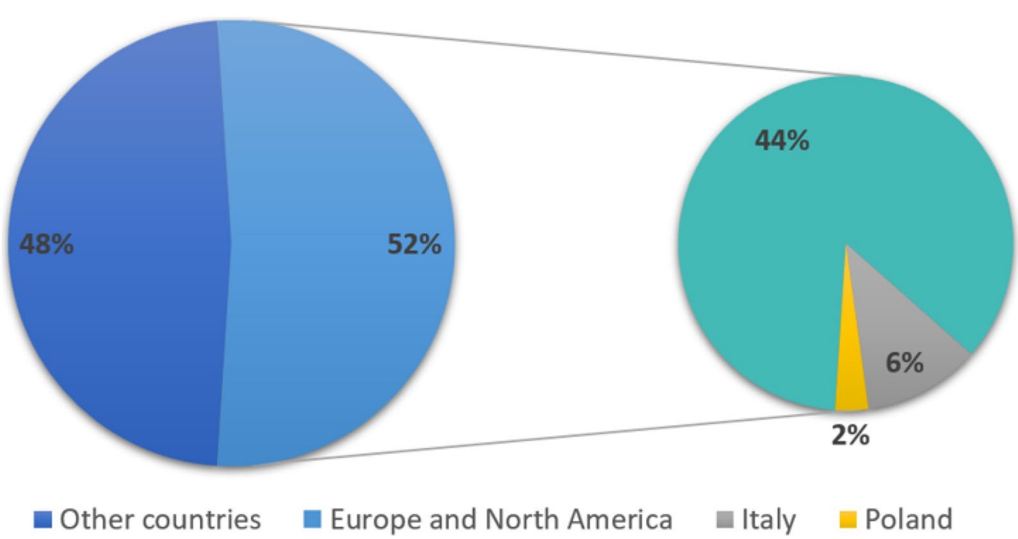

Fig. 3 Percentage share of cultural sites in the world (own elaboration, based on [33])

Heritage List. Figure 3 shows the percentage share of cultural sites in the world, highlighting Europe and North America (52%), where the number is significantly higher when compared to the rest of the world (48%). In Europe and North America, the dominant country with the highest number of cultural sites is Italy (6%). Poland has 2% of world cultural sites. It should be noted that each country has its own register of monuments, of which there are hundreds of thousands around the world.

Taking into consideration the problem of capillary rise in masonry [34], the amount of data (from laboratory and field studies) concerning the effectiveness of remedial methods is still limited [35].The studies that have been carried out to date do not provide a clear answer on how anti-damp insulation should be performed in order for it to be effective.

The conducted literature review shows that studies concerning anti-damp insulation focus primarily on workmanship. However, once anti-damp insulation is implemented, it is not further inspected. It is therefore not possible to clearly determine what is the reason for the ineffectiveness of secondary anti-damp insulation done with the use of the injection method [36–38].

Various factors regarding this method have been studied, such as the methods of injection [39, 40], the type of used injection material [41], the type of used masonry materials [42], and how the injection materials adhere to bricks [43]. Long-term [44] and short-term [45] studies have been performed. Unfortunately, there is still not enough data to be able to clearly identify the reason for the lack of effectiveness of secondary anti-damp insulation.

The most popular methods used for the secondary protection of brick masonry from moisture are masonry undercutting [46] and chemical injections [47, 48]. These methods make it possible to eliminate the causes of dampness (at least for a while), or to significantly reduce it until the problem returns. An important issue regarding the performance of secondary anti-damp insulation (with the use of injection) is its effectiveness. After this insulation is implemented, the problem of masonry dampness returns, and therefore the procedure needs to be performed again. For this reason, the authors of the paper have focused on research concerning the controlling of the injection procedure.

Figure 4a shows the injection procedure in brick walls. In turn, Fig. 4b, c show the probable way of the spreading of injection mass in a brick wall. In this case (Fig. 4b, c), there is not enough data supported by research to depict how exactly the injection material spreads in a brick wall. This probably depends on various factors.

Materials and methods

Paraffin injection

Article [49] describes how secondary insulation should be performed with the use of the injection method. Paraffin was used as an injection material during the research. The moisture content of the wall, the evaporation conditions and zeta potential were listed as factors that can affect the effectiveness of the injection process and the injection material. In addition, the authors focused on the porosity of building materials, and noted that pores must be completely sealed for the injection to be effective. The authors measured the amount of moisture in the walls before, immediately after, and 6 months after the paraffin injection. During the research, the authors also presented the results of using the paraffin injections, which significantly reduced the amount of moisture in the walls. According to the authors, the use of paraffin as an injection

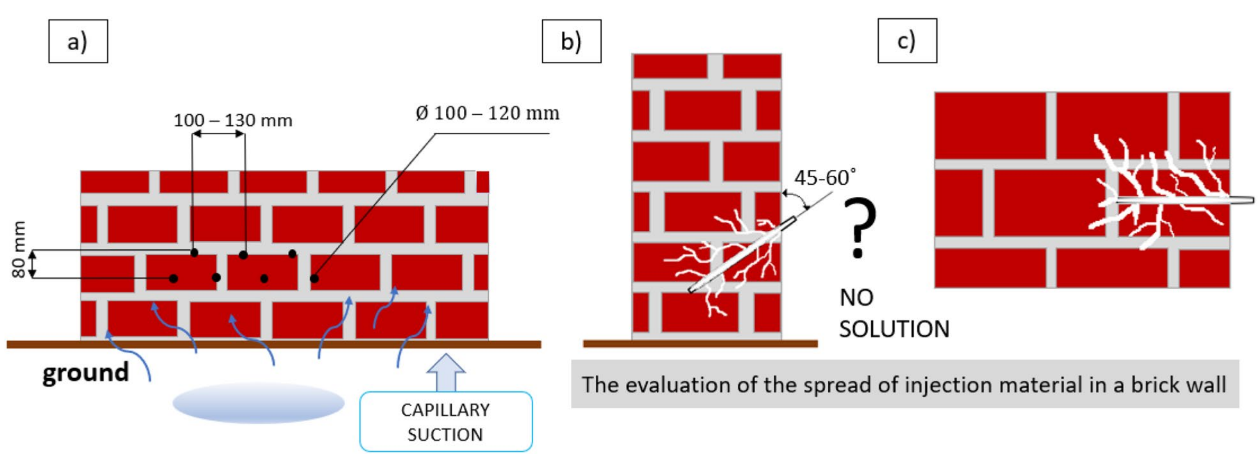

Fig. 4 Brick walls: **a** the implementation of injections in brick walls; **b** uneven distribution of the injection mass; **c** uneven distribution of the injection mass—top view

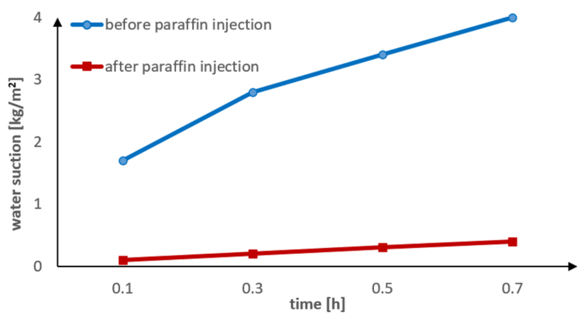

Fig. 5 The amount of water before and after the paraffin injection (based on the information provided in [49])

material solves the problem of sealing pores in materials, which is confirmed by the data shown in the graph in Fig. 5.

The graph shows that paraffin injection reduced the moisture in the walls by an average of 92% when compared to a sample in which paraffin injection was not performed. At this point, it should be noted that the moisture level in the material increased over time. The analysis of the effectiveness of the paraffin injection was monitored for only 6 months. After this time, the researchers did not monitor the effectiveness of the injection. Therefore, there is no knowledge regarding the effectiveness of the paraffin injection after this time. It can be assumed that this treatment would not prove to be effective and that it would need to be repeated. This is because the water level in the samples after each measurement is higher. The authors studied kerosene injection in individual materials, and also in brick and lime mortar when combined together. However, the article only describes the effectiveness of kerosene injection in individual materials. In the case of brick and lime mortar together, the authors focused on describing the flexural and compressive strengths, but the effectiveness of using kerosene injection was not studied. There are also no other studies that describe the use of kerosene injection in other conditions or in different material combinations. In addition, tests taking into account the salts in water and different wall structures have not yet been performed. Without studies that take into account the above factors, it is impossible to predict how the applied injection would perform under other conditions. Another unknown is the interphase between the material and the paraffin. The researchers did not consider this in their work. Paraffin melting is associated with temperatures of above 50 °C, which transforms solid state into liquid. Therefore, the question regarding the combination of these two materials remains unanswered.

Liquid and solid injection materials—their comparison, transport, and spread

Paper [50] presents a study that compares the effect of a brick/mortar joint on the transport of chemical injection materials, and how the use of selected injection materials affect capillary rise. One type of brick with an open porosity of 29%, lime-cement mortar with quartz sand, five liquid injection materials, and three injection creams were used in the studies. Among the tested materials were pore-filling and hydrophobic materials, as well as products based on water and organic solvent. Brick walls consisting of two bricks bonded together with mortar were made using these materials, and then the injection materials were injected. The authors divided the samples into 2 groups: samples in which 5 liquid materials were used, and samples in which 3 injection creams were used.

In the first group, in which the liquid injection materials were used, the samples were immersed in water until they reached 50% of their water saturation. The water-based substance was then applied to the brick sample, i.e. injected into it. The solvent-based samples only absorbed 8.3% of the substance. After applying the substances, the samples were stored for 3 weeks. After this time, a test was performed. The researchers noted that water-based injection materials are easily transported through the mortar. The situation is different in the case of injection materials based on an organic solvent. The high moisture content of the samples prevents the free spreading of organic solvent-based products.

Figure 6 shows the effectiveness of the liquid injection materials applied onto the bottom part of a masonry wall. The least effective was the injection material based on an organic solvent.

In the second part of the test, injection creams were used and 3 environments were prepared: a dry environment, a 100% damp environment with the possibility of drying out after injection, and a 100% damp environment without the possibility of drying out after injection. The samples with the injected creams were left to dry for 3 months. After this time, the samples were immersed in water, and capillary rise was tested. In the dry sample, the injection cream did not spread very much. In the environment where the sample was allowed to dry, the cream was visible and effective (it reduced moisture). In the environment where the sample did not have the opportunity to dry, the cream was visible but not effective (the samples were highly saturated with water). To sum up, the most favorable result were obtained by the sample that was damp and had the opportunity to dry.

Figure 7 shows a comparison of the injection creams in 3 different environments: in the dry environment, in the 100% damp environment with the possibility of drying, and in the 100% damp environment without the

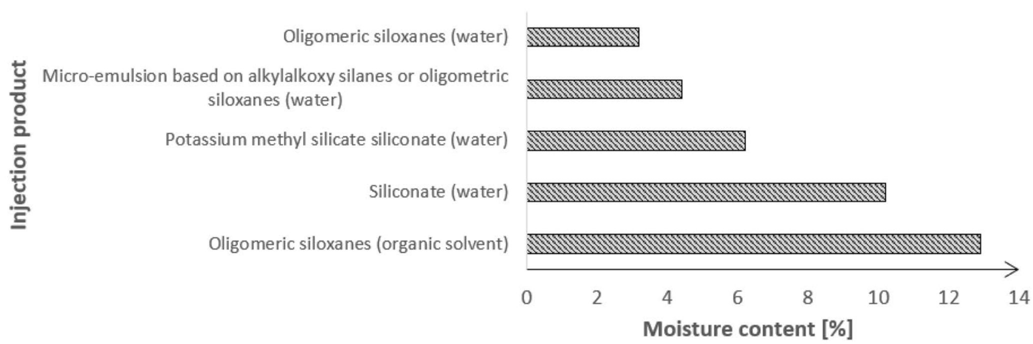

Fig. 6 The effectiveness of liquid injection materials (based on the information provided in [50])

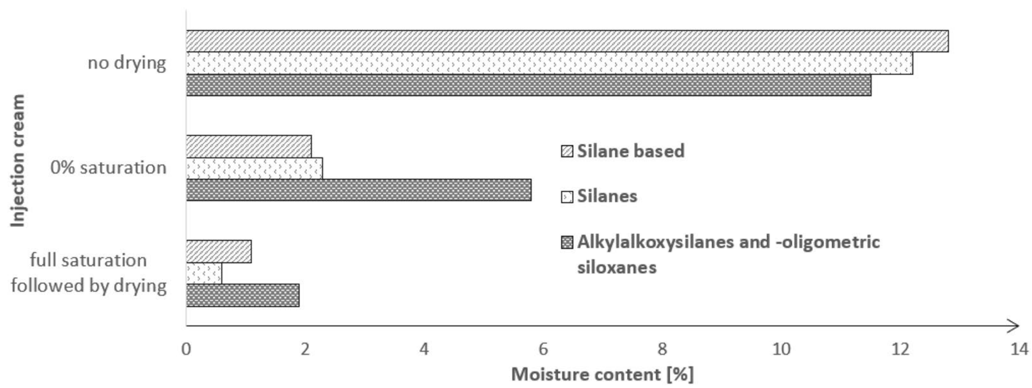

Fig. 7 The comparison of the injection creams in 3 different environments (based on the information provided in [50])

possibility of drying after injection. In the environment where the damp substrate was dried, the silane-based cream performed better than the other creams.

The researchers noted differences in the spreading and effectiveness of the injection materials that were applied on different substrates (mortar, brick). These differences are also apparent in the case of water-based and solvent-based products, as well as in the case of liquid and cream products. Water-based materials are easily transported through mortar, unlike materials based on an organic solvent. In addition, the moisture measurements of the samples show that the farther away from the injection point, the worse the result. This means that the injection material only reduces moisture to a in the area of the injected point. In this study, the researchers focused on analyzing the propagation of liquid (in water and organic solvent) and solid (creams) injection materials in brick masonry (brick/mortar). They wanted to conduct the study in a short time (3 months), and considered the following factors:

- Different types of injection materials,
- The degree of moisture in the environment and the possibility of drying out the masonry (only for the injection creams),
- The transport of water and injection materials in two joined materials with a different distribution and size of pores (brick, mortar).

However, the researchers did not take into account other factors, such as the different structures and masonry elements (different porosity), the interphase between the brick and the injection material, and the effect of salt on the selected products. The measurement of the capillary rise was done after 3 months, which means that there is no knowledge of the effectiveness of these injection materials after more than 3 months. Three months is far too short a time to be able to determine whether the selected injection material is effective. In addition, this study did not compare the effectiveness of liquid and solid products in the same environment. Tests with solid products were performed in different environments, while in the case of liquid products the tests were performed in a 50% moisture environment. There was no information on the reason why the performed injection is mainly effective in the area where the injection product is present. This is possibly related to the poor distribution of the product in the brick and mortar. There are also many unknowns in this study due to insufficient testing, with many factors affecting the possible effectiveness of the injection not being considered.

Using a brick of the same porosity, the researchers conducted another laboratory study using 15 different chemical injection materials: liquids, emulsions, microemulsions, creams and gels. Paper [51] focuses on the curing, transport and effectiveness of injection materials. The study used an SEM electron microscope to see how an injection material spreads in brick. Backscattered electron (BSE) and secondary electron (SE) modes were used during the observations. Energy dispersive X-ray spectroscopy (EDX) was applied to brick powder samples impregnated with selected chemical materials. The study considered different types of injection materials and varying degrees of water saturation. In contrast, the study did not take into account the saline environment. The different porosity and structure of the brick and the brick/mortar joint were also not taken into account. The spread of the injection material in brick with a porosity of 29% was determined during the study. The researchers state that there are many unknowns in their study. Not enough research has been carried out to be able to evaluate the actual effectiveness of these products in different environments.

Similar studies on the transport of liquid injection products (water, products in solvent) were also described by other authors, with comparable results being obtained [52–54]. Research taking into account the transport of injection products were presented in paper [55], in which the main reason for the failure of the used injection products was their insufficient spread (penetration) in the tested material. As the studies in paper [56] show, injection materials with similar chemical properties can spread differently in the same building materials. Penetration not only affected by the building material, but also by the used injection material. The same injection product spreads differently in environments with different moisture levels.

As can be seen, the way the injection material spreads in brick (brick/mortar) is an important factor that affects the effectiveness of the performed injection. The penetration of injection products in brick has not been fully studied, despite many publications concerning this subject. There are no concrete answers to questions about how an injection product spreads in brick, and also why this procedure fails. Studies carried out to date usually did not take into account major factors, such as the type of used material, the method of injection, the type of masonry, porosity, the presence of salts, the level of moisture in the masonry, etc. They instead focused on analyzing several factors that affect the effectiveness of the injection procedure.

An environment with a high water load

In paper [57], the author describes tests involving the application of injection cream onto a damp brick wall, using the Camberwell Pier brick pier as a model. For the tests, the author used brick with a water absorption rate of 14 percent, mortar (a mixture of lime and sand), and silane/siloxane injection cream (containing 64 percent of an active ingredient). In the research, the author focuses on an environment with a high water load. The load is acting on the bottom part of an exterior wall. The author began his research by preparing a brick and mortar wall. The model brick wall was, to some extent, a reproduction of a brick wall that was typical for nineteenth century Victorian terraced properties.

At the beginning of the study, the brick wall was immersed in water, with moisture levels being monitored for 55 days. The author noted that moisture rises faster in mortar when compared to brick. Brick also absorbs water, but to a much lesser degree. Moreover, despite the visible salinity and efflorescence on the lower part of the wall, the bricks above were also wet. Afterwards, the injection procedure was performed very carefully and with the proper dosage of injection cream. The author assumed that injecting alone would be effective. The study aimed to reduce moisture in the brick wall, and did not attempt to eliminate capillary rise completely. The brick pier is in constant contact with water, so the wall remains wet no matter if the injection is effective or not. The aim of the tests was also to show to what level moisture can rise in a brick wall, and whether chemical injection can stop this rise. The author noted that the conducted test did not give the answer to how long the performed injection can be effective. There are no studies on the effectiveness of this treatment over a longer period of time. After 9 months the effectiveness of the insulation was tested, and it was found that the performed injection reduced capillary rise. However, the author mentioned that not enough research has been done to conclude whether the chosen method is the best remedial option for such walls. The author concluded his research by saying that the chosen injection material controls moisture in a wall, which proves that the study was successful.

Figure 8 shows the results of measuring the moisture content in a brick wall. Initially, the test sample weighed 51.1 kg. After 55 days of being immersed in water, the weight of the sample increased by 13.1%. 9 months after the injection procedure, the weight of the sample decreased by 5.36%.

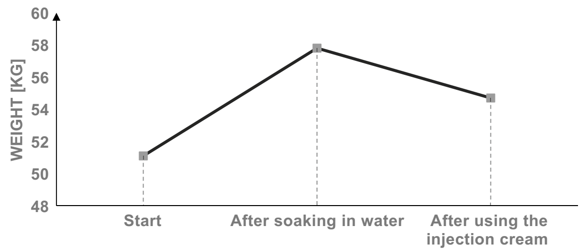

Fig. 8 Influence of the injection cream on the capillary suction in the wall (based on the information provided in paper [57])

In article [57], the cream injection procedure is described in detail. The author mainly focused on the problem of a constant contact of a wall with moisture. The conducted research proved the effectiveness of the injection procedure, but only in the case of the model masonry wall samples. There have been no studies that investigate how injection cream penetrates brick, and how the interphase between the brick and the injection material looks. One type of injection cream, one type of brick and one type of mortar were used in the study. Therefore, there is no knowledge to confirm whether the tested injection cream will perform well in other conditions. In addition, there is no information on whether using a different injection cream will reduce moisture to the same extent. A different injection cream could possibly reduce moisture in the masonry to a greater extent. This study lacks reference to the many variables (type of brick, types of mortar, masonry texture, varying degrees of salinity) that can affect the effectiveness of the injection procedure. Too many factors, which are not described in this study, may affect the effectiveness of this insulation.

The influence of salts

The authors of paper [58] presented a study of damage to a building caused by salts from the ground. The study examined 24 historic buildings located in Adelaide (Australia) and made of various materials (including brick). The salts that were found in the ground were sodium sulfate, sodium chloride, and sodium nitrate. The research aimed to gain knowledge about the effectiveness of the injection procedure, and took into account the type of substrate, the method of application, and the type of material.

X-ray diffraction (XRD) was used to identify the salts present in the samples, and to distinguish salts of the same composition. Ion chromatography was used to identify other salts present in the samples (salts in small amounts, salts mixed with building materials and the moisture barrier layer). Scanning electron microscopy (ESEM) with energy-dispersive X-ray spectroscopy (EDS) was also used to examine the samples. ESEM/EDS was used to identify some of the less common salts and to observe the morphology of the salt crystals. The study evaluated porosity and pore size distribution using mercury intrusion porosimetry (MIP).

The injection was performed using pressure and gravity methods. Pressure injection achieved better results when compared to gravity injection. In addition, fewer failures were recorded in buildings where the injection holes were spaced closer together (two per brick). It was also found that mortar, when compared to brick, was more susceptible to damage from excessive salinity.

In this study, the authors focused primarily on the effect of salts on the destruction of buildings. Gravity and pressure injection were compared. The distribution and pore size of building materials were checked. The salts present in the soil were also checked. However, the study lacks a comparison of different injection products. The authors used chemical injection (siloxane) in the study. Injection materials can have different effects, and can react differently with salts, and therefore several types of products should be tested. A test to see if salts in materials react with injection products was not performed. There have been no tests that investigate how injection material penetrates brick, and how the interphase between the saline material and the injection product looks. Different degrees of the moisture content in the materials were not taken into account. Without considering the above factors in research, it is impossible to predict how long the used method will be effective, and also whether this treatment will work in other buildings.

k. Authors who analyse saline environments mainly focus on ventilated plasters [59], plaster mortars, restoration plasters [60–62] etc., and do not consider the injection procedure. Some studies compare the use of chemical injection and the use of renovation plaster in saline environments [63]. Making plaster is important, but analysing the effect of salts on the effectiveness of chemical injection is much more crucial. This is because the salts in the soil can react with the used injection agents and cause the injections or plasters to be ineffective. In such a case, it is necessary to redo the anti-damp insulation, which adversely affects the structure of historic buildings.

Research gaps

The assessment of the effectiveness of secondary anti-damp insulation is a big challenge regarding the protection of walls against moisture, because most of the research is focused on the selection of anti-damp insulation without taking into account the need to examine the effects of this insulation. Therefore, there is no knowledge of how the injection mass penetrates the brick structure, and also whether it penetrates 100-year-old brick and 700-year-old brick in the same way. There is also no knowledge of what type of injection will work in a specific wall structure. The walls of historical buildings made of brick can have different structures, and therefore the tests should be performed on each structure separately: on a brick wall with all joints filled, on a brick wall with unfilled vertical joints, and on a layered wall (opus emplectum). The conducted preliminary tests with the use of the SEM electron microscope (Fig. 9a, b) showed that the structure of bricks from different periods differs with regards to the number and size of pores. For this reason, it can be assumed that depending on the structure of the brick and the structure of the wall, the injection mass may disperse in various ways. Moreover, it can also be assumed that depending on the type of brick and the type of wall structure, the effectiveness of different injection substances will be different. The selection of the injection procedure is currently not preceded by sufficient research. Due to the fact that correcting an already performed injection is a difficult procedure, and in some cases even impossible to perform, it is worth investigating this issue to order to consciously design the injection procedure.

The choice of a technological solution is influenced by many factors, e.g. the amount of salts in the wall, the level of moisture content in the wall, or the way the insulation was executed. The condition of the brick walls and the properties of the materials they are made of may be a limitation. Modern repair materials may react with the salts in masonry, which in turn may lead to undesirable effects, such as detachment or swelling. Therefore, another unknown issue is the behavior of the injection mass with regards to the type of salinity in the wall. There is a suspicion that the injection mass will react with a saline wall, and it is important to check the suitability of the various injection materials in a saline environment.

Figure 10 shows the most commonly studied factors that affect the effectiveness of anti-damp insulation. Scientists in their studies mainly focus on evaluating one, two or three of the listed factors. In contrast, there is a lack of studies that consider all of these factors simultaneously.

Based on data from Scopus and other research papers, Fig. 11 shows the number of studies that take into account the investigated number of factors affecting the effectiveness of anti-damp insulation. Most studies consider 1 or 2 factors. Far fewer (about25% fewer) studies consider 3 factors, and only a few consider 4 factors. There is no research that takes into account 5 or more factors that affect the evaluation of the effectiveness of secondary anti-damp insulation. Therefore, the authors of this paper will consider more than 5 factors that affect the evaluation of the effectiveness of anti-damp insulation in a brick wall. Such studies will allow the effectiveness of anti-damp insulation in different conditions to be compared, and also enable the effectiveness of anti-damp insulation to be evaluated not only in one heritage building, but in many.

The currently available international literature shows that the effectiveness of anti-damp insulation with the use of the injection procedure still needs to be fully clarified. Even though dozens of studies (that consider various factors) have been performed on this topic, it has yet to be fully understood. In addition, due to climate change and the increasing prevalence of extreme events (floods, heavy rains, rising water levels), the importance of the topic related to the effects of capillary rise is likely to increase in the coming decades.

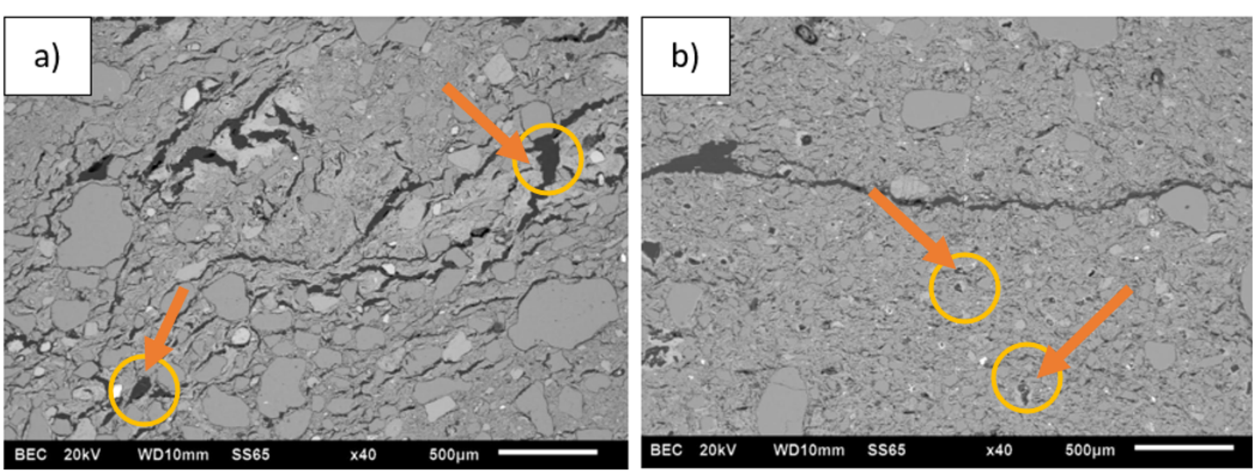

Fig. 9 Tests of the microstructure of brick: **a** historical brick; **b** contemporary brick

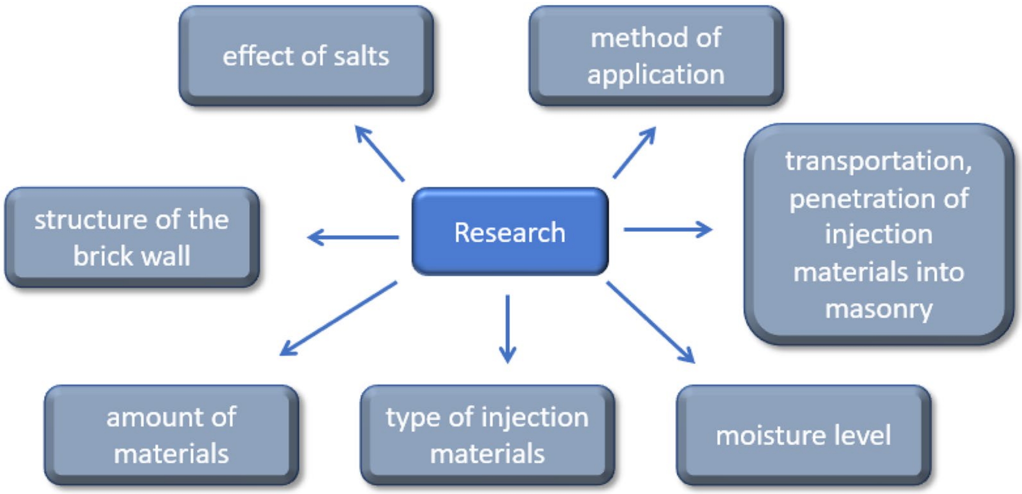

Fig. 10 Factors affecting insulation effectiveness studied in the literature

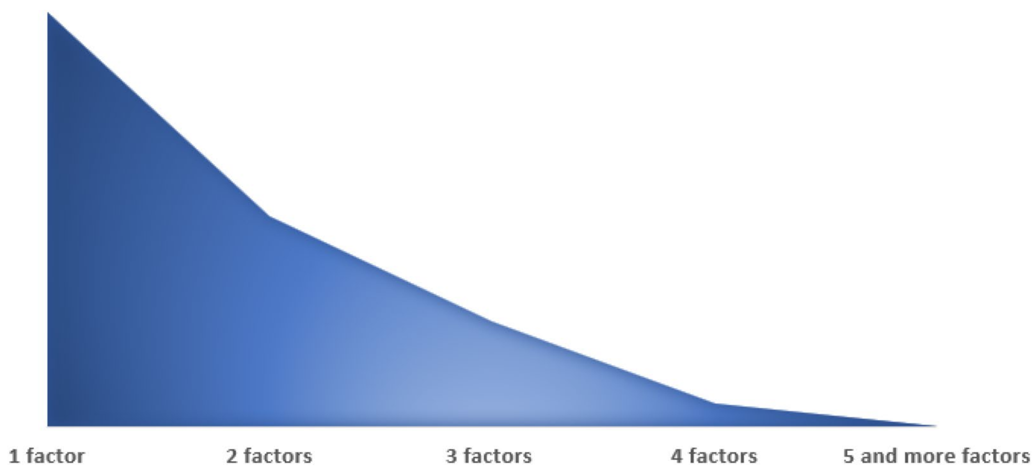

Fig. 11 Number of studied factors that affect the effectiveness of anti-damp insulation in a brick wall

Future research perspectives

The most technologically advanced method of reducing rising damp in brick walls is the chemical injection method. It involves drilling injection holes in the masonry, and introducing an injection agent into these holes, which is then distributed in the masonry structure. This method includes: pressure injection, non-pressure injection and gravity injection. Non-pressure injection is so simple that a person with no injection experience can perform it.

The origins of dealing with rising damp in brick masonry by using chemical injection date back to the 1950–60 s. Initially, liquid chemical materials such as acrylamide gels, silicates and hydrophobic resins (e.g. siloxanes, silanes, silicone resins) were injected. In contrast, the first laboratory studies of chemical injection date back to the 1970s, and evaluated the effectiveness of chemical materials [38]. In the 1990s, injection cream was first used. The advantage of injection cream is its consistency, which means that, unlike liquids, it slowly penetrates the structure of the material. As a result, the cream penetrates better than liquids. Injection creams are silane/siloxane-based products that do not contain organic solvents.

Taking into account the research to date and the research gaps, future studies will focus on the assessment of the effectiveness of secondary anti-damp insulation in brick walls. This knowledge can be particularly useful in the case of historic buildings with high cultural value. In order to study this issue, the authors propose to evaluate the effectiveness of anti-damp insulation in brick walls by conducting experimental studies. Non-destructive and destructive methods will be used in the research.

Table 1 Description, advantages and disadvantages of non-destructive methods for assessing the effectiveness of secondary anti-damp insulation

No	Method	Description	Advantages	Disadvantages
1	Microwave method	It involves the penetration of microwaves through the material being tested. Microwaves set the water molecules present in the damp material in motion, so that the speed of microwave propagation decreases [69]	- Quick identification of particularly damp areas, - The ability to perform a large number of tests in different sections of masonry, and at the time of one's choosing (there are no time or quantity limits) [70]	- The measurement result can be slightly influenced by the salinity of the tested material, - This method only allows the level of the moisture content to be determined. It is not possible to check other parameters that allow anti-damp insulation to be evaluated
2	Dielectric method	It involves the studying of the phenomena of changes in the electrical capacitance of a material and changes in its moisture content. The electrical capacitance depends on the absorption of moisture in the material, which in turn acts as a dielectric in the capacitor [71]	- Ease of use, - The ability to perform a large number of tests in different sections of masonry, and at the time of one's choosing (there are no time or quantity limits) [70], - The ability to perform measurements within the entire range of the moisture content	- This method only determines the level of moisture in the sample. On this basis, without performing additional measurements and tests, it is not possible to know the answers to questions about the reasons for the lack of effectiveness of the moisture barrier, - The accuracy of electrical methods is lower when compared to other non-destructive methods
3	Thermal imaging method	It involves recording the thermal quality for the building's external partitions. The study is carried out using a portable thermal imaging camera, which converts radiation into a thermal image of the surface of the object in question [72]	- Easy to interpret (the surface temperature of the masonry in a damp area is lower than the surface temperature of the masonry in a dry area), - Enables large areas to be tested [73]	- The moisture assessment of brick masonry takes on a purely qualitative character

The best way to determine the effectiveness of anti-damp insulation while maintaining the original structure of a wall is to use non-destructive methods. The most popular such methods in the construction industryare the microwave method, the dielectric method and the thermal imaging method. Table 1 shows a description of the above methods, as well as their advantages and disadvantages [64–68].

The accuracy of the results obtained using non-destructive methods is lower when compared to destructive methods. Therefore, in addition to the use of non-destructive methods, destructive methods should also be used in the laboratory to assess the effectiveness of secondary anti-damp insulations. An example of a destructive method is the cutting out of a section of a masonry wall, which is then subjected to examination using equipment such as an SEM electron microscope. The disadvantages of destructive methods are their limitations. It is not always possible to obtain a sample of historic masonry. In order to take a fragment of a masonry wall, permits are needed from the conservation authorities, which are often not issued.

The authors plan to conduct research that will be divided into 2 parts. In the first part, the authors will prepare bricks, and will take into account the following parameters:

- The type of brick (porosity, structure),
- The age of brick (ancient, old, new),
- The moisture level,
- The environment with salts (sodium and magnesium sulfate and sodium carbonate),
- The method of application (gravity, pressure),
- The type of used injection material,
- The penetration of the injection product into the brick,
- The interphase between the injection material and the brick.

The study of the bricks is designed to analyze all the factors mentioned above. Bricks that will obtain similar or the same results will not be used for further research. The structure of the bricks should be examined using SEM electron microscopy, microtomography, or mercury porosimetry in order to assess their porosity. The assessment of the porosity of the bricks will aim to determine to what extent the material is capable of capillary rise, and how the injection mass spreads in a particular brick wall.

After selecting the bricks, model walls should be made. Due to the fact that the walls of historic buildings can have different structures, the study should be carried out for each structure separately: brick masonry with all joints filled, brick masonry with unfilled vertical joints, and layered masonry. At this stage of the research, the factors selected in the first part of the study should be taken into account. In addition, different types of mortar should be used in the brick walls.

Afterwards, the injection procedure using a chemical injection material will be performed. Several types of injection materials will be used in order to compare and evaluate which of the selected materials is more effective, and under what conditions. The application of the injection material will be carried out by a specialist, who will take into account the recommendations of the injection material's manufacturer (included in the product sheet). The injection material will be applied into holes that will be drilled in the masonry. The holes, depending on the recommendations of the manufacturer of the injection material, will be made every 10 cm, which will not directly affect the safety of the investigated building. The injection procedure will be continuously monitored. A check of the injection pressure will be carried out, as well as an observation of whether the injection material escapes uncontrollably from the injection hole. The holes into which the injection material will be injected will be grouted with cement after the injection procedure. However, this is not required. In the case of pressure injection, non-pressure injection and gravity injection, undercutting of walls is not required. First, holes are drilled with a drilling machine, and then the injection material is applied.

All these tests are designed to check a number of factors and to answer the following questions:

- Does the chemical injection material react with the salts in the masonry?
- Does the type and age of the brick affect the penetration of the material?
- What is the interphase between the chemical injection material and the brick? What effect do salts have on this interphase?
- Does a particular injection material have the same effectiveness with regards to the used brick (age, structure), moisture level, presence of salts and type of penetration?
- What effect does the method of application of the injection material have on the above-mentioned factors?

The authors of this article aim to answer the above questions.

In addition, the following theses will be verified in the proposed research:

- The effectiveness of the secondary anti-damp insulation procedure is affected by the level of moisture in the masonry, the salt content, the type and age of the brick, the type of used injection material, and the type of application procedure.
- Depending on the used brick, the moisture content and the presence of salts, an injection material has different levels of effectiveness.

Figure 12 shows the research proposed by the authors in order to evaluate the effectiveness of secondary anti-damp insulation. Factors affecting the effectiveness of the injection material that will be used in future studies are listed. Moreover, the way the injection material spreads in brick, and the interphase between the brick and the injection material, will also be presented.

Summary

Secondary anti-damp insulation with the use of the injection procedure in historic buildings is the most popular method of reducing the capillary rise of water in brick walls. This method helps to eliminate its effects, such as the degradation of building materials, which in turn leads to the destruction of buildings, adverse health conditions (the appearance of moisture inside the building), and inadequate thermal and hygrometric conditions of walls. However, the effectiveness of this insulation is not sufficient over time. This procedure should be performed periodically, as the problem of moisture in brick walls reoccurs several years after the injection procedure. This means that the procedure itself is effective, but not for long. At the same time, there is a lack of research that shows the reason for the return of the problem. It should be noted that repeated interference with the structure of an old brick wall is not beneficial, and can cause damage to become worse. It can also generate more construction waste, is costly, and in many cases is time-consuming (due to the need of obtaining permission from the conservation services, which is not always granted). As already mentioned, performing chemical injection is associated with high costs. Depending on the used injection material, the region, or the method of execution, the cost of the performed injection varies, but is always high. The most expensive available products are injection creams. This is why the effectiveness of the performed injection is so important, as re-injection is costly and exposes the historic building to additional damage during the procedure.

The authors, in their studies, propose to take into account a number of factors that can affect the effectiveness of anti-damp insulation with the use of the injection procedure. Factors that will be taken into

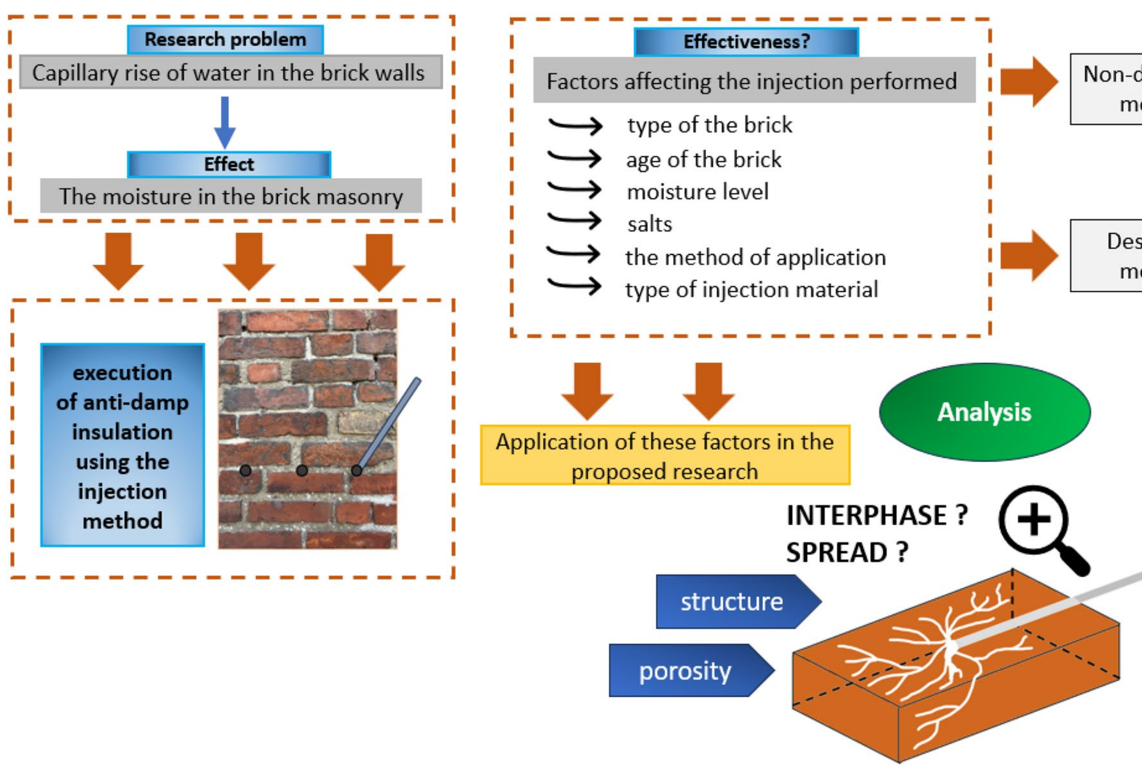

Fig. 12 The proposed research for the evaluation of the effectiveness of secondary anti-damp insulation

account include: the age (ancient, old, modern) and type (structure, porosity) of brick, the moisture content of the brick wall (less and more damp), the type of mortar, the effect of salts (sodium and magnesium sulfates, sodium carbonate), the structure of the wall (brick wall with all joints filled, brick wall with unfilled vertical joints, and layered masonry (opus emplectum)), the method of application, and the type of used injection material.

After taking into account the factors mentioned by the authors, it is necessary to determine how brick bonds with the injection material, and also how the injection material spreads in the masonry. The authors proposed nondestructive and destructive tests that take into account the above-mentioned factors when evaluating the effectiveness of secondary anti-damp insulation.

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Author contributions
NS, AH and ŁS Conceptualization; NS, ŁS Formal analysis; NS Investigation; NS Writing—original draft preparation; AH, Ł S Writing—review and editing; AH, ŁS Supervision. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials
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Declarations

Competing interests
The authors have no competing interests to declare that are relevant to the content of this article.

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