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Water as the main factor in the degradation processes of clay brick

Woda jako główny czynnik procesów degradacji cegły ceramicznej

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Abstract. The article characterizes the basic factors significantly affecting the durability of brick masonry, especially clay brick. The most significant of these is water, which itself poses a threat to the masonry, as well as enabling other corrosive processes. Water also changes the texture of the brick, which causes deterioration of its mechanical properties. It allows the transport of salts, which crystallize causing the material to lose its compactness. Also in frost destruction, freezing in the pores of the material leads to its destruction. Water is also necessary for the growth of living organisms and microorganisms, which are the cause of biodeterioration.

Keywords: durability; brick; water; salinity; biodetorioration; frost freeze destruction.

Streszczenie. W artykule scharakteryzowano podstawowe czynniki mające istotny wpływ na trwałość murów ceglanych, a przede wszystkim cegły ceramicznej. Najważniejszym z nich jest woda, która nie tylko stanowi zagrożenie dla muru, ale również umożliwia inne procesy korozyjne, zmienia teksturę cegły, co powoduje pogorszenie jej właściwości mechanicznych, a także umożliwia transport soli, które krystalizując, powodują utratę zwięzłości materiału. Ponadto zamarzając w porach materiału, prowadzi do jego zniszczenia. Woda jest również niezbędna do rozwoju organizmów i mikroorganizmów żywych, będących przyczyną biodeterioracji.

Słowa kluczowe: trwałość; cegła; woda; zasolenie; biodeterioracja; destrukcja mrozowa.

The durability of a building is a characteristic of the structure expressed in its ability to maintain its stability and load-bearing capacity over its intended lifetime without a marked reduction in performance or the occurrence of unforeseen maintenance costs for the structure [1 ÷ 4]. Clay brick is considered to be one of the most durable building materials. However, despite its resilience, it is subject to environmental influences and slow deterioration processes. The principal external factors that cause deterioration of brickwork include physical impacts due to freezing water, chemical impacts due to the presence of salt and biological impacts. In actual conditions, the external influences as well as the corrosive processes are usually synergistic in nature. The mechanisms that cause damage to structures interpenetrate and amplify each other. Sometimes the effects of one interaction enable the initiation of another process. For instance, a change in the pH of the substrate or an increase in its salinity as a result of chemical corrosion enables and promotes the initiation and growth of microorganisms that cause biological corrosion. The prerequisite for all the above corrosion processes to occur is the presence of water [Fig. 1]. It can even be stated that it is the biggest 'aggressor'. Its impact can be divided into direct and indirect. The direct one involves a change in the texture of the material due to the presence of water. In the indirect mechanism, on the other hand, water acts as a factor that allows certain corrosion processes to occur. As mentioned, this includes frost damage, chemical corrosion and biological corrosion.

Water is a factor that in itself poses a threat to the material as under its influence the texture of the material changes resulting in a deterioration of the mechanical properties [6]. In addition, its presence is a prerequisite in the process of chemical corrosion leading to the occurrence of efflorescence and subflorescence, which in turn results in aesthetic deterioration and loss of material compactness, respectively. Also in frost attack,

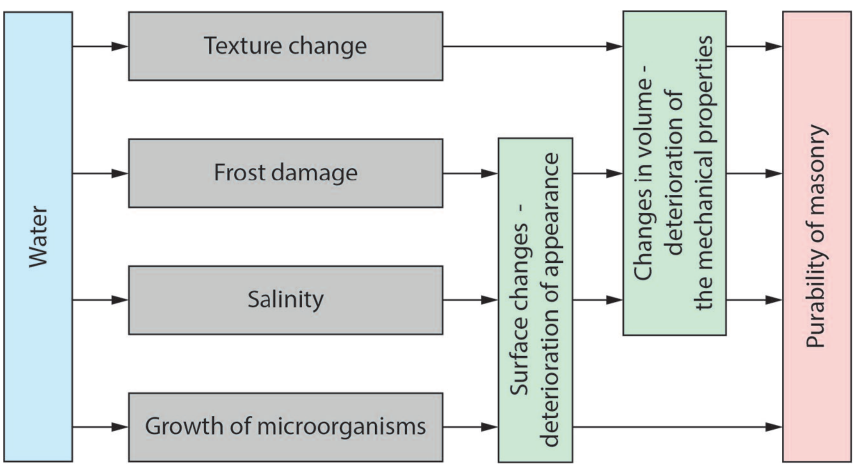

Fig. 1. Factors determining the durability of brickwork [5]
Rys. 1. Czynniki kształtujące trwałość murów [5]

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water freezes and expands, which is accompanied by crystallisation pressure causing tensile stresses. Water is also of crucial importance as the growth of both organisms and microorganisms is only possible in a humid environment.

The effect of water on the mechanical properties of bricks

Masonry materials belong to the group of capillary-porous materials which are characterised by an open porosity of a few to several tens of per cent. Mineral clay materials with a capillary-porous structure have a natural tendency to wet out in the presence of water and/or moisture. Irrespective of the type of bricks tested, a decrease in compressive strength byapprox. 10% is observed with short-term (about 1 month) water saturation [7]. On the other hand, long-term saturation with water can cause a decrease in strength byeven 20% and more [7], but in this case this depends on the composition of the brick [8] (e. g. the presence of fly ash significantly contributes to the deterioration of the mechanical characteristics with prolonged exposure to water). To assess the effect of water on the mechanical properties of bricks, it may be helpful to use the compressive strength reduction factor ηf, defined as the ratio of the strength in the dry state to the value of this characteristic determined after short-term or long-term conditioning in water. For bricks made today, it is approximately 0.79 [7]. The cause of the deterioration of the mechanical properties of bricks under the influence of water is the increase in the porosity of the ceramic material and the degradation of the silicon-oxygen network through the breaking of Si-O-Si bridges [7 ÷ 8]. It was observed that this process mainly affects the amorphous phase which is the dominant component of brick [7]. Furthermore, the processes of hydrolysis of aluminosilicates and rehydration, which promote structural relaxation, are responsible for the deterioration of the mechanical characteristics as a result of exposure to water. Also, the presence of salts, which dissolve under the influence of water, can intensify the deterioration of mechanical properties.

Frost damage

Another cause of deterioration of brickwork that is notprotected from water, especially in historic buildings, is the freezing of water in the pores of the materials. The factors that determine frost resistance of bricks are known and often described in the literature. These are first and foremost the mechanical properties, especially the tensile strength [9 ÷ 10], the phase composition of the firedbrick and the degree of vitrification of the texture [11], the permeability, which enables and determines the free movement of water in the porous material without destroying the texture, as well as the porosity and thestructure of porosity [9 ÷ 12]. In contrast, anissue that is little recognised is the form of frost damage to bricks. As it was observed, bricks are liable to be damaged by freezing and thawing. The various forms of damage, i. e. spalling, include powdering, flaking and cracking. The powdering of the surface of bricksleads to the formation of fine ceramic dust which systematically removes itself from the surface of the material. The process of deterioration starts at the surface and gradually progresses into the material. The second form of deterioration that also progresses from the surface is flaking. In this case, distinct flaking layers form on the surface and come off and fall off over time. Cracking, on the other hand, is associated with the formation of sharp fragments of several to over ten millimetres in size. This process does not only take place on the surface, but also involves the deeper layers. Depending on the structure of porosity, the mineral composition and the spatial arrangement of the texture components, the bricks deteriorate by crumbling into powder, flaking or cracking [13]. Figure 2 shows the interdependence of the material characteristics (structure of porosity, FFD factor, mineral and phase composition, and strength) determiningthe form of frost damage to the bricks used in the investigation.

It appears that it is the structure of porosity that is the essential and most important parameter determining the form of frost damage. A clear correlation was observed between the form of frost damageand the ratio of the percentage of pores with diameters of 3 – 10 μm to the total number of pores with diameters of 0 – 10 μm. This correlation was referred to as the form of frost damage (FFD) factor [13]. For specimens without any signs of frost damage, this factor is in the range 75 – 90 whereas for flaking specimens the FFD factor is 4 – 10, for cracking specimens it is 2 – 7, and for powdering specimens the FFD is 45 – 50. The second important factor determining the form of frost damage is the mineral and phase composition of the bricks and the spatial distribution of the texture components (the constituent phases, i.e. the binder and grains). In bricks that were affec-

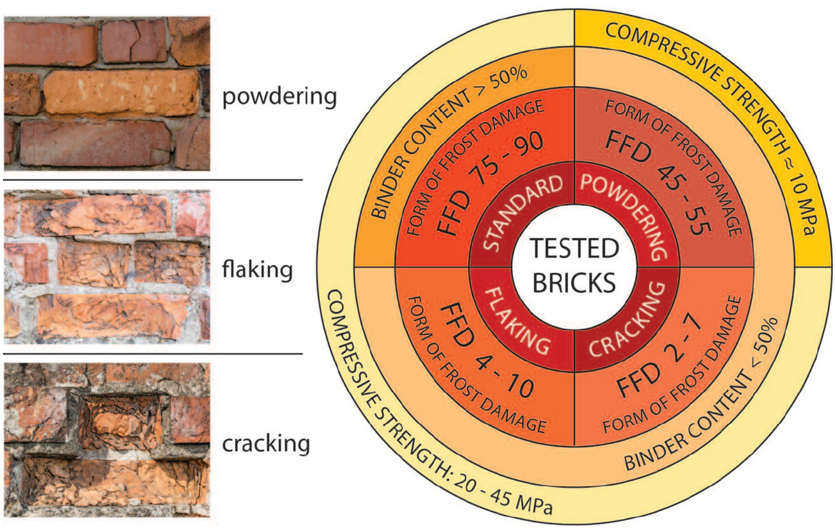


Fig. 2. Forms of frost damage to bricks and graphical illustration of factors shaping the form of frost damage [13]
Rys. 2. Formy destrukcji mrozowej cegieł oraz graficzna ilustracja czynników kształtujących formę destrukcji mrozowej [13]

ted by frost damage, the proportion of binder (matrix) is approx. 40% while in bricks without any signs of deterioration it is 50% or more. The lack of appropriate volume of the matrix can be the cause of the weakening of the texture of the material, poor grain embedment and bad envelopment, which consequently makes the material more susceptible to frost damage. Another parameter mentioned in Fig. 2 and characterising the bricks that were tested is the compressive strength. For specimens without signs of frost damage and for specimens affected by damage in the form of flaking and cracking, the compressive strength is similar and ranges from 20 to 45 MPa. No direct correlation was observed between the strength and the form of frost damage. An exception is powdering bricks, which are characterised by a much lower strength, at 10 – 15 MPa. Thus, it can be concluded that the occurrence of this form of frost damage is determined by the low strength of the bricks, not exceeding 20 MPa.

Salinity

Salt content in masonry structures is a common cause of their gradual degradation [14, 15]. With regard to the origin, a distinction can be made between primary salts, resulting from the composition of the raw materials themselves and the production process, and secondary salts originating from the external environment, e.g. salts from soils, from polluted air, from sea breeze and mist, from de-icing agents, from acid rain, resulting from biological metabolism, as well as salts introduced into the masonry structure with modern repair materials during repair or maintenance work. In addition, the type of salts may indicate the main cause of salt contents in a particular building, e.g. large amounts of chlorides and/or nitrates may indicate moisture from the ground while high concentrations of sulphates indicate moisture from acid rain. On the other hand, nitrates, nitrites and ammonium compounds may indicate problems due to biological corrosion caused by microorganisms.

The factor that triggers the harmful action of salts is the presence of water in the material. Salts in the material dissolve in the presence of water and can be transported [16]. They then crystallise under favourable conditions [5, 6]. The location of salt crystallisation depends on the saturation rate and the drying rate. Under conditions of high humidity, when the evaporation rate is low, the evaporation zone may be close to the surface or even on the surface of the material. The salt deposits formed on the surface are referred to as efflorescence. Its presence is relatively harmless in terms of the durability of the material. In contrast, when the evaporation rate is much higher, the evaporation zone remains within, and salts crystallise in the pores of the material. Such a phenomenon is referred to as subflorescence. The force exerted by rapidly crystallising salts is very high and is sufficient to destroy even very strong masonry materials [14, 16]. The growth of the crystals results in a relaxation of the texture throughout the volume and not only in the surface layers. This is dangerous as it causes damage to the materials not only on the surface, but alsowithin- the material volume.

The presence of salt also significantly alters the process of drying of masonry [5]. Depending on the type of salt, the drying efficiency varies markedly. Figure 3 shows the drying and saturation curves for bricks with 10% sulphate, chloride and nitrate salt solutions.

The bricks were saturated with salt solutions in cycles comprising 2 days of saturation with a particular salt solution by capillary action and 8 days of drying under laboratory conditions. For comparison, a cycle of saturation with distilled water was carried out in the same manner. A brick saturated with distilled water loses its total water content during the drying process, its moisture content at the end of each cycle being close to zero. On the other hand, it was observed that the drying of bricks containing salts is clearly hindered and is either more or less effective depending on the type of salt. The rate of the drying process is most reduced for bricks saturated with potassium sulphate solution and least for bricks saturated with sodium sulphate. The other chloride salts and magnesium sulphate have a comparable effect on the drying process of the brick, the effect of the chloride salts being almost identical and therefore not dependent on the cation present in the solution.

Microbial growth

Deterioration of masonry structures can also be due to certain biological factors, such as living organisms and microorganisms, and the products of their life processes. The group of organisms includes bryophytes, lichens and algae while the group of microorganisms includes fungi and bacteria.

The group of organisms primarily causes mechanical damage as a result of root growth and surface overgrowth. These organisms often cause a temporary or permanent increase in the moisture content of the substrate. In addition, some of them produce organic acids (lactic acid, oxalic acid, succinic acid, acetic acid and pyruvic acid), which can lead to erosion and degradation of the substrate. On the other hand, biological corrosion processes (microbial deterioration) caused by microorganisms such as fungi and bacteria occur differently as they cause decomposition of an organic substrate for the nutritional needs of the microorganisms. Where the substratesare inorganic, the degradation process occurs as a result of the action of secreted metabolic products which are the cause

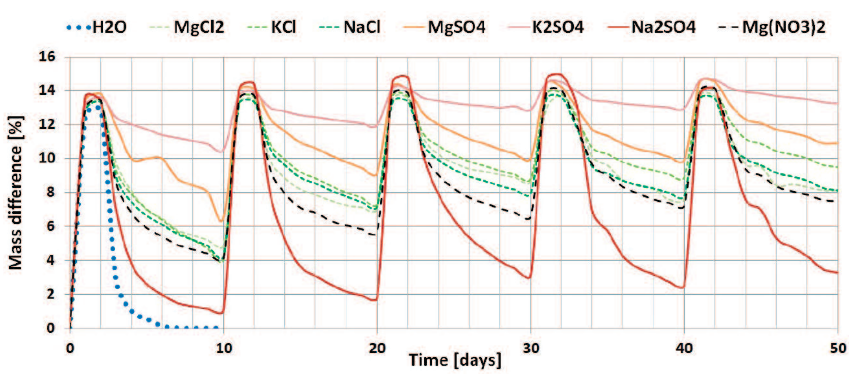
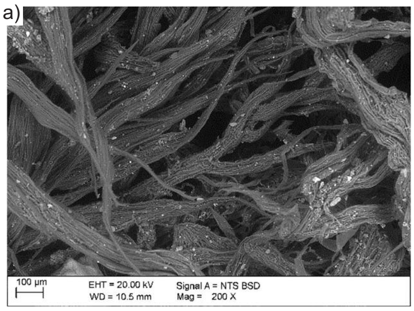


Fig. 3. Brick saturation and drying curves as a function of time [5]
Rys. 3. Krzywe nasycania i suszenia cegieł w funkcji czasu [5]

a)

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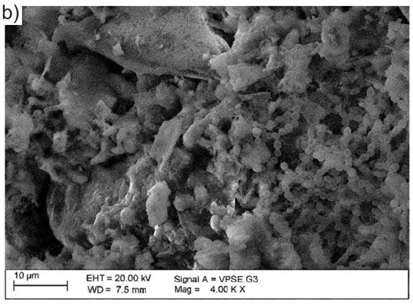

SEM image of: a) mosses, mag. 200x; b) bacteria, mag. 4000x, on the ceramic substrate
Obraz SEM: a) mchów – powiększenie 200x; b) bakterii – powiększenie 4000x na podłożu ceramicznym

of the typical processes, e.g.chemical corrosion. Deterioration of materials due to the action of organisms and microorganisms results in mechanical damage, surface overgrowth, and chemical assimilation and dissimilation [17]. The effects of biological decomposition [18] include macroscopic changes (discolouration, surface growth of organisms, pitting, dents, brittleness, deformations, and structural decomposition), changes in physical properties (increased absorbability and compromised strength) and changes in chemical properties (composition and changed pH), etc.

Factors that determine the growth of organisms and microorganisms include, above all, the availability of water. Fungi, which are the worst wreckers of building materials, can already develop at a relative humidity of approx. 60% while bacteria require a relative humidity of more than 85% to develop [19]. Furthermore, the pH value of the substrate, the climate, the presence and availability of nutrients as well as the chemical composition of the substrate are all important. In the case of mineral materials, such as stone, brick, mortar and concrete, the mineralogical composition, porosity, type of binder and permeability to water are important parameters [20]. Also, the presence of certain salts in building materials can promote the growth of halophilic bacteria [21]. When analysing the biological hazard of organisms and microorganisms, it is also worth paying attention to the pH value of the substrate being colonised. Values that are favourable for the development of microorganisms, i. e. fungi and bacteria, are in the range 5 ÷ 11; however, there are also acidophilic bacteria colonising substrates with a relatively low pH.

Summary

In actual conditions, external impacts are usually synergistic. The mechanisms that cause damage to structures interpenetrate and amplify each other. Sometimes the effects of one interaction enable the initiation of the development of another one. For example, a change in the pH of the substrate, which is brick and mortar, as a result of chemical corrosion enables and promotes the initiation and subsequent development of biodeterioration. Another example is the freezing of groundwater which causes movement of shallow foundations resulting in deformation of the walls and the presence of numerous cracks and fissures. Thus, the durability of a building or group of buildings is influenced by many interlocking processes. The connecting factor of all corrosion processes is water. Its prolonged contact with the material can in itself pose a threat as the texture of the material is changed under its influence with a consequent deterioration of the mechanical properties. Moreover, its presence is a prerequisite for chemical corrosion leading to efflorescence and subflorescence and resulting in a deterioration of the aesthetic of the material and its strength, respectively. Water is also of crucial importance for biological corrosion. The growth of both organisms and microorganisms is only possible in a humid environment.

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