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WOOD DRY-ROT FUNGI AS BIODEGRADATION FACTORS OF POROUS BUILDING MATERIALS

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SYNOPSIS. The paper presents an overview, based on the authors' long studies and the literature, of the biodegradation of porous building materials such as concrete, brick, mortar and plaster by wood dry rot fungi in buildings. The biodegradation mechanism and the effect of dry-rot fungi on the technical properties of building materials are discussed.

KEY WORDS: biodegradation, wood dry-rot fungi, inorganic building materials

INTRODUCTION

Biodeterioration of porous building materials has been an interest of microbiologists, biotechnologists, conservators and (to a lesser degree) civil engineers. Numerous papers on this subject have been reviewed in several major works (Hueck-van der Plas 1968, Strzelczyk 1981, Krumbein 1987, Warscheid and Braams 2000, Cwalina 2004). The overwhelming majority of the papers concentrate on microbial infections of natural stone sculptures and sculptural building decorations. Autotrophs (bacteria, algae and lichens) and heterotrophs (mould fungi), often oligotrophic ones, have been found to grow on the surfaces of buildings in favourable moisture and thermal conditions in the presence of chemicals in the air. The corrosive impact of such processes usually does not extend for more than a few millimetres and it mainly manifests itself in visual aesthetic effects.

Apart from the prominent group of mould fungi (Deuteromycetes), which numbers at least tens of species (mostly cosmopolitan ones), the so-called house (or dry rot) fungi (Basidiomycetes) occur much more rarely. They are heterotrophs but with a different physiology and, as opposed to mould, with a mobile mode of growth. Dry rot fungi obtain energy from the decomposition of lignocellulose materials such as wood, wood composites and other organic materials, proliferating on their surface and growing into the substratum. In mixed-construction buildings, sooner or later in their growth they naturally encounter inorganic materials such as brick, concrete, mortar and plaster and come into direct physicochemical contact with them. This phenomenon has been commonly observed since the pioneering works by Falck (1912), Vanin and Vladimirskaya (1932) and others, usually without any attempt to explain the interactions involved and the biological-technical consequences for the durability of the buildings. In Poland the first theories about the impact of dry rot fungi on inorganic construction materials were formulated in connection with the translocation of recycled bricks during the reconstruction period after World War II (Ważny 1951, 1956) and evolved in later papers (Caravantes 1952, Janczewski 1962, Ważny and Czajnik 1963 a, Ważny 1980, 1984).

The aim of the present paper was to present, on the basis of the authors' long studies and the literature on the subject, the contemporary views on the biodegradation of porous inorganic materials in buildings by dry rot fungi, using as an example the main species occurring in Poland, i.e. *Serpula lacrymans* and *Coniophora puteana* (Ważny and Czajnik 1963 b). A more detailed explanation of the development and corrosive impact of dry rot fungi should contribute to a better understanding of their peculiar effect on the technical properties of inorganic structures, particularly in special purpose buildings, and to avoiding frequent failures in dry rot elimination from infected buildings.

DEVELOPMENTAL BIOLOGY OF DRY ROT FUNGI AT ORGANIC/INORGANIC MATERIAL CONTACT IN BUILDINGS

A building is infected by dry rot fungi mainly through spores forming on the fruiting body in previously infected other building structures. The dry rot fungi *Serpula lacrymans* and *Coniophora puteana* produce oval spores about 5-10 µm in diameter, which means that they are very small (single spores are visible only under a microscope). A single spore weighs about $1{\cdot}10^{-11}$ g whereby it can freely migrate inside and outside a building. Propagation takes place via water (hydrochory), animals (zoochory), people (anthropochory) or construction materials (hylochory), but mostly via air (anemochory). A spore coming across organic matter germinates in favourable conditions, forming a mycelium which spreads over the surface (aerial mycelium) as well as grows into the substrate (substrate mycelium) (Ważny 2003). The decomposition of organic materials is the source of energy for the life processes and the decomposition products constitute a material for the synthesis of structural compounds enabling the mycelium and its strands (rhizomorphs) to grow. The growth is usually radial and proceeds at a maximum rate of 15 mm per 24 h. Considering the dimensions of rooms in a building, the fungus vegetative organs quickly come into contact with inorganic materials, e.g. ceramic bricks joined by mortar and covered with plaster, concrete bases and so on. Such materials do not hinder the expansion of the fungus which covers and grows through them (both vertically and horizontally in the building) at a slightly lower rate. It has been reported that the fungus spreads (under the plaster layer or sometimes by penetrating through thick walls) for large distances from the food base (e.g. wood) from one storey to another. The fungus penetrates into the above substrates by searching for places of least resistance such as fractures, cracks or (through or pseudothrough) microcapillaries natural for the materials. This is possible owing to the high agreement between the diameter of micropores in brick and concrete and the average diameter (about 10 µm) of mycelial hyphae. Besides, the hyphae can adapt their dimensions to the actual structure of the substratum. When the fungus encounters difficulties in spreading, it activates its mechanism of biochemical corrosion (WAŻNY and CZAJNIK 1963 b). The growth and spreading of the fungus in inorganic materials are possible thanks to its phenomenal ability to convey water and the nutrients dissolved in it and sometimes air (oxygen or carbon dioxide) from the food base to the current place of development of germ hyphae (BUTLER 1957, LOW et AL. 2000). According to THOMPSON at AL. (1985), the rate of water movement is on average 120 $cm \cdot h^{-1}$, with water moving thanks to the hydrostatic differential pressure of the cellular substance.

Also phenomenal is dry rot fungi growth orientation. Both the mycelium and the rhizomorphs do not grow arbitrarily in inorganic materials, but towards the location of a new food base or favourable microenvironmental conditions. This is possible owing to the (not fully understood) phenomenon of chemotropism characteristic of fungi: the mycelium and its strands by sensing the presence (sometimes at a long distance) of certain substances, e.g. water, cellulose or other organic compounds, orient their growth towards them (LEPIDI and SHIPPE 1972).

MECHANISM OF BIODEGRADATION OF INORGANIC BUILDING MATERIALS BY DRY ROT FUNGI

Dry rot fungi as heterotrophic organisms take up nutrients and draw energy through exclusively the biochemical decomposition of organic building materials. Their food base in buildings is mainly wood, wood composites or other lignocellulose materials which are decomposed through hydrolysis and oxidation in the presence of biocatalysts – enzymes produced and secreted by the hyphae. Energy is liberated, e.g. from the decomposition of cellulose (a major constituent, besides lignin, of wood), in two stages. In the presence of cellulase (a hydrolytic enzyme) cellulose decomposes into glucose according to this chemical formula:

$$(C_6H_{10}O_5)_4 + \text{enzyme} + H_2O \longrightarrow nC_6H_{12}O_6 \qquad (1)$$

Then in the presence of oxidase (an oxidizing enzyme) the glucose undergoes oxidation and as a result, energy, water and carbon dioxide (basic metabolites) are produced according to this chemical formula:

$$C_6H_{12}O_6 + \text{enzyme} + 6\ O_2 \longrightarrow 6\ CO_2 + 6\ H_2O + 674\ \text{kcal} \qquad (2)$$

In optimum conditions the fungi *Serpula lacrymans* and *Coniophora puteana* cause rapid decomposition of wood, which manifests itself in large amounts of metabolites, i.e. water and CO_2. For example, during the decomposition of 1 kg of pine or birch wood by 50% relative to the initial mass about 139 l of water are produced. The same fungus decomposing 1 m^3 of wood produces 2-3.5 kg of CO_2 (Rypáček 1966). The produced substances partially evaporate and partially accumulate in the material's micropores and combine to form carbonic acid (H_2CO_3). Carbonic acid is undoubtedly the main degrader of the constituents of concrete, ceramic brick, mortar and plaster, i.e. calcium carbonate, aluminocalcic hydrates, calcium silicate and calcium hydroxide (Hueck-van der Plas 1968). Simplified formulas for the basic processes are as follows:

$$H_2CO_3 + CaCO_3 \longrightarrow Ca(HCO_3)_2 \tag{3}$$

$$H_2CO_3 + Ca(OH)_2 \longrightarrow CaCO_3 + 2\ H_2O \tag{4}$$

Thus calcium carbonate and other cohesion reducing salts are formed and after drying cause surface pulverization. The process of carbonate corrosion is similar to alkaline corrosion and acidic corrosion which occur more frequently in building materials (Kurdowski 1991). Obviously H_2CO_3 reacts in concrete first with $Ca(OH)_2$ and $CaCO_3$ and as the latter compounds diminish, with C_3AH_{12}, C_4AH_{13} and C_4AH_{19} (Taylor 1990) at a much lower rate. The action on C_3S_2H and $C_3S_2H_3$ is rather insignificant. The carbonic acid medium may contribute to a high degree (XA3) of aggressiveness at considerable amounts of $Ca(OH)_2$ and $CaCO_3$ (concrete, mortar and marl containing brick) as well as to a low degree (XA1) of aggressiveness towards C_4AH_X and CSH_I, CSH_{II}. Although the porosity of composite materials temporarily decreases as $CaCO_3$ forms, the pH also decreases. However, as additional amounts of H_2CO_3 are supplied by dry rot fungi $Ca(HCO_3)_2$ forms which can be easily removed by, e.g. rainwater, since this compound is highly soluble (165 g·dm^3) at a temperature of +20°C. The carbonate undergoes decomposition at elevated temperatures which may occur periodically in buildings close to the roof. The products of this process are: $CaCO_3$, CO_2 and H_2O, whereby carbonate aggressiveness towards the calcareous constituents of concretes, mortars and ceramic brick increases there.

Carbonic acid does not cause significant damage to well fired ceramic brick in which mullite ($3\ Al_2O_3 \cdot 2\ SiO_2$) predominates, but it can, to some degree, act on sillimanite ($Al_2O_3 \cdot SiO_2$) which occurs in poorly fired ceramic brick ($T \leqslant 900°C$). The marl in brick strongly reacts with carbonic acid (reactions 3 and 4), but since it occurs in small quantities in brick, the damage will be local.

In practice, the decomposition of organic materials which constitute nutrients for dry rot fungi is not fully complete. Under the influence of the environment the fungi also produce metasilicic acid and numerous mono- and bicarboxylic acids such as: formic acid, succinic acid, lauric acid, oxalic acid and malonic acid and hydracids: apple acid, citric acid and tartaric acid (Takao 1965). The acids are produced by the hyphae and when released into the environment, they add to the corrosive action of carbonic acid. The mechanism of this action is very complex: some of the acids, e.g. tartaric acid, make cement composites more impermeable, but most of them cause the formation of calcium salts which are not sufficiently stable and some of them are washed out from cement and lime composites whereby the materials being in contact with the hyphae undergo degradation (Ważny 1951). For instance, succinic acid reacts with $Ca(OH)_2$, CaO and $CaCO_3$ which occur in cement and lime composites and in small amounts in ceramic brick (Brewster and McEwen 1968). Its action on the sillimanite in ceramic brick is very weak, similarly as in the case of carbonic acid (Kleinogel 1960). The solubility of succinic acid is very low (6.9 g/100 g H_2O at a temperature of +20°C) and so its acidic character is weak (Gruener 1983). Its aggressiveness ranges from weak (XA1) to medium (XA2). The acid dissociates according to the following reactions:

$$\text{HOOC-(CH}_2)_2\text{-COOH} \longleftrightarrow \text{HOOC-(CH}_2)_2\text{-COO}^- + \text{H}^+ \quad (5)$$

$$^-\text{OOC-(CH}_2)_2\text{-COOH} \longleftrightarrow {}^-\text{OOC-(CH}_2)_2\text{-COO}^- + \text{H}^+ \quad (6)$$

As a result of a reaction between succinic acid and phases: CH, CSH_I, SCH_{II}, C_4AH_x (brief notation) calcium succinate $C_4H_4O_4Ca{\cdot}5\ H_2O$ (full notation) forms. Because of its poor solubility the succinate can damage mineral composites through swelling.

One should note again that even though they undergo biodegradation induced by the substances secreted by the hyphae of dry rot fungi, inorganic materials cannot constitute any form of energy for them. Nevertheless, taking up nutrients from organic substrates they need minute (often trace) quantities of such inorganic elements as: Ca, Mg, K, Mn, Co, Cu, Zn and others for their normal development. Organic materials are a sufficient source of inorganic elements, but it is possible that the latter may be taken up as the fungi proliferate in inorganic building materials (Ważny 1963 a, b).

EFFECT OF DRY ROT FUNGI ON TECHNICAL PROPERTIES OF INORGANIC MATERIALS

The above information about the biological and biochemical determinants of the development of dry rot fungi in the organic-inorganic material complex corroborate the previous theories about the nature of this remarkable phenomenon. Using wood or other organic materials as a food base, the mycelium and its strands have the ability to overgrow the surface, grow into and through the inorganic base without using it as a source of energy at all. Settlement is possible thanks to the ability of the fungus's organs to convey water with dissolved organic substances or air, depending on the building structure and the microenvironmental conditions. It is a forced process oriented towards a search for new sources of nutrients or favourable conditions, based on chemical affinity (chemotropism).

If the mycelium or its strands are cut off from a food base in a wall or in a substratum, the growth of the fungus is arrested (anabiosis), but the latter preserves its viability (ability to germinate) even for 10-12 years. For these reasons one cannot plan and carry out dry rot eliminating renovations without proper tests of the infected inorganic components.

Biodegradation of inorganic materials manifests itself in biochemical changes and also in changes of some of the technical properties: the moisture content, the pH of the water solution and the strength increase. The range and extent of the changes are closely dependent on the character of the building and the degree of infection.

Laboratory tests were carried out on small mortar specimens (1.0 × 1.0 × 6.0 cm) made of 450 Portland Cement (CEM I 42.5) with and without sand, using the Heidelberg method (Biczok 1972). They showed an elevated moisture content during the growth of the mycelium, by up to 30% after 2.5 months with a slight decrease (down to 20%) after 6 months of exposure. The acidity from pH 13 decreased to pH 7 after 2 months with a further slight downward trend over 6 months. The infected mortar's pH values correspond with the results obtained for wood (Ważny 1960). Also interesting were changes in bending strength which decreased by 25-75% depending on the mortar's grade and degree to which the fungus penetrated it (Ważny 1980, 1984).

Examinations under an electron microscope show hyphae to be present in mortar and concrete specimens across their entire width. The corrosive action of dry rot fungi on inorganic materials can vary greatly in its extent. The degree of degradation depends mainly on the natural properties of the substratum, but also on the character of the infection. If there are only a few single hyphae penetrating the substratum, the changes are relatively small and only minimally affect the stability of the structure. This type of infections occurs in typical dwelling houses. The course of degradation is different in special building structures constantly or periodically exposed to moisture and temperature which create optimum conditions for microbial strokes. A classic example here are the linings of underground headings, tunnels and sewers. Numerous accumulations of hyphae and rhizomorphs penetrating through retaining walls cause intensive biodegradation posing a hazard to the stability of the structures. Such a situation arose during the abandoned construction of the underground in Warsaw in 1951 where the large surfaces of the concrete tunnel wall lining penetrated through by fungi posed a serious threat to the durability of the structure (Ważny and Czajnik 1963 a, Nica at al. 2000, Picco and Rodolfi 2000).

CONCLUSION

The fact that porous inorganic building materials become infected with dry rot fungi which grow on wooden or composite organic constructions has been known for a long time. But until recently the mechanism of the degradation of concrete, brick, mortar and plaster has not been fully understood. Dry rot fungi have a phenomenal ability to overgrow and grow through inorganic materials even at a large distance from vital energy sources in the form of organic materials.

Through their own investigations and in situ observations the authors have found that the biodegradation of porous inorganic building materials is mainly caused by carbonic acid (formed through the combination of water and CO_2 in the process of energy liberation) produced and secreted by fungal cells (mycelial hyphae) and by other numerous organic acids being metabolites of fungi.

As a result of the reaction of the above compounds with the components of porous building materials fungi's mycelia and mycelial strands can spread in micropores and cracks inside them. In the case of a severe fungal infection, the physical and strength properties of inorganic building materials may badly deteriorate, posing a threat to their durability. Knowing the mechanisms of biodegradation of inorganic materials in contact with wooden or composite organic constructions one can avoid (so far frequent) failures in planning and carrying out preventive and remedial work in buildings infected with dry rot fungi.

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