TALLINN UNIVERSITY OF TECHNOLOGY
DOCTORAL THESIS
52/2020

Indoor Air Microbiological Quality in Reed-Bale and Straw-Bale Houses in Estonia

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This dissertation was accepted for the defence of the degree 04/11/2020

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for doctoral or equivalent academic degree.

Jane Raamets ________________________________
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ISSN 2585-6898 (publication)
ISBN 978-9949-83-623-9 (publication)
ISSN 2585-6901 (PDF)
ISBN 978-9949-83-624-6 (PDF)
Printed by Koopia Niini & Rauam

TALLINNA TEHNIKAÜLIKOOL
DOKTORITÖÖ
52/2020

Siseõhu mikrobioloogiline kvaliteet Eesti roo- ja põhupakist elamutes

JANE RAAMETS

TALTECH KIRJASTUS

Contents

List of Publications

The thesis is based on four academic publications which are referred to in the text as Paper I, Paper II, Paper III and Paper IV.

Paper I **Raamets, J**., Kutti, S., Ruus, A., Ivask, M. (2017). Assessment of indoor air in Estonian straw bale and reed houses. WIT Transactions on Ecology and the Environment, 211, 193−196. Doi:10.2495/AIR170191

Paper II Vares, O., Ruus, A., **Raamets, J**., Tungel, E. (2017). Determination of hygrothermal performance of clay-sand plaster: influence of covering on sorption and water vapour permeability. *Energy Procedia*, 132, 267−272.

Paper III Altmäe, E., Ruus, A., **Raamets J**., Tungel, E. (2019). Determination of Clay-Sand Plaster Hygrothermal Performance: Influence of Different Types of Clays on Sorption and Water Vapour Permeability. In: Johansson D., Bagge H., Wahlström Å. (eds) Cold Climate HVAC 2018. CCC 2018. Springer Proceedings in Energy. Springer, Cham.

Paper IV **Raamets, J**., Ruus, A., Ivask, M., Nei, L., Muoni, K. (2020). Siseõhu kvaliteet põhu- ja pilliroopakkidest seintega elumajades (*Indoor air quality in residential buildings with straw- and reed-bale walls*). *Agraarteadus*, 31(1), 84–95. Doi:10.15159/jas.20.05

Copies of these publications are included in Appendix.

Other publications in relevant areas:

Raamets, J., Kutti, S., Vettik, A., Ilustrumm, K., Rist, T., Ivask, M. (2016). The antimicrobial effect of three different chemicals for the treatment of straw bales used in housing projects. Sustainable Housing 2016. Proceedings of the International Conference on Sustainable Housing Planning, Management and Usability: Sustainable Housing 2016, Porto, Portugal 16-18.11.2016. Ed. R. Amoêda, C. Pinheiro. Green Lines Institute for Sustainable Development, 537−545.

Author’s Contribution to the Publications

The point of departure of this thesis is an understanding that the building and its indoor climate affect each other as interdependent parts of a complex whole. As preliminary approach, the research presented in this thesis (Paper I) focused on indoor air quality, wherein microorganisms were studied. The following steps (described in Paper II and Paper III) examined how the boarders, especially inner surface, are acting hygrothermally. Finally, differenct aspects of a building as a complex whole were studied (Paper IV).

The work described in Paper I enabled to map most common microorganisms of indoor air in straw bale and reed buildings. Plasters are widely used in straw bale and straw buildings.

Paper II gives information concerning the ability of inner surfaces of the boarders to buffer moisture. Plaster as inner surface enables to reduce the internal moisture excess and internal humidity load on the boarders.

Paper III presents the research carried out with the aim of studying hygrothermal properties of clay-sand plasters. This information is of utmist importance due to the fact that straw and reed are sensitive materials to mould.

Paper IV is to finalise the outcomes of the work. Microorganisms inside the boarders were the same as indoors. Internal moisture excess was low as was expected according to moisture buffering data of indoor finishing materials. Air temperature and relative humidity conditions inside the boarders were significally lower than needed for mould growth.

Paper I The aim of this study was to evaluate the quality of indoor air in sleeping areas of straw bale and reed houses. The microorganisms were identified from isolated colonies. Total colony forming units (CFU) per m^3 were determined. The most abundant bacterial and fungal genes isolated from samples were *Alternaria, Aspergillus, Cladosporium* and *Penicillum*. Most of these species can present a health risk for humans, especially for those with allergies, asthma and weakened immune systems. The results of this study clearly showed the importance of the work directed to the securement of the air quality when using straw and reed as construction materials. The author developed study design and selected suitable experimental methods. She was responsible for data collection and handling, contributed to result interpretation and manuscript preparation. She was the corresponding author.

Paper II This paper focuses on the impact of finishing materials on the hygrothermal performance of boarders. Hygrothermal properties of clay plaster and clay plaster system (plaster + covering) were studied. The work concentrated on the initial rate of moisture uptake and release after a sudden change in relative humidity and played an important role in the development and testing the methodology applicable in the evaluation of indoor air quality. The author was actively involved in data collection and handling, contributed to result interpretation and manuscript preparation.

Paper III Indoor finishing materials considerably influence indoor climate because of their moisture buffering ability occurring due to the sorption and diffusion properties of materials. The study proved that there are differences within the "same material" i.e. different products known by the common name "clay plaster". The main components of clay plaster are sand and clay. The correlation between the calcite content in plaster mixture and water vapour uptake was evident. The author participated in data collection and handling, contributed to result interpretation and manuscript preparation.

Paper IV The indoor climate of buildings with straw- and reed-bale walls was studied and the factors influencing indoor air quality were determined. In order to fulfil the set aim: (1) air quality was tested in the bedrooms of the studied houses, and the microbial species in air and walls were determined; (2) the indoor air quality parameters (CO_2, relative humidity and temperature) were measured. Also air temperature and relative humidity inside the walls were studied. The results enabled to conclude that the walls of straw or reed-bale house are suitable in temperate climatic conditions, which as a result of professional design, usage of materials suitable for building, and high-quality craftsmanship provides a healthy and environmentally friendly housing. Also the approach as complex study to evaluate the building was offered. The author prepared study design and found suitable methods. The author was responsible for conducting measurements, interpretation of results and manuscript preparation. She was also the corresponding author.

Introduction

The impacts of climate change are becoming evident worldwide (Bowden, Nyberg Wright, 2019), but despite the knowledge about it, global greenhouse gas emissions (GHG) from buildings continue to increase (Hurlimann, Warren-Myers, Browne, 2019). Projected future effects of this process pose more extensive changes in the form of temperature increases, rising sea level, and storms (Hurlimann et al., 2019). With this in mind there is a need for sustainable technologies and materials to fight against changing climate conditions (Karakosta, Doukas, Psarras, 2010; Ferreira, J.J., Fernandes, Ferreira, F.A., 2020; Marques, Tadeu, Almeida, António, Brito, 2020).

Different studies (Horr et al., 2016; Katsoyiannis and Cincinelli, 2019) have shown that people spend 80-90% of their time indoors and a third of a person's lifetime is spent sleeping (Strøm-Tejsen, Zukowska, Wargocki, Wyon, 2015). In recent years many studies dealing with indoor air quality have been published, but bedrooms, where people spend on average 7-8 hours every day, have been dealt with very little within those studies (Strøm-Tejsen et al., 2015; Canha, Lage, Coutinho, Alves, Almeida, 2019). Sleep has a really important role to play in human welfare (Canha et al., 2019), as it helps to recover from physical and psychological fatigue, increases productivity, and overall wellbeing (Krueger, Frank, Wisor, Roy, 2016; Reis, Mestre, Canhão, Gradwell, Paiva, 2016).

Conventional construction materials drain natural resources and the production of these consumes a great amount of energy as well (Hurlimann et al., 2019). Earthen building materials are obtained locally, they are nontoxic, biodegradable, and reusable (Minke and Mahlke, 2005). Buildings where these materials are used are known to be lasting and durable, requiring almost no maintenance and they can provide a passive house standard worthy insulation quality (Kubba, 2012).

Straw bale and reed buildings gather popularity because of their affordability, sustainability and ease of construction. They cause minimum impact on their surrounding environment. Natural materials, which are renewable, offer low-embodied energy; their low impact has a promising potential as construction alternatives (Magwood, 2004). They are attractive to self-builders, because working with these kinds of materials is easy, but the houses built using these materials can carry a potential health hazard via microbial population (Raamets, Ruus, Ivask, Nei, Muoni, 2020).

The aims of the thesis were:

The main goal of the current work was to evaluate through the studies of indoor climate and relevant construction materials the suitability of reed and straw-bale houses for temperate climate zone. No similar microbiological indoor air quality studies carried out elsewhere have been reported in the scientific literature.

The aims of the study were to investigate the indoor climate of straw and reed-bale buildings, to determine the factors influencing indoor air quality, and to assess the suitability of straw or reed-bale houses in Estonian climatic conditions. In order to fulfil the set aim: (1) moisture buffering properties of natural finishing materials were studied; (2) air quality was tested in the bedrooms of the studied houses, and the microbial species in air and walls were determined; (3) the indoor air quality parameters (CO_2, RH%, and temperature) in air and at two different heights in the walls were measured; (4) it was determined how the microbial communities of indoor air in the buildings from straw and reed-bale influence indoor air quality in bedrooms.

These undertakings are reflected in the following publications:

- Moisture buffering properties of natural finishing materials were determined in laboratory conditions ((Paper II and, Paper III);
- Air quality was tested in the bedrooms (Paper I, Paper IV) of the studied houses and the microbial genera in air and walls was determined and identified (Paper IV);
- It was determined how the microbial community of indoor air and indoor climate indicators (CO_2, temperature, RH%, internal humidity load of the boarders, mould index) influence indoor air quality in the bedrooms of reed-bale and straw-bale houses (Paper IV);
- An original approach involving microbiological studies was developed for evaluating indoor air quality in the houses built from straw-bales and reed-bales (Paper I, Paper IV).

1 Background

1.1 Straw and reed as construction materials

The construction sector is the largest resource consumer in the world contributing significantly to climate change (Dutil, Rousse, Quesada, 2011; Iacovidou and Purnell, 2016). The need for buildings and infrastructure, as well as extraction of materials and emissions is growing rapidly (Krausmann et al., 2017). Reducing carbon emissions throughout the life cycle of a building is a possible mitigation measure for both design and construction (Pomponi and Moncaster, 2016); it is possible to use carbon-neutral materials there as well (Chel and Kaushik, 2018). Natural materials have little impact on the environment, and these kinds of materials provide healthy living environment for residents (Brojan, Petric, Clouston, 2013).

Agricultural biomass residues are produced worldwide annually, but they are mostly underutilized (Cornaro, Zanella, Robazza, Belloni, Buratti, 2020). Biomass-based materials capture CO_2 from the environment and improve it (Barreca, Gabarron, Yepes, Pérez, 2019; Cornaro et al., 2020). The use of natural materials in construction is gaining popularity (Barreca et al., 2019), because at the same time their use helps to minimize both primary energy and resource consumption (King and Aschheim, 2007). Agricultural plant fibre is an eco-friendly, biodegradable, cheap, and renewable material for construction (Fernea, Manea, Tămaș-Gavrea, Roșca, 2019). Agricultural plants which provide such materials (straw, hemp, flax, etc), are rich in fibres and are used as building materials (Fernea et al., 2019).

Straw, which is one of the green building materials, is defined as dry stalks of cereal plants (barley, oats, rice, rye, wheat), after the grain and chaff have been removed (Marks, 2005; Cornaro et al., 2020). This material is a mixture of cellulose, hemicellulose, lignin and silicia and the stalks are covered with wax-like water repellent layer (Goodhew and Griffiths, 2005; Liuzzi et al., 2020). Straw has a high-bending and strong tensile strength (Liuzzi et al., 2020), it is a regenerative resource which uses minerals and water from the ground for photosynthesis, and it is easily available in most countries (Drozd and Leśniak, 2018). Straw does not have value as animal feed, but it can be used for bedding or as a conditioner to soil (Cascone, S., Rapisarda, Cascone, D., 2019). Spelt, wheat and rye straw are most suitable as building materials, but bales can be made from other fibrous materials (cornstalks, rice husk, pine needles, any kind of grass, beanstalks) too (Marks, 2005).

Common reed (*Phragmites australis*) is a tall grass (reaching at its best the height of four meters on the coasts of the Baltic Sea), which can be found all over the globe (Paist et al., 2005). It is common in many kinds of wet habitats; in Estonia it is mainly found around shallow bays on the coastline and inland waters (Paist et al., 2005). During summer it is green and durable, in the wintertime it becomes hard and yellowish, which makes it possible to be used for the construction work (as a roofing material or for thermal insulation) (Stenman, 2008).

Reed is widely used all over the world in many traditional building cultures (Milutiene, Staniškis, Kručius, Augulienė, Ardickas, 2012). Reed buildings were already known in Sumerian culture 5,000 years ago, and in Iraq they are widely constructed nowadays (Köbbing, Thevs, Zerbe, 2013; Al-Jumeily, Hashim, Alkaddar, Al-Tufaily, Lunn, 2018), in Europe the use of reed is mostly connected with lowland regions as well as mountainous areas (Paist et al., 2005). From the 19th century due to the lowering quality of rye straw in Europe, reed was the only organic thatch material alternative (Zamolyi and Herbig, 2010). Reed attracts attention because of the healthy indoor climate in the buildings made of it, and the high content of silicon in reed makes it unattractive to insects and other animals as well (Al-Jumeily et al., 2018).

Reed cutting starts when reed leaves have fallen and the plant is dry (Stenman, 2008). Cutting is dependent on the weather and usually cutting season lasts from early summer to late summer, though it is collected during wintertime as well (Häkkinen, 2007). Cutting is not possible when the wind is strong or there is rain, when the water is high or there is a lot of snow (Stenman, 2008). It is possible that the effective cutting time may only be as short as a couple of days per year (Häkkinen, 2007). During manual cutting with the sickle about 30-40 bundles per person can be cut, bound and transported in a daytime (Stenman, 2008), but when using a harvester the corresponding number is much higher – 3,000-4,000 bundles per day (Stenman, 2008). The only problem with the harvester-cut material is the quality – the harvester cuts all the reed without any selection (Stenman, 2008). First-year reed is suitable for insulation plates or as chaff in clay construction (Häkkinen, 2007). Second-year reed can be used as a roofing material too (Stenman, 2008).

Reed has a lower energy demand when it is used to produce building elements ((Al-Jumeily et al., 2018). Reed-bale buildings enable control of indoor temperature more efficiently and thus offer better well-being for the building´s occupants (Barreca et al., 2019). The disadvantages of reed and straw include high flammability and low compressive strength which limits their application to one-storey houses with load-bearing walls (Al-Jumeily et al., 2018). If reed has been cut during a wrong season, it may decompose and contribute to mould growth (Al-Jumeily et al., 2018). Mould has an important role in decomposing organic building materials (Brischke and Hanske, 2016). It has been found that reed rots easily, but the decomposition can be remarkably suppressed with thermal treatment (Brischke and Hanske, 2016).

A method, how to build with straw, was first used by the settlers in the Nebraska area mainly due to poverty and lack of traditional building materials like timber and stone around 1880s (Lacinski and Bergeron, 2004; King and Aschheim, 2007). With the invention of horse-powered straw baler they were able to use compressed straw as blocks for building (King and Aschheim, 2007). The oldest existing straw-bale building, the Burke homestead, was constructed in 1903 outside Alliance, USA (King and Aschheim, 2007). The first European straw bale building (Figure 1 on the next page) was built by Èmile Feuillette in 1921 in Montargis, France (King and Aschheim, 2007).

It is difficult to obtain the accurate numbers of straw-bale buildings (Beaudry and MacDougall, 2019). Online registry of straw-bale houses has 1,670 records worldwide as of 2019, but it is believed to under-estimate the true numbers (Beaudry and MacDougall, 2019).

The spread of using cement as a construction material in Europe after WWII stopped the diffusion of straw-bale construction technique (King and Aschheim, 2007). Building with straw was rediscovered during the 1970s due to the energy crisis and since the 1980s many straw bale constructions have appeared in the Northern Hemisphere (Wanek, 2003; D'Alessandro, Bianchi, Baldinelli, Rotili, Schiavoni, 2017.; Cornaro et al., 2020). Nowadays, houses made of straw bale can be found in the Unites States, Europe, Canada, Australia, and Asia (Holzhueter and Itonga, 2010).

Figure 1. First European Straw Bale building – "Maison Feuillette" in Montargis. On the left there is a picture from 1921, in the right picture the same house was captured in 2011 (Ruppert, 2013).

At the end of the 19th century, many straw and clay houses were built in southern Estonia, because the building resources (straw, clay) were easily available (Itse, 2012). The first modern straw-bale building in Estonia, a sauna, was built in 2002 in Soomaa (Veenre, 2011; Itse, 2012) and the first straw-bale residential building was completed in Koordi village in Järva County in 2007 (Itse, 2012). The first main terraced house in Estonia was built using straw, reed and clay in Lahemaa and its construction started in 2015 (Kivi, 2015). The interest in the construction of straw-bale houses remains high (Itse, 2018). About 150 straw-bale houses have been completed in Estonia (Pata, 2016).

Studies have shown that the heating and cooling of stone buildings requires more energy than the heating and cooling of reed-bale buildings (Barreca et al., 2019). Adding reed to the concrete mix significantly reduces the thermal conductivity of the material (Shon et al., 2019). The high silica content of reed makes this material unattractive for insects and other animals (Al-Jumeily et al., 2018). However, the drawbacks are high flammability and low pressure strength, due to which only single-decked houses can be built with load-bearing walls (Al-Jumeily et al., 2018). Reed has been found to be sensitive to rotting, but the decomposition process can be significantly suppressed by heat treatment (Brischke and Hanske, 2016). To use straw and reed as building materials, moisture content should be lower than 15% and there should be no evidence of rotting (King, 2003). Straw is more susceptible to rotting because of the presence of weed in the material and it is often pre-treated with chemicals to ensure suitable material quality for building (Minke and Mahlke, 2005).

For classical straw bales, straw is harvested from the field with automatic balers which are able to cut, compress and tie the steams of plants with wire or twine (King and Aschheim, 2007; D'Alessandro et al., 2017). Commonly two string or three-string bales are used (D'Alessandro et al., 2017). Small, medium or jumbo bales can be used for building (Minke and Mahlke, 2005; King and Aschheim, 2007). Bale size can vary and it depends on the packing density (Minke and Mahlke, 2005; D'Alessandro et al., 2017). Most commonly used bale has dimensions 32-35x50x50 cm (King and Aschheim, 2007) and their density varies from 90 to180 kg/m^3 (King and Aschheim, 2007; D'Alessandro et al., 2017).

The strength and insulation properties of straw bales are strongly dependent on the packing density. According to the California Building Code a dry density of 104 kg/m^3 is considered suitable minimum for construction (Hammer, 2013). The Australian guide to eco-friendly construction recommends a maximum moisture content of 15% (Downtown, 2013).

Thermal insulation is one of the most investigated properties of straw bale material (Brojan et al., 2013; Brojan, Petric, Clouston, 2014; Costes et al., 2017). Straw bale has good insulation values (R-30 to R-35 or more) – thicker bales have better R-values (Brojan et al., 2014). The straw bale thermal transmission (U) value meets the passive house standard, where U value should be lower than 0.15 W/m^{2}K (Brojan et al., 2014). Brojan et al., (2013) calculated that the studied clay-plastered straw-bale wall has a thermal transmission value 0.12 W/m^{2}K. It has been found that straw bale insulation is most effective in climatic conditions where the heating or cooling of dwellings is essential for comfort (King and Aschheim, 2007). The thermal conductivity values of straw bales are comparable to other insulation materials' thermal conductivity values (Brojan et al., 2013). A bale with 45 cm of thickness provides thermal conductivity value 0.05 W/m^{2}K (Brojan et al., 2014). Costes et al., (2017) found that for the average density (100 kg/m^3) of a straw-bale, the calculated thermal transmission coefficient is between 0.15-0.2 W/m^{2}K. It is dependable on the bale width and how the bale is installed into a wall (Costes et al*., 2017).*

1.2 Building technologies

When building a straw-bale house, the rules and principles are similar to the usual case of building (Steen et al., 1994). The main problem of using straw-bales in construction is excess moisture, which destroys the structure of the bales and results in mould spreading ((Minke and Mahkle, 2005). Under moisture protected conditions, these houses last for centuries (Wanek, 2003). For straw-bale houses, a high foundation, a breathable layer of plaster, and longer eaves are extremely important. (Wanek 2003)

A straw-bale or reed-bale house needs a good foundation, which is strong enough to withstand the weight of the building, does not let through the moisture from the ground, and is located deep in the ground (Wanek 2003). Straw packs must be insulated from moisture coming from the ground – packs are most vulnerable to moisture coming from below and above, moisture from the sides dries more easily and does not permanently damage the straw (Steen et al. 1994). It is ideal for straw packs to be at least 0.3 meters above the ground, covered with a water-repellent plaster, such as lime plaster, and in addition there may be air permeable boarding (Minke and Mahkle, 2005). For straw-bale houses it is recommended to make longer eaves than usual (Steen et al. 1994). It helps to draw rainwater from the walls and beyond the plaster layer, thereby reducing both water saturation and erosion (Wanek 2003).

Traditionally, straw-packed houses have been thickly plastered both inside and outside to protect them from insects, rodents, excessive moisture and wind (Minke and Mahkle, 2005). In addition, the plaster provides fire resistance, is aesthetic, and stores heat (Wanek, 2003). The appropriate type of plaster should be selected depending on the climate and availability of materials (Steen et al., 1994). It is not wise to use water vapour barriers in straw houses because they rather become places where water vapour condenses and causes moisture damage (Minke and Mahkle, 2005). It is recommended to remove excess moisture in damp areas using forced ventilation. (Wanek 2003)

There are several different systems to build with straw-bales. Load-bearing system is known as Nebraskan style, which is a way of building where bales are structural elements and they can be used as bricks (King and Aschheim, 2007; Cornaro et al., 2020). The load-bearing walls support the wooden structure of the roof and transmit the loads to the foundation, but there are some limitations to this technology (King and Aschheim, 2007). Houses which have been built using Nebraskan style cannot have openings that exceed 50% of the wall surface (Minke and Mahkle, 2005). If the openings exceed 50% of the wall surface, the wall system could be unstable (King, 2003). The rigidness of this technique does not allow one to construct more than four storey buildings (Lymath, 2016).

Nebraska-style construction has been further developed in a number of different ways (King and Aschheim 2007). In one case, the packages are covered with mortar and then laid on the wall like large bricks that can still be fastened together with additional mortar ((Minke and Mahlke, 2005). In this case, the hardened mortar bears a part of the weight (King and Aschheim 2007). Such a system is accompanied by cold bridges in cooler climates, so it is not a very common way of building in northern hemisphere. (Minke and Mahlke, 2005) The second method to build with straw is a post and beam construction technique (King and Aschheim 2007). Straw-bales and reed-bales can be used as infill insulation material within a metal or timber structure or as load-bearing walls (King and Aschheim 2007; Marques et al., 2020).

There are several other construction techniques for building with straw – GREB (Hoxha, Ungureanu, Belayachi, Do, Thevard, 2012; Cornaro et al., 2020), modular (Wall et al., 2012) and mixed systems (Lacinski and Bergeron, 2000; King, 2007). There are two styles in which Nebraskan style and the post and beam technologies are mixed – cell under tension system (CUT (Chaussinand, Scartezzini, Nik, 2015)) and Gagné (Steen et al., 1994) technique. In these systems the structural function is partially or completely performed by other elements rather than straw bales (D´Alessandro et al., 2017).

On the market there are pre-compressed straw boards and prefabricated construction elements (main producers Mod-Cell® in United Kingdom, Ecococon in Lithuania and Paille Tech in France) with straw bales (wood frame and the bales are preassembled) (Cornaro et al., 2020). Straw panels have already been produced in Switzerland and France from the 1920s under Solomite brand (Cornaro et al., 2020). In England, Starmit panels, where the straw is compressed over high heat without the use of additives, are very popular (Minke and Mahlke, 2005). Both techniques allow saving time and costs on the construction site (Cornaro et al., 2020).

In Figure 2 on the next page the described building systems are presented. On the left there is a load-bearing wall structure, in the middle there is a frame-based wall and on the right, there is the base panel.

All the exterior walls covered with plaster must be protected from water and moisture on both sides – top and bottom (Minke and Mahlke, 2005; Cornaro et al., 2020). The lower part of the straw-bale wall, which is up to 0.3 m above the ground, must be covered with a waterproof layer to protect it against the splashes (Minke and Mahlke, 2005). Under ideal conditions, the main wall starts at about 0.3 m (Ezennia and Alibaba, 2017). It is possible to reduce the risk of splash water damage by using light gravel or vegetation cover along the perimeter (Minke and Mahlke, 2005). Hard ground is not suitable because it increases the risk of splash water damage (Minke and Mahlke, 2005; Ezennia and Alibaba, 2017). In addition, the straw-bale wall must be protected from rain, hail and wind (Ezennia and Alibaba, 2017). This can be achieved with a weatherproof and crack-free plaster or with a ventilated coating (Minke and Mahlke, 2005; Gupta, 2015; Ezennia and Alibaba, 2017).

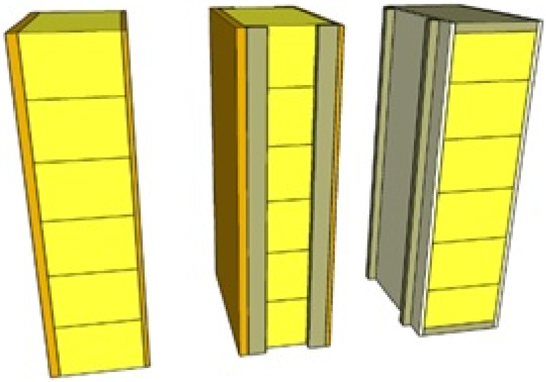

Figure 2. Sections of straw bale walls. From left to right: Nebraska style (load-bearing) wall, frame-wall, base panel; the inside is shown on the left, the outside on the right) (Pata, 2016).

Theoretically, due to the formation of condensed water, the moisture content in the straw wall should increase in winter endangering the properties of straw as an insulation material (Steen et al., 1994). In the literature there are data on experiments with straw walls plastered on both sides, which have shown that the moisture content in straw packs remained relatively unchanged at around 13.4% (Steen et al., 1994). A similar result has been confirmed by 11% moisture content in a straw house built in Germany (Ashour, Georg, Wu, 2011) and a longer-term study in England where straw confirms moisture resistance (Thomson and Walker 2014). In general, the moisture content of the base wall should not exceed 15% (Steen et al., 1994). If this value is exceeded in a short period of time, the straw does not decompose immediately but the thermal insulation properties of the wall decrease (Minke and Mahlke, 2005).

In rooms with a more than 70% moisture content, it is recommended to increase the diffusion coefficient of the inner wall finishing layer (adding linseed oil to the plaster/coating or coat the plaster with water vapour resistant paints (latex paints or seed oil paint)) (Sharma et al., 2010). Vapour barrier layer is generally not required for a vapour-permeable wall construction if lime plaster or some other breathable finishing material is used in the exterior finish (Minke and Mahlke, 2005; Cascone et al., 2019).

The extremely high sorption parameters of loose straw are of no practical importance in shaping the indoor moisture balance, as the straw bales used are tightly pressed and plastered which together significantly inhibit the process of sorption (Cascone et al., 2019). Therefore, it is recommended to apply a relatively thick and multi-layered clay-sand plaster to the base wall (Minke and Mahlke, 2005). To achieve even better sorption capacity indoors, the partitions could be laid of unfired clay bricks (Marks, 2005; Bronsema, 2010).

Official tests in Austria have confirmed that unprocessed wheat straw, packed at a density of 120 kg/m^3 was non-flammable enough (Steen et al., 1994). The straw wall, with a frame plastered with clay plaster lime plaster on the inside, achieved a fire resistance rating of F90 (Steen et al., 1994). Various tests in Germany and Austria have replicated this result, and similar tests in the USA (SHB AGRA test) even gave the result F120 (Steen et al. 1994). Even if the plaster is cracked, the charred layer formed by primary contact with the fire prevents the passage of oxygen into the straw pack (Theis, 2003, Doleman, 2017).

Although straw may appear to be a suitable habitat for rodents and insects, only a few houses have had problems with these organisms (Steen et al., 1994). Plaster does not only provide structural strength and stiffness, but also protects against pests, fire and moisture (Beaudry and MacDougall, 2019). If the walls of the straw-bale house are not plastered, the risk factor is higher, and it is easier for pests to access the house or its walls (Steen et al., 1994). If living in an area where additional pest protection is justified, the straw house can be protected with various techniques, such as fine wire nets below the plaster layer, installing termite shields, sand barriers, borax mixture, etc. (Steen et al., 1994; Beaudry and MacDougall, 2019).

1.3 Microbiological studies

Fungi are a large group of eukaryotic and heterotrophic organisms that include microorganisms ranging from unicellular forms to moulds, yeasts and mushrooms (Khan and Karuppayil, 2012). They get organic matter from the external environment for vital activities (Moon, 2005). Fungi are free living organisms which are capable of breaking down nutrients and biosynthesise the necessary biochemicals (Khan and Karuppayil, 2012).

When talking about moulds, we refer to microscopic, primarily multi-celled and filamentous, composed of hyphae and mycelium (Nwakanma and Unachukwu, 2017). They are beneficial to the environment because they break down dead materials (Khan and Karuppayil, 2012). There are four stages in mould lifecycle: sporulation, germination, hyphal growth (vegetative development) and reproduction (Moon, 2005). Moulds do not have chloroplasts and thus they cannot undergo photosynthesis (Khan and Karuppayil, 2012). They reproduce by the means of spores produced, by an asexual process or as a result of sexual reproduction (Moon, 2005). Many fungi are able to produce several other types of spores and the spore types are unique to each individual species (Nwakanma and Unachukwu, 2017). When spores are carried by air currents and land on a moist surface, they begin to grow (Moon, 2005). Moulds are normally present indoors at levels which do not have any impact on healthy individuals (Curtis, Lieberman, Stark, Rea, Vetter, 2004).

In germination phase the spores settle on surfaces and stay inactive until they find a possibility to absorb nutrients and moisture from the substrate (Moon, 2005). Both factors are highly important and in their absence germination process does not occur (Rajasekar and Balasubramanian, 2011; D'Orazio, 2012). The exposure time for the formation of moulds varies greatly and is dependent on the environmental conditions in which the building material is located (Pasanen et al., 2000; Lawrence, Heath, Walker, 2009). If germination is successful, the growth of hyphae takes place immediately after germination (D'Orazio, 2012). When pluricellular filaments thicken, they form a mycelium which allows the fungi to metabolize necessary nutrients and moisture from the substrate material (Moon, 2005).

Every year the microbiological population living on a given piece of land differs and varies from place to place (Arnolds, 1992). The number of microorganisms present in a given place depends on available nutrients (Arnolds, 1992). The microbial population at the time of straw or reed harvest is of special interest to the builder because the microbes are baled with the straw and then used for building (Summers et al., 2003). Straw has adequate amounts of energy and nutrients to provide the growth and sustenance for microbial populations (Hoorman, 2010). If the conditions are favourable for microorganisms, they can multiply (Tian et al., 2020). Aerobic microorganisms, which colonize the straw, need nutrients, the availability of oxygen, suitable temperature and the availability of free moisture in the material to grow (Vereecken and Roels, 2012).

Bacteria dominate the decomposition process during the initial phases, while fungi or actinomycete have higher abundance in the later stages of decomposition (Paterson et al., 2008; Marschner, Umar, Baumann, 2011). If the bales have been affected by rain prior to using them in building a structure, it is possible to experience some microbial growth and therefore more spores are present as well (Summers et al., 2003). Inside the wall the decomposition process is aggravated due to the lack of oxygen (Veerecken and Roels, 2012). The oxygen inside the straw-bale wall is replaced during active microorganism respiration by carbon dioxide (Summers et al., 2003).

Plant surface (phyllosphere) is hostile environment for microorganisms, because the temperatures and relative humidity always fluctuate (Yang et al., 2001). Surfaces have limited nutrient resources but despite that the above-ground parts of plants are colonized by a number of microbiota living in their organs and tissues (leaves, roots, stems, seeks, fruits, bulbs, rhizo- and phyllosphere) (Rahman et al., 2018). Legard et al. (1994) identified 37 genera and 88 different species of fungi in total from spring wheat. Members from genus *Penicillium* have been reported from the phyllosphere of wheat (Uddin and Chakraverty, 1996; Larran, Perelló, Simón, Moreno, 2006). Four species from the genus *Cladosporium* have been found from common reed plants (Wirsel et al., 2002). Several authors have reported that the fungal species found in straw can be divided into three groups according to their need for water (Grant, Hunter, Flannigan, Bravery, 1989; Gravesen, Frisvad, Samson, 1994). The primary colonizers in straw were from genera *Wallemia, Penicillium, Aspergillus* and *Eurotium*, secondary colonizers from genera *Cladosporium, Ulocladium* and *Alternaria* and tertiary colonizers from genera *Stachybotrys, Chaetomium, Trichoderma* and *Auraeobasidium* (Grant et al., 1989; Gravesen et al., 1994). Typical moulds in rye and wheat of Estonian origin are from the genera *Cladosporium*, *Alternaria*, *Aspergillus*, *Fusarium*, *Penicillium*, *Helminthosporium*, *Mucor* and *Rhizopus* ((Lõiveke, Ilumäe, Akk, 2008). The occurrence of *Aspergillus* species is more characteristic of the southern regions of Estonia (Lõiveke, 2008). Most likely, these same fungi are common colonizers in straw produced in Estonia (Ilustrumm, 2014). Bacterial and fungal genera have been isolated from Estonian straw bales as well (Raamets, Kutti, Ruus, Ivask, 2017). The fungal genera *Aspergillus, Penicillium* and *Cladosporium* were present, as well as two bacterial genera – *Streptomyces* and *Pseudomonas* (Raamets, Kutti, Vettik, Ilustrumm, Rist, Ivask, 2016).

There is no uniform international standard for the permitted levels of the colony forming units indoors (Jyotshna and Helmut, 2011). Nevalainen and Morawska (2009) found, that the amount of colony forming units indoors should not exceed 1000 CFU/m^3 (Nevalainen and Morawska, 2009). In Estonia, there are no recommended limit values for moulds in the indoor environment (Kivi, 2008; Pilt, 2017), but recommended limit values have been established in Finland. (Soumaa and Pekuri, 2009).

1.4 Clay plasters, natural colours and their hygrothermal performance

Indoor finishing materials can considerably influence indoor climate due to their moisture buffering ability (Svennberg, 2006). Moisture buffering in the indoor environment is the ability of surface materials to attenuate the moisture variations of the indoor air (Rode et al., 2005). It has an important role in understanding the risks for biological growth in the indoor environment (Svennberg, 2006). Moisture buffering has an impact on occupants’ health too (Rode et al., 2007; Svennberg, 2006). Different materials can be used to regulate humidity levels by absorbing or releasing moisture in indoor climates (Rode et al., 2007).

Earthen construction materials have been used for more than 9,000 years and they include adobe bricks (made from sand, clay and straw), cobs (made from clay, sand and straw), rammed earth, which is compressed with different fibres for stabilization, and clay plaster, which is usually used indoors (Minke and Mahlke, 2005). It can be used as an external plaster and therefore it should be strengthened by adding certain additives as well (Niroumand, Zain, Jamil, 2013). The most common clay minerals are smectite or montmorillonite, kaolinite, illitem and chlorite (Sinisalu and Kleesment, 2002). The aforementioned clay minerals form combined clay minerals such as illite smectite and illite chlorite (Sinisalu and Kleesment, 2002).

Natural clay plaster is a fixed mixture of silt and sand, clay and some form of fibres (straw, sawdust, flax etc) (Allen and May, 2003). Silt and sand provide the strength and structure, clay acts as a binding agent (Allen and May, 2003). Natural fibres are added to resist the tensile stresses within the plaster surface (Ashour, 2011; Liblik and Just, 2016). Earthen plasters are permeable to water vapour and their mechanical behaviour is as good as earthen walls (Liblik and Just, 2016). This kind of plaster provides optimal moisture content of clay by keeping the place cool in summer and warm in wintertime (Minke and Mahlke, 2005). It creates comfortable and healthier living environment (Minke, 2013; Deliniere et al., 2014). In addition to clay plaster, whitewash and lime plaster are used too (Ashour, 2011). All these finishing materials are antibacterial and therefore disable the growth of mould and bacteria (Minke, 2013; Dettmering, 2019).

Depending on their moisture capacity and vapour permeability, Ge et al (2014) have categorised materials into 3 groups. Materials belonging to group A have high moisture capacity and low vapour permeability (Ge et al., 2014). Materials with low moisture capacity and high vapour permeability belong to group B (Ge et al., 2014). Group C consists of materials, which have high moisture capacity and high vapour permeability as well (Ge et al., 2014). The addition of fibres has little influence on both the moisture adsorption and desorption properties of plasters (Lima and Faria, 2016).

Clay shapes the moisture content of air in the most convenient way for humans thanks to its suitable sorption parameters: when the room relative humidity rises above 50%, the clay absorbs moisture, and when it falls below 50%, it begins to release moisture (Minke and Mahlke, 2005). When comparing different finishing materials (clay plaster, spruce board, lime-cement plaster, gypsum plaster), clay has the lowest sorption capacity and gypsum plaster has the highest; the addition of different fibres accelerates sorption (Lima and Faria, 2016). Clay plastering capacity varies greatly between different ready-mixed plaster mixtures depending on the clay content, type, and organic impurities. (Minke and Mahlke, 2005)

1.5 Indoor air quality and its impact on building performance and occupants' health

Indoor air quality (IAQ) is one of the most important factors, which affects our life quality – health, wellbeing, and human performance (Bird, Balshaw, Anderson, 2012; Rogawansamy, Gaskin, Taylor, Pisaniello, 2015). Every day a person breathes 10m^3 air and most of our lives (80-90%) we spend indoors (Brasche and Bischof, 2005; Horr et al., 2016; Katsoyiannis and Cincinelli, 2019). Humans are more exposed to indoor air pollutants than to those which can be found from outdoor air (Branco, Alvim-Ferraz, Martins, Sousa, 2015). Inadequate indoor air quality may lead to illness, tiredness and to adverse health symptoms such as respiratory problems and headache (Dharmage et al., 2002; Portnoy, Kwak, Dowling, Vanosdol, Barnes, 2005). Continuous exposure to moulds can cause problems for immunocompromised people, chronic patients, children, and the elderly (Li, Hsu, Tai, 1997; Portnoy et al., 2005; Hernberg, Sripaiboonkij, Quansah, Jaakkola, J. J., Jaakkola, M. S., 2014).

There are many factors, which can affect indoor air quality and sleep comfort in the bedrooms – air temperature, relative humidity, contaminants occurring in bedroom air (biological, chemical, or physical agents) (Bird et al., 2012). Carbon dioxide ($CO_{2)}$, which is used to monitor human employment, is a common indicator of indoor air quality (Batog and Badura, 2013). Carbon dioxide does not have any colour, taste, odour and it is a non-flammable gas, and is heavier than air (IPCS, 2006). During the past five years carbon dioxide concentrations in the atmosphere have been over the 400-ppm level and the rise will continue (WMO, 2020). CO_2 is a main contributor to the greenhouse effect and therefore it accelerates global warming as well (Bertonia, Ciuchini, Tappa, 2004).

The type and the condition of the ventilation system of buildings has a big impact on indoor air quality (Batog and Badura, 2013). To maintain the indoor air quality within acceptable limits, an efficient building ventilation system is needed (Asif, Zeeshan, Jahanzaib, 2018).

From indoor environments several hundreds of bacterial and fungal species can be found (Uddin and Chakraverty, 1996; Verdier et al., 2014). Indoor air pollutants are harmful chemical, physical and biological factors, which can come from living discharges, decoration and furniture, and building materials (Tran et al., 2020). Moulds (mainly from genera – *Cladosporium, Penicillum, Aspergillus, Alternaria)* and large groups of gram-negative bacteria and mycobacteria can be found inside buildings (Verdier et al., 2014). Indoor air microbiological community may produce contaminants – allergens, toxins and other metabolites, as well as spores - which can contribute to the degradation of indoor air quality and can pose a health hazard to occupants (Nielsen, K., Holm, Uttrup, Nielsen, P, 2004; Torvinen et al., 2006).

Indoor air microorganisms have four sources – humans, contaminated water tanks, dusts and wet surfaces (Verdier et al., 2014). Wet surfaces can become major sites for microbial growth when there is contact contamination to a source (human, dust, animal etc.) (Verdier et al., 2014). Between 20% and 40% of the indoor climate in European and North American buildings is affected by mould, which causes various health problems (Laborel-Préneron, Magniont, Aubert, 2018). Mould does not damage the material directly, but its presence refers to high humidity level in the structure and possible risks (decomposition) (Lelumees, 2016).

Indoor air quality is influenced by temperature, humidity, lighting, ventilation and different airborne particles and airborne chemical pollutants (Verdier et al., 2014). Dwellings can pose environmental risk factors like mould and dampness, allergens and different chemical emissions from building materials (Mendell, 2007). To reduce the problems caused by poor indoor air quality, there is a need to develop new ecologically friendly materials and components to create more energy-efficient and healthier buildings (Da Silva et al., 2016; Khoshnava et al., 2020).

Exposure to indoor mould is a major health issue (Hurrass et al., 2017). Studies have shown, that there is a strong relationship between excessive moisture, mould growth and respiratory health effects (Hargreaves et al., 2003; Liao, Luo, Chen, S., Chen, J., Liang, 2004). Mould in buildings represents a danger on children, the elderly and people with chronic illness depending on individual vulnerability (Ginestet, Aschan-Leygonie, Bayeux, Keirsbulck, 2020).

1.6 Humidity load and mould growth index in boarders

Relative humidity (RH) inside a dwelling has an important role to play in the comfort and health of users (Ramos et al., 2010; Maskell, Thomson, Walker, Lemke, 2018) and it is the most investigated criterion for mould growth (Gradeci, Labonnote, Time, Köhler, 2017). Mould growth depends on relative humidity and temperature conditions at the surface of the material (Pasanen et al., 2000; Viitanen et al., 2009; Johansson, Ekstrand-Tobin, Svensson, Bok, 2012), the type of substrate and exposure to it and the time of favourable conditions, and on the pH-level of the material surface and oxygen, which is always freely available too (Viitanen, 1994; Vereecken and Roels, 2012). If favourable conditions persist, a fungal growth can take place and there can be consequences for human health and on economic and social levels as well (Jaakkola and Jaakkola, 2004; Ramos et al., 2010).

Relative humidity influences the humidity regime of the building envelope and the indoor climate of the building (Kalamees et al., 2011). Big internal humidity load may adversely affect indoor climate and cause humidity problems to the building envelope (Kalamees et al., 2010). A family with 2 adults without children excreted water on average 341 g/h and a family with 1-3 children 504-600 g/h (Yang, 2010). Tenwolde and Walker (2001) made the annual measurements, which resulted in an average value of 300 g/h in a family without children and 490-600 g/h of water per family with 1-3 children (Tenwolde and Walker, 2001).

To predict the potential of mould growth during the design stage on and inside different building materials, several mould growth prediction models have been published based on different experiments or assumptions – isopleth models (Hukka and Viitanen, 1999; Sedlbauer, 2001; Arya and Singh, 2016), ESP-r mould prediction model (Clarke et al., 1999; Rowan et al., 1999), empirical VTT-model (Hukka and Viitanen, 1999; Ojanen et al., 2010; Viitanen et al., 2011), biohygrothermal model (Sedlbauer, 2001; Krus, Kilian, Sedlbauer, 2007), temperature ratio (Sedlbauer, 2002). A part of existing models based not only on relative humidity (RH) and temperature (T), but the substrate and exposure time (Moon and Augenbroe, 2004) have impact on the mould growth process too (Sedlbauer, 2001).

A complex model for mould growth was first introduced by Hukka and Viitanen in 1999 (Hukka and Viitanen, 1999). They reported that the ideal environment for mould development is the temperature between 20-28 °C and relative humidity of more than 55% (Hukka and Viitanen, 1999). For mould growth the critical range of relative humidity is 75-95% (Pasanen, Niininen, Kalliokoski, Nevalainen, Jantunen, 1992; Hukka and Viitanen, 1999; Nielsen et al., 2004; Gobakken, Høibø, Solheim, 2010; Gradeci et al., 2017). The most suitable temperature range varies from 20-35 °C, but basically moulds can grow in temperatures between 0 and 50°C (Hukka and Viitanen, 1999). There should be enough food for microorganisms, and the pH level should be between 5 and 6 (Moon, 2005). It is very important that the growing conditions are available for a certain time (Hukka and Viitanen, 1999; Moon, 2005; Gradeci et al., 2017).

Ojanen and Viitanen (2016) mould model has a principle for visual findings (Ojanen and Viitanen, 2016). Mould index has six levels for visual findings – 0 being the lowest (no growth) and 6 being the highest (heavy and tight growth, coverage about 100%) (Viitanen et al., 2015).

2 Materials and methods

2.1 Structure of the study

The schematic structure of the work carried out with the aim of completing the tasks of the current study is given in Figure 3.

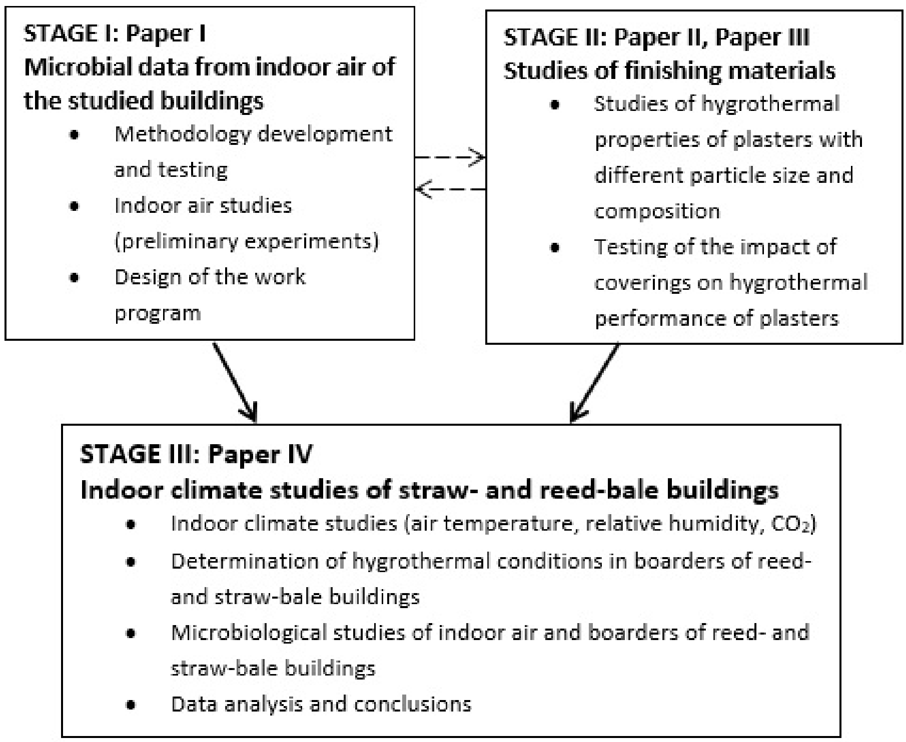

Figure 3. Structure of the study Indoor air microbiological quality in reed-bale and straw-bale houses in Estonia

2.2 The hygrothermal performance of plasters

Indoor finishing materials considerably influence indoor climate because of their moisture buffering ability occurring due to the sorption and diffusion properties of materials. Paper II and Paper III are focused on the influence of finishing materials on the hygrothermal performance of plasters. Full description of materials and methods used can be found from Paper II and Paper III.

The recipe for specimens contained local clay, sand, cattail and flax in the form of solid powder and water. For the specimens for Paper II, six different covering materials were used, specimen (with a diameter of 100 mm approx. and thickness of 25 mm) were marked. For covering materials fine finishing mortar with cellulose, fine finishing mortar without cellulose, casein paint, cellulose base coat, lime paint, casein paint coat and not covered clay plaster were used. The description and properties of specimens are presented in the Paper II.

Hygroscopic sorption properties were determined by following the principle of the standard (ISO, 2013). A detailed description of the methodology is given in paper II.

Eight different clay-sand plaster mixtures (6 specimen each, diameter approx. 100 mm, thickness approx. 25 mm) were used as specimens for Paper III. The particle size distribution and mineral content were estimated for all specimens. The exact content of all tested plaster mixtures is unknown because all specimens were produced by manufacturers and only water was added in the laboratory. All the specimens were marked. The description and properties of clay plaster specimens are presented in the Paper III.

To estimate the consistence of the fresh mortar ISO standards ISO 10153:2004+ A2:2007 (ISO, 2009) and Cooper flow table Cooper TCM-0060/E flow table was used. The hygroscopic sorption properties were determined according to ISO 12571 standard (ISO, 2013). Three different RH levels were chosen: 30%, 50% and 80%.

To describe the dynamics during the first hours, the specimens were weighted at 1, 2, 3, 6, 12, 24, 48, 72 hours after changing the humidity level (Paper II). The To determine the hygrothermal performance of clay-sand plaster specimens, they were weighed at 1, 2, 3, 6, 12 and 24 hours after the humidity level in the climate chamber had been changed using a 24-hour long interval until the specimen's weight had been stabilized (Maddison, Mauring, Kirsimäe, Mander, 2010).

To determine the water vapour permeability properties ISO 1015-19 standard was used (ISO, 2005). For both tests the same specimens as described in Paper II and Paper III were used.

To prepare the specimens used in Paper III and Paper III, clay plaster was embedded into a cylinder (diameter approx. 100 mm), which was cut from a plastic pipe. For tightening, a plastic film and silicon hermetic were used.

Chemicals and equipment

To carry out the experiment described in Paper II and Paper III, climate chamber RUMED 4101 (RH 20-95%, accuracy ±2-3%, temperature 0-60 °C, accuracy ±0.5 °C) was used. To weigh the sorption test specimen the digital weight Memmert PC440 Delta Range (range 0-5400 g, accuracy ±0,01 g) was used. For water vapour permeability, the digital weight Mettler (range 0-1200 g, accuracy ±0.01 g) was used. KNO_3 was used to ensure relative humidity of 93% for wet cup method.

For mineralogical composition the X-ray diffraction method with the XRD spectrometer Bruker D8 Advance was used. To estimate the particle size, wet sieving analyses were performed according to the standard ISO 1015-1 (ISO, 2004).

2.3 Studies carried out in buildings

The assessment of bacteria and fungi present in indoor air in straw-bale (n = 4) and reed-bale (n = 4) houses was carried out from October 2014 to October 2016 in the Northern part of Estonia. Description of materials and methods used can be found from Paper I and Paper IV.

2.3.1 Description of the studied buildings

Some of the houses were Nebraska-style structures (2 houses, walls bearing the weight of the roof), some with a framework (1 straw-bale house and 3 reed-bale houses), where straw/reed had an important role in insulating. In the case of one straw-bale house factory manufactured modules were used. All the structures had been designed and built by qualified experienced building companies. Visual examination did not reveal any moisture damage or mould growth. The studied structures were 2-7 years old.

The average wall thickness was 50±5 cm except for one dwelling whose wall was 100 cm thick. All the structures had plaster on the internal and external walls. The plaster thickness was usually 5 cm on the internal and external walls except for two dwellings. The plaster thickness of one dwelling was 7 cm on the internal and external walls (lime plaster), the other dwelling had a 10-cm-thick plaster on the internal and a 12-cm-thick plaster on the external wall. Generally, clay plaster was used; two structures had lime plaster on the internal and external walls.

All the studied structures had high plinths and wide eaves (Figure 4). Both, shallow foundation (5 structures) and pile foundation (3 structures) were used. Wood construction was used for the indoor floors in all the dwellings. Three houses had wood shingle roofs, three houses PVC, one stone and one green roof.

Figure 4. The examples of the plinths (left image) and eaves (right image) of the studied buildings. (Raamets et al., 2020)

2.3.2 Microbiological studies from indoor/outdoor air and walls

Chemicals and equipment

The media components were weighed by an analytical weight (ABJ 120-4M, accuracy ±0.2 mg, manufactured by Kern and Sohn, Balingen, Germany). The media were autoclaved using the HMT 260 MB autoclave (HMC Europe, Tüssling, Germany). The culture plates were poured under a fume hood (conforming to ISO 13150, Retent AS, Nõo, Estonia). The samples were collected with the Mirobio MB2 (Cantum Scientific, Dartford, UK) air samplers. For the microbial identification of moulds a microscope (model SP100, Brunnel Microscopes LTD, Chippenham, United Kingdom) was used.

The data were collected on carbon dioxide (CO_2) content, temperature and relative humidity in each bedroom with the datalogger Green-Eye Model 7798 (accuracy ±50 ppm for carbon dioxide, ±0.6 °C for temperature, ±3% for humidity) (10-90%), manufactured by TechGrow, The Hague, The Netherlands. Hobo UX100-023 data loggers (measuring range -20 °C to +70 °C, 5% to 95% RH, accuracy ±0.35 °C and ±2.5% RH, manufacturer Onset Computer Corporation, Bourne, United States) were used to collect temperature and humidity data from the walls.

Sampling method

The media (malt extract agar (MEA) and dichlorane 18% agar (DG18)) were prepared and the sampling procedure was performed according to ISO standard 16000-18 (ISO, 2011). The samples for both publications (Paper I, Paper IV) were collected with air samplers on 9 cm Petri dishes 4 times a year (winter, spring, summer, autumn) from the bedrooms 1 meter above the floor level. The sampling time was 1 min and the volume of air passing was 100 litres per sample. Four replicates of each medium were collected from each area. As a reference, air samples were collected too in four replicates from outdoor air 1.5 m above the ground level. The collected samples were processed according to ISO Standard 16000-17 (ISO, 2008).

The samples were incubated at 25 °C for 7 days, after which the colony forming units (CFU) were counted. For identification further cultures were used (Paper I, Paper IV).

The walls were studied using the previously developed methodology (Raamets et al., 2016) as well. The samples of 10 g were plated directly on the malt extract agar (MEA) supplemented with chloramphenicol. The samples were incubated at 32 °C for 72 hours and then the colony forming units were counted and the microbial growth was identified.

In addition, background data on carbon dioxide content, temperature and humidity of one of the sensors' data recorders was collected from the bedrooms of the studied houses (the sensor was located 1.2 m above the floor recording at 30-minute intervals). Data was also collected on temperature and relative humidity within the walls. For this purpose, 7 mm diameter holes were drilled in the walls at two heights (0.2 m and 1.2 m). The measuring heads of the data loggers were placed in the wells at a depth of 20 cm and automatic measurements were made at 10-minute intervals.

Identification procedure

Moulds were identified on the basis of their morphological characteristics with a microscope (SP100, Brunnel Microscopes LTD, Chippenham, UK). Lactophenole blue was used as a staining agent. The cultures were identified to family level using different indicators (Bergey et al., 2000; Domsch et al., 1980; Kilch, 1988; Samson et al., 1996; Larone, 2002; Kilch, 1988; Winn & Koneman, 2006; Watanabe, 2010). Samples were taken from outer boarders (walls) to study the straw and reed using the methodology developed earlier (Raamets et al., 2016). 10-gram samples were plated directly on Malt Extract Agar (MEA) with added chloramphenicol. The samples were incubated at 32 °C for 72 hours and then the colony forming units were counted.

3 Results

The results described in this chapter are based on four publications. Only an extract of the results is presented here. The following discussion is organized by predominant themes which can be found in the added publications.

3.1 Indoor air microbiology in straw-bale and reed-bale buildings

Exact data about indoor air microbiology in straw bale and reed-bale buildings can be found in Paper I and Paper IV. Only the most important results are presented here.

3.1.1 Mould abundance, dynamics and composition in indoor and outdoor air by season and by genus

In Paper IV the mould abundance, dynamics and composition in indoor and outdoor air by season and by genus were described. The dynamics of the seasonal colony forming units (CFU) are similar in straw-bale and reed-bale buildings; differences occur in the number of CFU. The most abundant was the indoor air microbial community in straw-bale houses during summer (from June to August) with indoor air cultured colonies from malt extract agar (MEA) averaging 537±102 CFU m^{-3} and dichlorane 18% agar (DG18) averaging 46±12 CFU m^{-3}. The same correlation was found for reed-bale buildings where indoor air cultured colonies from malt extract agar (MEA) averaged 858±106 CFU m^{-3} and from dichlorane 18% agar (DG18) averaged 36 ± 11 CFU during summer. At the same time, outdoor air (Table 1) contained on average 289±32 CFUm^{-3} on malt extract agar (MEA) and on average on dichlorane 18% agar (DG18) 50±11 CFU m^{-3} outside straw buildings. Outdoor air contained on average 353 ± 41 CFU m^{-3} on malt extract agar (MEA) and 45±12 CFU m^{-3} on dichloran 18% agar (DG18) outside reed-bale buildings. During spring and autumn, the result for indoor and outdoor air samples was comparable.

Table 1. Seasonal variation in airborne mould indoors and outdoors shown as mean with the standard error (±SE), range of CFU m^{-3} air

	Indoors			
Sampling site	Winter	Spring	Summer	Autumn
Straw-bale (MEA)	149±29	298±100	537±102	307±99
Reed-bale (MEA)	380±136	518±145	858±106	548±155
Straw-bale (DG18)	14±8	29±9	46±12	20±11
Reed-bale (DG18)	22±13	23±9	36±11	22±10
	Outdoors			
Sampling site	Winter	Spring	Summer	Autumn
Straw-bale (MEA)	94 ± 19	197 ± 43	289 ± 32	168 ± 34
Reed-bale (MEA)	118 ± 15	198 ± 48	353 ± 41	212 ± 34
Straw-bale (DG18)	18 ± 7	30 ± 9	50 ± 11	22 ± 10
Reed-bale (DG18)	24 ± 9	27 ± 11	45 ± 12	23 ± 9

During the study, indoor air fungi were identified up to genus level (Table 2). During the winter period, the most identified moulds in straw buildings belonged to the genus *Penicillium* (74%). Moulds, belonging to the same genus (*Penicillium* (70%) also dominated in the reed-bale buildings during the winter months.

During spring and summer months in indoor air, most of the identified moulds belonged to the genus *Cladosporium*. In autumn the most common mould genus both in straw bale and reed-bale buildings was *Penicillium* (straw-bale – 31%, reed-bale – 37%).

Table 2. The distribution of moulds identified by genus to families by season and building material. The first figure represents the number of colony forming units (CFU) and the second percentage (%) of the seasonal total (Paper IV).

	Winter		Spring		Summer		Autumn	
	Straw-bale	*Reed-bale*	*Straw-bale*	*Reed-bale*	*Straw-bale*	*Reed-bale*	*Straw-bale*	*Reed-bale*
Alternaria	1 (1)	4 (1)	9 (3)	16 (3)	32 (6)	43 (5)	25 (8)	49 (9)
Aspergillus	25 (17)	72 (19)	24 (8)	36 (7)	11 (2)	9 (1)	71 (23)	110 (20)
Cladosporium	1 (1)	23 (6)	**235 (79)**	**420 (81)**	**451 (84)**	**738 (86)**	92 (30)	142 (26)
	Winter		Spring		Summer		Autumn	
	Straw-bale	*Reed-bale*	*Straw-bale*	*Reed-bale*	*Straw-bale*	*Reed-bale*	*Straw-bale*	*Reed-bale*
Penicillium	**110 (74)**	**266 (70)**	24 (8)	36 (7)	38 (7)	51 (6)	**95 (31)**	**203 (37)**
Others	10 (7)	15 (4)	6 (2)	12 (2)	5 (1)	15 (2)	25 (8)	44 (8)

3.1.2 Mould abundance, dynamics and composition by genus in the boarders

Samples were collected from the walls of the buildings during autumn and the full results can be found from Paper IV. Only a few colonies were found to grow from the collected samples (min. 6 CFU, max. 14 CFU). The genus distribution of the colonies was similar to the distribution in indoor air.

36% of the identified moulds belonged to the genus *Cladosporium*, 32% to the genus *Penicillium*, 25% to the genus *Aspergillus* and 2% to the genus *Alternaria*. 3% of the identified moulds did not belong to any genera mentioned before and were classified as others.

3.2 Indoor air quality in the studied bedrooms

Exact data about humidity load, mould growth index in boarders, hygrothermal properties of natural finishing materials and indoor air indicators are presented in Paper II, Paper III and Paper IV.

3.2.1 Hygrothermal conditions inside the boarders

In Paper IV the humidity load and mould growth index in boarders were in focus. In the boarders, higher relative humidity and temperature values than in indoor air were recorded but the likelihood that the conditions were suitable for mould growth was very low.

The average temperature in the boarders at 1.2m was the lowest (17.5±1.3 °C) in the straw-bale buildings in winter but in the reed-bale buildings in spring (15.6±1.5 °C). The highest average temperature was recorded at 1.2m in the boarders of the straw-bale (20.6±0.8 °C) and the reed-bale dwellings (19.3±1.1 °C) in summer. The temperature in the boarders of the straw-bale buildings at 1.2m was higher (17.3-20.6 °C) than in the reed-bale buildings (15.6-19.3 °C). The difference was much bigger at 0.2 m where the average air temperature in the straw-bale buildings varied from 14.4-19.2 °C respectively and in the reed-bale buildings from 7.3-16.3 °C respectively. At 0.2 m in the boarders the average temperature was the lowest in both the straw-bale and reed-bale dwellings in winter (14.4±2.4 °C and 7.3±2.5 °C respectively). The highest average temperature was recorded in summer when the temperature was 19.2±1.0 °C in the straw-bale dwellings and 16.3±1.6 °C in the reed-bale buildings.

The average RH% indicators at 1.2 m height in the boarders of the straw-bale and reed-bale buildings were the lowest in winter (33±12% and 33±14% respectively), and the highest in summer (53±7% in the straw-bale dwellings and 57±1% in the reed-bale buildings). For the most part the relative humidity indicators were similar – 33-53% and 33-57% respectively.

The average RH% at 0.2 m in the boarders was the lowest in winter (38±4% in the straw-bale dwellings and 45±6% in the reed-bale buildings respectively), the highest average values were recorded in summer (54±2% in the straw-bale dwellings, 58±1% in the reed-bale buildings). In the reed-bale buildings the relative humidity at 0.2 m was higher (42-58%) than in the straw-bale dwellings (38-54%).

3.2.2 The hygrothermal properties of natural finishing materials

In Paper II and Paper III the hygrothermal properties of natural finishing materials were studied. The results were registered after the 1, 2, 3, 6, 12 and 24 hours, and after a 24-hour-long stabilization period.

For clay plaster with different coverings the rate of moisture uptake at range 0-30% RH was the highest during the first hour (10.4-16.6 g/(m^{2}h) being 11-15% of total moisture content received by stabilization at 72 h. The rate of moisture uptake within the first hours was the highest for uncovered plaster (total moisture uptake within 3 hours 32.7 g/m^2) and the lowest for casein base coat (total moisture uptake within 3 hours 21.2 g/m^2). At that range relative humidity total uptake and moisture content were equal. The total absorbed moisture content at RH of 30% was from 105.0 to 111.3 g/m^2.

During the first hour at range 30-50% uncovered clay plaster, plaster with casein paint and cellulose paint coverings absorbed at the rate of 8.2-8.7 g/(m^{2}h) while plaster with casein base coat absorbed only 3.3 g/(m^{2}h). Within the first hour the amount of water vapour absorbed is 5.2-13.4% of the total uptake of range 30-50% (58.4-65.5 g/m^2).

For clay plaster made of different types of clays in sorption range from RH = 0-30% the rate of moisture uptake within the first hour was the highest for the plaster groups I, II, VI and VIII (Table 3). All the specimens contained red (I) or dark red 0-2 mm clay (VI) with some additions (cattail (III), hemp shives (VIII)). First group stabilized the fastest (48 hours), but for groups II, VI and VIII the stabilization time was 120 h. Group VII (White 0-2 mm) showed the lowest moisture uptake rate and it stabilized at 24 hours.

Rooms with high occupation and inadequate ventilation level can have the RH = 50-80%, but it is not common in a ventilated living room. During the first hour uncovered clay plaster, plaster with casein paint and cellulose paint coverings moisture absorbed with the rate of 14.9-15.7 g/(m^{2}h) while plaster lime paint and fine finishing with cellulose absorbed 11.5-12.0 g/(m^{2}h). The total moisture uptake within three hours was 23.5-31.1 g/m^2 lining up accordingly. Within the first hour the amount of water vapour absorbed was 6.9-9.0 % of the total uptake of range 50-80% (160.3-180.9 g/m^2.

In both ranges (30-50% and 50-80%) the most active was plaster group I (red 0-2 mm cattail) and the least active was group VII (white 0-2 mm).

Results from Paper II showed, that lime paint increased slightly the resistance of the plaster-coating system, but clay finishing mortar did not have significant influence on water vapour permeability.

Table 3. Sorption and desorption at RH = 30-50 %. Moisture uptake/release rate g/(m²h) and total moisture uptake/release g/m² (Paper III)

	Sorption				Desorption			
	1h	2h	3h	120h	1h	2h	3h	120h
	g/(m²h)	g/(m²h)/ g/m²	g/(m²h)/ g/m²	g/m²	g/(m²h)	g/(m²h)/ g/m²	g/(m²h)/ g/m²	g/m²
I	9.4	-1.2/8.2	4.1/12.3	45.3	-8.3	-6.3/- 14.5	-6.3/- 20.8	-53.3
II	4.7	0.5/5.2	1.6/6.8	63.1	-6.5	-4.4/- 10.9	-4.0/- 14.9	-71.3
III	7.8	3.3/11.1	1.2/12.3	147.8	-11.9	-7.0/- 18.9	-4.3/- 23.2	-148.2
IV	5.5	0.8/6.3	0.9/7.2	69.5	-6.6	-4.3/- 10.9	-2.8/- 13.7	-78.0
V	3.9	-0.3/3.6	1.9/5.5	55.7	-6.7	-4.8/- 11.5	-2.8/- 14.3	-65.1
VI	6.5	7.4/13.9	-0.8/13.1	164.8	-15.3	-6.8/- 22.1	-5.9/- 28.0	-165.1
VII	3.4	-1.2/2.2	0/2.2	8.1	-3.5	-2.3/-5.8	-1.9/-7.7	-13.7
VIII	7.4	4.3/11.7	0.8/12.5	164.1	-12.7	-6.3/- 19.0	-5.1/- 24.1	-161.6

3.2.3 Indoor air indicators

Indoor air indicators are reflected in Paper IV. During the whole studied period, the average level of carbon dioxide (Table 4) was the lowest in summer (607±26 ppm in the straw-bale buildings, 568±48 ppm in the reed-bale buildings). The highest average level of carbon dioxide in the straw-bale dwellings was in spring (636±26 ppm) and in the reed-bale dwellings in autumn (626±65 ppm).

Table 4. Indicators of average indoor climate (CO_2, relative humidity, temperature) in the bedrooms of the straw bale and reed-bale buildings shown as a mean with the standard error (±SE) (Paper IV).

	Winter		Spring		Summer		Autumn	
	Straw-bale	*Reed-bale*	*Straw-bale*	*Reed-bale*	*Straw-bale*	*Reed-bale*	*Straw-bale*	*Reed-bale*
CO_2 (ppm)	618± 28	574± 46	636± 26	573± 55	607± 26	568± 48	616± 27	626± 65
Tempe-rature (°C)	19.0± 0.5	19.0± 0.5	19.0± 0.4	19.3± 0.9	19.0± 1.3	20.6± 1.8	20.4± 0.6	20.7± 0.9
RH (%)	36±2	41±2	36±2	42±2	36±2	43±2	39±2	44±3

The average temperature remained between 19-21 °C in the bedrooms of the studied dwellings. The respective indicators were homogeneous remaining on average between 19.0-19.3 °C in both types of buildings in winter and spring. In summer the indoor temperature of the reed-bale dwellings was on average 1.6 °C higher than in the straw-bale buildings. The average temperature was the highest in both straw-bale (20.4±0.6 °C) and reed-bale buildings (20.7±0.9 °C) in autumn.

The average relative humidity remained between 36-44%, being the lowest in the straw-bale dwellings (36-39%) and higher in the bedrooms of the reed-bale buildings (41-44%). The humidity indicator in the reed-bale buildings was 41±2% in spring. In summer and autumn, the value was higher by 1% (42±2% and 43±2% respectively) compared to the value of the previous season.

3.3 Mould growth index and the internal moisture excess of the walls

In Paper IV mould growth index and the internal moisture excess of the walls was described. In the outdoor wall higher relative humidity and temperature values than in indoor air were recorded but the likelihood that the conditions were suitable for mould growth was very low. (Paper IV)

The internal moisture excess of the boarders was evaluated in winter and summer on the basis of one certain day. The internal moisture excess of the reed-bale buildings varied from 0.46 g m^{-3} to 3.42 g m^{-3} in summer and from 0.62 g m^{-3} to 2.73 g m^{-3} in winter. The internal moisture excess of the straw-bale buildings varied from 2.1 g m^{-3} to 1.99 g m^{-3} in summer and from 0.06 g m^{-3} to 1.43 g m^{-3} in winter. Internal moisture excess was negative at daytime when the residents were not in the dwelling.

3.4 Approach for the complex assessment of indoor air quality in straw-bale and reed-bale buildings

A complex assessment of indoor air quality in straw-bale and reed-bale buildings helped to develop an approach, which is described in Paper IV. In the study, indoor air quality was investigated comprehensively collecting simultaneously indoor climate parameters (air temperature, RH, CO_2) and microbiological data (the abundance of colony forming units and taxonomic composition) both in air and the material of the outer boarders (walls). In the interdisciplinary study the indoor climate of the straw-bale and reed-bale buildings was evaluated comprehensively using data loggers, air and material samplers. Two data loggers were placed approximately 20 cm deep in the boarder – one at 0.2 m from floor level to determine possible problems at joints (capillary rise, construction fault, possible air leaks) and the other at 1.2 m from the floor in the stable part of a wall.

Based on the data acquired with the data logger, and the collected air and material samples, it was found that the risk of mould growth in the straw-bale and reed-bale dwellings was low. It is necessary to stress the extraordinarily low temperature (7.3±2.5 °C) in the boarders at 0.2 m from the floor level in winter which referred to the inadequate density of the used reed bales. Because of the stack effect there was air infiltration at the lower joints and the humidity level was not high.

4 Discussion

During this study straw and reed were materials whose properties were studied (Paper I, Paper IV). Both materials use carbon dioxide for photosynthesis when they grow, and their use in construction is growing (Minke and Mahlke, 2005). As they are biodegradable materials, it is important to be informed about the microbial communities accompanying these materials and their possible effects on indoor air and building envelope when using them in construction.

Lawrence (2009) stated that microorganisms need humid environment and suitable temperature to survive. There were three mould genera (*Aspergillus, Penicillium* and *Cladosporium*) and two bacterial genera (*Streptomyces* and *Pseudomonas*) identified from fresh straw and reed. Uddin and Chakraverty (1996) and Larran et al. (2006) have reported members from genus *Penicillium* on plant surface. Wirsel et al. (2002) reported to have found four species from the genus *Cladosporium* from common reed plants. Both of these genera were identified from fresh straw and reed grown in Estonia (Raamets et al., 2016). Grant et al. (1989) and Gravesen et al. (1994) have found that the fungal species found in straw can be divided into three groups by their need for water. The genera *Penicillium* and *Aspergillus* belong to the primary colonizers, the genera *Cladosporium* and *Alternaria* are the secondary colonizers of materials. These four genera along with some other mould genera (*Fusarium*, *Helminthosporium*, *Mucor* and *Rhizopus*) are typical moulds in the cereals of Estonian origin (Lõiveke *et al*., 2008). Ilustrumm (2014) has pointed out that the same moulds are common colonizers in straw produced in Estonia.

Fungal contamination in indoor environments can cause adverse health effects for the inhabitants (Rogawansamy et al., 2015) and is therefore one of the leading causes of indoor air quality (IAQ) complaints in occupational settings (Bird et al., 2012). Four genera identified during our experiments are amongst the most common allergenic genera and these moulds have been associated with the symptoms of respiratory tract allergies (Dharmage et al., 2002). *Aspergillus* sp. and *Penicillium* sp. are known as significant indoor air allergens (Li et al., 1997).

Different indoor finishing materials can be used to regulate humidity levels in indoor climates (Rode et al., 2007). Earthen plasters have good mechanical behaviour and they are permeable to water vapour (Liblik and Just, 2016). It has been found by Lima and Faria (2016) that the addition of fibres has little influence on the moisture sorption and desorption properties of plasters. When the room RH falls below 50%, clay plaster begins to release moisture; if the humidity is higher than 50%, clay starts to absorb moisture. In addition to being a low-energy product compared to other forms of plaster, its application on the interior surface of the walls makes a major contribution to the safety and comfort of the occupants (Lima and Faria, 2016).

Clay has a relatively low equilibrium moisture content (0.4-6% by weight), and it absorbs the moisture of possible organic matter surrounded by wood or other clay and thus prevents damage to the materials by microorganisms or insects too (Minke and Mahlke, 2005). The balanced moisture content of wood is usually in the range of 8-12%, animal pests need 14-18% moisture for their activities, and microorganisms more than 20% moisture content (Minke and Mahlke, 2005).

Eight different clay-sand plaster mixtures were used for the tests describer in Paper II and Paper III. The base for four of them was red/dark red clay, which is the most used finishing plaster in the straw-bale and reed-bale dwellings in Estonia, four specimens were based on blue, grey and brown clay with the addition of cattail, white clay was used without the addition of fibres. Uncoated clay plaster adsorbs an average of 74% within 24 hours and an average of 93% within 48 hours of stabilized moisture at the time of stabilization. The humidity level RH 30-50% in reality corresponds to the humidity in living areas for people and the normal humidity level of the room. A sharp increase in humidity in area of 30-50% took 72 hours for the test specimens to stabilize. A sharp drop in humidity in the RH region of 50-30% took 96 hours for the specimens to stabilize. The humidity level RH 50-80% corresponds to wet room conditions. A sharp increase in humidity in RH 50-80% area took 120 hours for the test specimens to stabilize. It took 120 hours to abruptly lower the humidity in the RH region to stabilize 80-50% of the specimens. The curves based on the equilibrium humidity found during wetting and drying did not overlap - this indicates hysteresis that should not occur in raw clay bricks (Minke and Mahlke, 2005) and clay plaster (Maddison et al., 2008).

According to the results from Paper II and Paper III, the 2.4 cm thick layer of clay plaster contained a moisture content of 105.0-111.3 g/m^2 at 30% relative humidity. The sorption rate was more intense in the first hours. The sorption rate in the first hours can be influenced by the use of different finishing materials, but over time the rates will nevertheless converge and will not affect the equilibrium humidity. (Paper II, Paper III)

Within the sorption range RH=0-30% the moisture uptake within the first hour was the highest for 4 plaster groups, three of which contained added fibres. There was a statistical correlation between the moisture absorption and calcite content of clay plasters (87.1%). Calcite was present in the plaster mixtures in 4.2-8.6%, the exception was group VII, where no calcite was present.

Based on the data collected during these experiments, the best indicator of the effect of the coating is the rate of sorption in the first hours. Therefore the use of clay plaster in interior finishing did not provide sufficient protection against relative humidity fluctuations due to the incorrect construction of the building (deficiencies in the ventilation system), which resulted in that the interior air was constantly too humid or too dry. The use of clay plaster as a buffer material had the best effect on stabilizing diurnal and / or short-term humidity fluctuations.

In heated rooms where people spend longer periods of time the temperature has to be at least 18 °C offering warmth and creating and maintaining healthy indoor climate which meets the set requirements (Kalamees et al., 2011). The average air temperature of the studied buildings was between 19 and 21 °C during the test period meeting the EVS-EN 16789-1:2019 standard (ISO, 2019) indoor climate class III. In summer when the temperature and humidity levels in buildings are higher and if the unfavourable conditions appear, microbial growth may occur (Hukka and Viitanen, 1999; Johansson, et al., 2012). Mould does not damage the material directly, but its presence refers to high humidity level in the structure and possible risks (decomposition) (Lelumees, 2016).

In addition to suitable temperature, relative humidity and nutrients play a role in the growth of microorganisms (Rajasekar and Balasubramanian, 2011). Critical relative humidity from microbial growth standpoint is 75-95% depending on temperature and building material (Johansson et al., 2012). In their model characterising mould growth Hukka and Viitanen (1999) pinpoint the duration of environmental conditions which are necessary for microbiological growth to start. In the studied buildings the relative humidity was between 36% and 44% and the temperature between 19 °C and 21 °C. Carbon dioxide was measured during the whole study period and the results presented in Paper IV can be a base to conclude that level was in the desired range (≤800ppm (ISO, 2019)) belonging to indoor climate class II (≤800ppm) on the basis of ISO standard EVS-EN 16789-1:2019 (ISO, 2019) in all the studied bedrooms. The relative humidity and values of temperature indicators in the bedrooms of the studied houses were too low to promote mould growth. In the reed-bale buildings, the values of colony forming units (CFU) were higher than in the straw-bale buildings which could refer to possible microbial growth near the upper joint.

Yang (2010) found that a family with 2 adults without children excreted water on average 341 g/h and a family with 1-3 children 504-600 g/h. The annual measurements resulted in an average value of 300 g/h in a family without children and 490-600 g/h of water per family with 1-3 children (Tenwolde and Walker, 2001). Relative humidity influences the humidity regime of the building envelope and the indoor climate of the building (Kalamees et al., 2011). When internal humidity load is big, it may adversely affect indoor climate and cause humidity problems to the building envelope (Kalamees et al., 2010). The internal moisture excess in the studied buildings was relatively low: it was bigger in the reed-bale buildings (from 0.46 g m^{-3} to 3.42 g m^{-3} in summer and from 0.62 g m^{-3} to 2.73 g m^{-3} in winter) belonging to the II class on the basis of the standard EVS-EN ISO 13788 (ISO, 2012). Humidity in dwellings changes during the day depending on the intensity of use of the room and the purpose and it also changes according to the season (Yang, 2010). Considering internal moisture excess in the straw-bale dwellings, they belonged to the Ist class on the basis of the standard EVS-EN ISO 13788 (ISO, 2012). According to the results presented in Paper IV the internal moisture in the straw-bale dwellings was negative in winter when the residents were not at home.

In winter the average temperature at 0.2 m was only 7.3±2.5 °C in the reed-bale buildings which might refer to high relative humidity, but in the given situation it was only 41±2% on average. This might have been caused by possible low density of the building joints, and because of the stack effect cold air was infiltrated in this area. As measurements were carried out only at two heights (0.2 and 1.2 m) there might have been an outflow of air (warm, humid) from the upper joint because of the stack effect which could directly contribute to the occurrence of mould. The finding causes concern because the building envelope might be threatened by moisture and the reed-bale might be at the risk of microbial growth if suitable conditions occurred. The indoor air samples taken on Malt Extract Agar (MEA) and on dichlorane 18% agar (DG18) showed higher values during every season, as can be seen from Paper I and Paper IV, if compared to the samples taken from outside air.

For apartment buildings and small dwellings with a heated surface area of less than 120 m^2, the maximum CO_2 concentration above the ambient air concentration of 800 ppm is permitted according to the standard (ISO, 2019). By default, the standard states 550 ppm above the external concentration for category I, 800 ppm above the external concentration for category II, and 1350 ppm above the external concentration for category III. The standard separately sets out the calculated carbon dioxide concentration for bedrooms as well. For bedrooms in category I, the concentration can be up to 380 ppm above the external concentration, for category II 550 ppm above the external concentration and for category III 950 ppm above the external local concentration (ISO, 2019). The average content of CO_2 in all the studied bedrooms belonged to the indoor climate category II (≤800ppm) on the basis of the standard EVS-EN 16789-1:2019 (ISO, 2019).

Different countries have different standards for the permitted levels of the colony forming units, but there is no uniform international standard (Jyotshna and Helmut, 2011). A study by a WHO expert group found that the amount of colony forming units indoors should not exceed 1000 CFU/m^3 (Nevalainen and Morawska, 2009). In Estonia, there are no recommended limit values for moulds in the indoor environment (Pilt, 2017). Recommended limit values have been established in Finland and it is stated that the recommended values are up to 500 CFU/m^3 in winter and up to 2,500 CFU/m^3 in summer (Soumaa and Pekuri, 2009). For this study of colony forming units (CFU) in indoor air, which results are presented in Paper I and Paper IV, the average concentrations of indoor air colony forming units over the study period remained at 323±80 CFU/m^3 for the straw-bale dwellings and 576±94 CFU/m^3 for the reed-bale dwellings. The samples taken from one of the reed-walled dwellings in the summer of 2015 (1060±8 CFU/m^3) exceeded the recommended concentration (1000 CFU/m^3) given by the WHO expert group suitable for indoor conditions but were below the Finnish recommended limit values (up to 2500 CFU/m^3).

The concentration of colony forming units was higher in indoor air than in outdoor air during every season (Paper I, Paper IV). The mould families identified in the indoor air of the buildings did not differ from the mould families found in outdoor air (Paper I, Paper IV). In the boarders the concentrations were very low in the measured areas and their distribution to genera similar to the identified genera in indoor and outdoor air (Paper I, Paper IV). There were no significant differences in the mould distribution to genera and their percentage share (Paper I, Paper IV). Similar dynamics in indoor seasonal air sampling as in this study has been noted in previous studies on the indoor climate of buildings (Medrela-Kuder, 2003; Haas et al., 2007; Frankel et al., 2012).

5 Conclusions

- Moisture buffering properties of natural finishing materials were studied. Different clay-sand plasters were tested. Large differences in sorption properties depending on clay type and plaster recipes were followed. There was a clear positive correlation between the plaster mixture calcite content and the water vapour uptake. Therefore it can be concluded that the buffering ability of indoor finishing materials enables to smooth the peaks of indoor humidity. As inner surface (2.5 cm plaster) is able to deposit the moisture more than 300 g/m^2 at relative humidity of 80%, it enables to reduce the internal moisture excess and therefore internal humidity load on the boarders. When coverings (paints or other finishing) are chosen carefully the influence of them to plaster system could be minimal.

- Indoor air quality parameters (CO_2, RH%, and temperature) in air and at two different heights in the walls were measured. Internal moisture excess in the buildings was relatively low: it was bigger in the reed-bale buildings (from 0.46 g m^{-3} to 3.42 g m^{-3} in summer and from 0.62 g m^{-3} to 2.73 g m^{-3} in winter) belonging to the II class on the basis of the standard EVS-EN ISO 13788 (ISO, 2012). Considering internal moisture excess in the straw-bale buildings, they belonged to the I^{st} class on the basis of the standard EVS-EN ISO 13788 (ISO, 2012). The content of CO_2 in all the studied bedrooms belonged to the indoor climate class II (≥800ppm) on the basis of the standard EVS-EN 16789-1:2019 (ISO, 2019).

- Microbial species in air and walls of the studied straw-bale and reed-bale houses were determined. Microbial community inside the wall and indoors was similar to outdoor microbial community. Moulds belonging to four different genera were identified during the study (*Alternaria, Aspergillus, Penicillium, and Cladosporium*) in the bedrooms. Higher colony forming unit (CFU) values were registered in the reed-bale buildings during the study. In the straw-bale buildings the same values were lower. The study carried out revealed that the indoor air of the straw-bale and reed-bale buildings included more colonies than the outside air. No visual growth was detected during the study.

- The concentration of mould was higher in indoor air than in outdoor air during every season. The mould families identified in the indoor air of the buildings did not differ from the mould families found in outdoor air. In the boarders the concentrations were very low in the measured areas and their distribution to families similar to the identified families in indoor and outdoor air. There were no significant differences in the mould distribution to families and their percentage share.

- It was evaluated how the microbial community of indoor air and indoor climate indicators (CO_2, temperature, RH%, internal humidity load of the boarders, mould index) influence indoor air quality in the bedrooms of reed-bale and straw-bale houses according to the standard EVS-EN 16789-1:2019. Microbial community in indoor air had no effect on indoor air quality. According to Finnish limit values (winter – up to 500 CFU/m3, summer up to 2500 CFU/m^3) the studied indoor air in the buildings had good air quality. The average concentrations of CFUs during the study period remained at 323±80 CFU / m^3 for the straw-bale houses and at 576±94 CFU/m^3 for the reed-bale houses. In the studied buildings the relative humidity was between 36 and 44% and the temperature between 19 and 21 °C during the studied period meeting the EVS-EN 16789-1:2019 standard (ISO, 2019) indoor climate category III. The average content of CO_2 in all the studied bedrooms belonged to the indoor climate category II (≤800ppm) on the basis of the standard EVS-EN 16789-1:2019 (ISO, 2019).

- The current work was to evaluate through the studies of indoor climate and relevant construction materials the suitability of reed and straw-bale houses for temperate climate zone. No similar microbiological indoor air quality studies for reed-bale and straw-bale houses have been reported in the scientific literature. The results of this research clearly show that straw-bale and reed-bale houses are suitable in Estonian climatic conditions and are healthy and environmentally friendly buildings when expert planning, suitable materials, and quality craftsmanship are used.

References

Al-Jumeily, D., Hashim, K., Alkaddar, R., Al-Tufaily, M., Lunn, J. (2018). Sustainable and Environmental Friendly Ancient Reed Houses (Inspired by the Past to Motivate the Future). 2018 11th International Conference on Developments in Energy Systems Engineering. *(DeSE)*, Cambridge, United Kingdom, 2018, pp. 214–219. Doi: 10.1109/dese.2018.00032

Allen, P., May, N. (2003). Clay Plasters. Retrieved July 28, 2020, from http://www.buildingconservation.com/articles/clayplaster/clayplaster.htm

Altmäe, E., Ruus, A., Raamets J., Tungel, E. (2019). Determination of Clay-Sand Plaster Hygrothermal Performance: Influence of Different Types of Clays on Sorption and Water Vapour Permeability. In: Johansson D., Bagge H., Wahlström Å. (eds) Cold Climate HVAC 2018. CCC 2018. Springer Proceedings in Energy. Springer, Cham.

Arnolds, E. (1992) Macrofungal communities outside forests. In Winterhoff, W, (Ed.), *Fungi in Vegetation Science* (pp. 113–149). Dordrecht, NL: Kluwer Academic Publishers.

Arya, G., Singh, J. (2016). The Mathematical Isopleth Model For Fungi Growth In Building Material. *Journal of Drug Delivery and Therapeutics*, 6(4). Doi: 10.22270/jddt.v6i4.1258

Ashour, T., Georg, H., Wu, W. (2011). Performance of straw bale wall: A case of study. *Energy and Buildings, 43*(8), 1960–1967. Doi:10.1016/j.enbuild.2011.04.001

Asif, A., Zeeshan, M., Jahanzaib, M. (2018). Indoor temperature, relative humidity and CO_2 levels assessment in academic buildings with different heating, ventilation and air-conditioning systems. *Building and Environment*, 133, 83–90. Doi: 10.1016/j.buildenv.2018.01.042

Barreca, F., Gabarron, A.M., Yepes, J.A.F., Pérez, J.J.P. (2019). Innovative use of giant reed and cork residues for panels of buildings in Mediterranean area. *Resources, Conservation and Recycling*, 140, 259–266. Doi:10.1016/j.resconrec.2018.10.005

Batog, P., Badura, M. (2013). Dynamic of Changes in Carbon Dioxide Concentration in Bedrooms. Procedia Engineering, 57, 175–182. Doi:10.1016/j.proeng.2013.04.025

Beaudry, K., Macdougall, C. (2019). Structural performance of non-plastered modular straw bale wall panels under transverse and gravity loads. *Construction and Building Materials*, 216, 424–439. Doi:10.1016/j.conbuildmat.2019.04.186

Bergey, D., Holt, H. John G. (Ed.). (2000). Bergey's manual of determinative bacteriology. Philadelphia, PA: Lippincott Williams & Wilkins.

Bertoni, G., Ciuchini, C., Tappa, R. (2004). Measurement of long-term average carbon dioxide concentrations using passive diffusion sampling. *Atmospheric Environment*, 38(11), 1625–1630. Doi:10.1016/j.atmosenv.2003.12.010

Bird, C., Balshaw, S. Anderson, W. (2012). Getting the Best Answer by Asking the Right Question – Case Studies in Occupational Exposure to Mould. *Journal of Health & Safety Research & Practice*, 4(1), 19–27.

Bowden, V., Nyberg, D., Wright, C. (2019). Planning for the past: Local temporality and the construction of denial in climate change adaptation. *Global Environmental Change*, 57, 101939. Doi:10.1016/j.gloenvcha.2019.101939

Branco, P., Alvim-Ferraz, M., Martins, F., Sousa, S. (2015). Children's exposure to indoor air in urban nurseries-part I: CO2 and comfort assessment. *Environmental Research*, 140, 1-9. Doi:10.1016/j.envres.2015.03.007

Brischke, C., Hanske, M. (2016). Durability of untreated and thermally modified reed (*Phragmites australis*) against brown, white and soft rot causing fungi. *Indrustial Crops and Production*, 91, 49–55. Doi:10.1016/j.indcrop.2016.06.031

Brojan, L., Petric, A., Clouston, P.L. (2013). Comparative study of brick and straw bale wall systems from environmental, economic and energy perspectives. *ARPN Journal of Engineering and Applied Sciences*, 8, 980–926. Doi: 10.1016/j.applsci.2013.8.008

Brojan, L., Petric, A., Clouston, P.L. (2014). Advantages and disadvantages of straw-bale building. *AR: Arhitektura, Raziskave*, 15 (1), 21–26.

Bronsema, N.R. (2010). *Moisture Movement and Mould Management in Straw Bale Walls for a Cold Climate*. [Master´s thesis, University of Waterloo]. Institutional Repository at the University of Waterloo. https://uwspace.uwaterloo.ca/bitstream/handle/10012/5536/Bronsema_Nicholas.pdf

Canha, N., Lage, J., Coutinho, J.T., Alves, C., Almeida, S.M. (2019). Comparison of indoor air quality during sleep in smokers and non-smokers' bedrooms: A preliminary study. *Environmental Pollution*, 249, 248–256. Doi:10.1016/j.envpol.2019.03.021

Cascone, S., Rapisarda, R., Cascone, D. (2019). Physical Properties of Straw Bales as a Construction Material: A Review. *Sustainability*, 11(12), 3388. Doi: 10.3390/su11123388

Chaussinand, A., Scartezzini, J., Nik, V. (2015). Straw bale: A Waste from Agriculture, a New Construction Material for Sustainable Buildings. *Energy Procedia*, 78, 297–302. Doi:10.1016/j.egypro.2015.11.646

Chel, A., Kaushik, G. (2018). Renewable energy technologies for sustainable development of energy efficient building. *Alexandria Engineering Journal*, 57(2), 655–669. Doi:10.1016/j.aej.2017.02.027

Clarke, J., Johnstone, C., Kelly, N., Mclean, R., Anderson, J., Rowan, N., Smith, J. (1999). A technique for the prediction of the conditions leading to mould growth in buildings. *Building and Environment*, 34(4), 515–521. Doi:10.1016/s0360-1323(98)00023-7

Cornaro, C., Zanella, V., Robazza, P., Belloni, E., Buratti, C. (2020). An innovative straw bale wall package for sustainable buildings: experimental characterization, energy and environmental performance assessment. *Energy and Buildings*, 208, 109636. Doi:10.1016/j.enbuild.2019.109636

Costes, J.-P., Evrard, A., Biot, B., Keutgen, G., Daras, A., Dubois, S., Lebeau, F., Courard, L. (2017). Thermal Conductivity of Straw Bales: Full Size Measurements Considering the Direction of the Heat Flow. *Buildings*, 7(4), 11. Doi: 10.3390/buildings7010011

Curtis, L., Lieberman, A., Stark, M., Rea, W., Vetter, M. (2004). Adverse Health Effects of Indoor Molds. *Journal of Nutritional & Environmental Medicine*, 14(3), 261–274. Doi:10.1080/13590840400010318

D'Alessandro, F., Bianchi, F., Baldinelli, G., Rotili, A., Schiavoni, S. (2017). Straw bale constructions: Laboratory, in field and numerical assessment of energy and environmental performance. *Journal of Building Engineering*, 11, 56–68. Doi: 10.1016/j.jobe.2017.03.012

D'Orazio, M. (2012). Materials prone to mould growth. In: Torgal, F.P., Jalali, S., Fucic, A. (Ed.). *Toxicity of building materials* (pp. 334–350). Cambridge, UK: Woodhead Publishing.

Da Silva, C.F.F.P. Rana, C., Maskell, D., Dengel, A., Andsell, M.P., Ball, R.J. (2016). Influence of eco materials on indoor air quality. Green Materials, 4 (2), 72–80. Doi: 10.1680/jgrma.16.00002

Dettmering, T. (2019). Modernised Traditional Lime Plasters for Modern Historic Living of Built Heritage: Case Studies from Germany and Reflection for China. *Built Heritage* 3, 26–36. Doi:10.1186/BF03545733

Dharmage, S., Bailey, M., Raven, J., Abeyawickrama, K., Cao, D., Guest, D., Rolland, J., Forbes, A., Thien, F., Abramson, M., Walters, E.H. (2002). Mouldy houses influence symptoms of asthma among atopic individuals. Clinical & Experimental Allergy. 32:714–720. Doi:10.1046/j.1365-2222.2002.01371.x.

Doleman, L. (May 9, 2017). The Advantages and Appropriate Use of Light Straw Clay. *The Green Builder Media*. Retrieved July 27, 2020, from: https://www.greenbuildermedia.com/buildingscience/the-advantages-and-appropriate-use-of-light-straw-clay

Domsch, K.H., Gams, W., Anderson, T.H. (1980). Compendium of Soil Fungi, Vol. 1. London, UK: Academic Press.

Downtown, P. (2013). Your Home: Australia's guide to environmentally sustainable homes. Canberra: Commonwealth of Australia.

Drozd, W., Leśniak, A. (2018). Ecological Wall Systems as an Element of Sustainable Development—Cost Issues. *Sustainability*, 10(7), 2234. Doi:10.3390/su10072234

Dutil, Y., Rousse, D., & Quesada, G. (2011). Sustainable Buildings: An Ever Evolving Target. *Sustainability*, 3(2), 443–464. Doi:10.3390/su3020443

Ezennia, I.K., Alibaba, H.Z. (2017). A Systematic Review Of Thermal And Moisture Performance OF Straw-Bale Houses In Hot And Humid Climates. *International Journal of Scientific & Technology Research*, 6(1), 12–18.

Fernea, R., Manea, D.L., Tămaș-Gavrea, D.R., Roșca, I.C. (2019). Hemp-clay building materials - An investigation on acoustic, thermal and mechanical properties. *Procedia Manufacturing*, 32, 216–223. Doi:10.1016/j.promfg.2019.02.205

Ferreira, J.J., Fernandes, C.I., Ferreira, F.A. (2020). Technology transfer, climate change mitigation, and environmental patent impact on sustainability and economic growth: A comparison of European countries. *Technological Forecasting and Social Change*, 150, 119770. Doi:10.1016/j.techfore.2019.119770

Frankel, M., Bekö, G., Timm, M., Gustavsen, S., Hansen, E.W., & Madsen, A.M. (2012). Seasonal variations of indoor microbial exposures and their relation to temperature, relative humidity, and air exchange rate. Applied and Environmental Microbiology, 78(23), 8289–8297. Doi:10.1128/AEM.02069-12

Ginestet, S., Aschan-Leygonie, C., Bayeux, T., Keirsbulck, M. (2020). Mould in indoor environments: The role of heating, ventilation and fuel poverty. A French perspective. *Building and Environment*, *169*, 106577. Doi: 10.1016/j.buildenv.2019.106577

Gobakken, L.R., Høibø, O.A., Solheim, H. (2010). Factors influencing surface mould growth on wooden claddings exposed outdoors. *Wood Material Science & Engineering*, 5(1), 1–12. Doi:10.1080/17480270903511642

Goodhew, S., Griffiths, R. (2005). Sustainable earth walls to meet the building regulations. *Energy and Buildings*, 37(5), 451–459. Doi: 10.1016/j.enbuild.2004.08.005

Gradeci, K., Labonnote, N., Time, B., Köhler, J. (2017). Mould growth criteria and design avoidance approaches in wood-based materials – A systematic review. Construction and Building Materials, 150, 77–88. doi: 10.1016/j.conbuildmat.2017.05.204

Grant, C., Hunter, C., Flannigan, B., Bravery, A. (1989). The moisture requirements of moulds isolated from domestic dwellings. *International Biodeterioration*, 25(4), 259–284. Doi:10.1016/0265-3036(89)90002-x

Gravesen, S., Frisvad, J.C. and Samson, R.A. (1994) *Microfungi*. Copenhagen: Munksgaard.

Gupta, M.S. (2015). Straw bale construction a revolutionary building material in low cost housing for rural areas. *International Journal of Recent Advances in Multidisciplinary Research*, 2(7), 583–587.

Haas, D., Habib, J., Galler, H., Buzina, W., Schlacher, R., Marth, E., Reinthaler, F. (2007). Assessment of indoor air in Austrian apartments with and without visible mold growth. Atmosheric Environment, 41(25), 5192–5201. Doi: 10.1016/j.atmosenv.2006.07.062

Hammer, M. (2013, October 4). Straw Bale Residential Building Code. Retrieved July 28, 2020 from: http://www.strawbale.com/wp-content/uploads/IRC_StrawbaleConstructionAppendix_Approved_10.4.13r2.pdf

Hargreaves, M., Parappukkaran, S., Morawska, L., Hitchins, J., He, C., Gilbert, D. (2003). A pilot investigation into associations between indoor airborne fungal and non-biological particle concentrations in residential houses in Brisbane, Australia. *Science of The Total Environment,* 312(1-3), 89–101. doi:10.1016/s0048-9697(03)00169-4

Henderson, K. (2007). Achieving legitimacy: visual discourses in engineering design and green building code development. *Building Research & Information*, 35(1), 6–17. Doi:10.1080/09613210600979780

Hernberg, S., Sripaiboonkij, P., Quansah, R., Jaakkola, J.J., Jaakkola, M.S. (2014). Indoor molds and lung function in healthy adults. *Respiratory Medicine*, 108(5), 677–684. Doi:10.1016/j.rmed.2014.03.004

Holzhueter, K., Itonaga, K. (2010). The Hygrothermal Environment and Potential for Mold Growth within a Straw Bale Wall. *Journal of Asian Architecture and Building Engineering*, 9(2), 495–499. Doi:10.3130/jaabe.9.495

Hoorman, J. (2010). Understanding Soil Microbes and Nutrient Recycling, Retrieved July 27, 2020 from: https://ohioline.osu.edu/factsheet/SAG-16

Horr, Y.A., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A., Elsarrag, E. (2016). Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment*, 5(1), 1–11. Doi:10.1016/j.ijsbe.2016.03.006

Hoxha, D., Ungureanu, V.N., Belayachi, N., Do, D.P., Thevard, J.B. (2012). Hydromechanical Properties of some Mortars Used in some Ecologic Construction Techniques. *Advanced Materials Research,* 587, 6–10. Doi: 10.4028/www.scientific.net/amr.587.6

Hukka, A., Viitanen, H.A. (1999). A mathematical model of mould growth on wooden material. Wood *Science and Technology*, 33(6), 475–485. Doi: 10.1007/s002260050131

Hurlimann, A.C., Warren-Myers, G., Browne, G.R. (2019). Is the Australian construction industry prepared for climate change? *Building and Environment*, 153, 128–137. Doi:10.1016/j.buildenv.2019.02.008

Hurrass, J., Heinzow, B., Aurbach, U., Bergmann, K-C., Bufe, A., Buzina, W., Cornely, O.A., Engelhart, S., Fischer, G., Gabrio, T., Heinz, W., Herr, C.E.W., Kleine-Tebbe, J., Klimek, L., Köberle, M., Lichtnecker, H., Lob-Cozilius, T., Merget, R., Müööeneisen, N., Nowak, D., Rabe, U., Raulf, M., Seidl, H.P., Steiss, J-O., Szewzyk, R., Thomas, P., Valtanen, K., Wiesmüller, G.A. (2017). Medical diagnostics for indoor mold exposure. International Journal of Hygiene and Environmental Health, 220 (2), 305–328.

Häkkinen, J. (2007) Traditional use of reed. In: Ikonen, I. & Hagelberg, E. (eds.) Read Up On Reed. Southwest Finland Regional Environment Centre, Turku, Finland, 62–72.

Iacovidou, E., Purnell, P. (2016). Mining the physical infrastructure: Opportunities, barriers and interventions in promoting structural components reuse. *Science of The Total Environment*, 557-558, 791–807. Doi:10.1016/j.scitotenv.2016.03.098

Ilustrumm, K. (2014). *Ökoehituses kasutatavate põhuplokkide steriliseerimisvõimalused seenorganismide vastu.* [Master's thesis, Tallinn University of Technology]. Digital Collection of TalTech Library. https://digikogu.taltech.ee/en/Download/f14d5d1f-d107-454a-80b4-37e56eee16be

International Organisation for Standardization. (2005). Methods of test for mortar for masonry - Part 19: Determination of water vapour permeability of hardened rendering and plastering mortars (ISO Standard No. 1015-19). Retrieved from https://www.evs.ee/en/evs-en-1015-19-2005

International Organisation for Standardization. (2008). Indoor air. Detection and enumeration of moulds — Culture-based method (ISO Standard No. 16000-17). Retrieved from https://www.iso.org/standard/41215.html

International Organisation for Standardization. (2009). Methods of test for mortar for masonry - Part 3: Determination of consistence of fresh mortar (by flow table) (ISO Standard No. 1015-3:2004+A2:2007). Retrieved from https://www.evs.ee/en/evs-en-1015-3-2004+a2-2007

International Organisation for Standardization. (2011). Detection and enumeration of moulds -- Sampling by impaction (ISO Standard No. 16000-18). Retrieved from https://www.iso.org/standard/44325.html

International Organisation for Standardization. (2012). Hygrothermal performance of building components and building elements — Internal surface temperature to avoid critical surface humidity and interstitial condensation — Calculation methods (ISO Standard No. ISO 13788). Retrieved from https://www.iso.org/standard/51615.html

International Organisation for Standardization. (2013). Hygrothermal performance of building materials and products - Determination of hygroscopic sorption properties (ISO Standard No. ISO 12571). Retrieved from https://www.evs.ee/et/evs-en-iso-12571-2013

International Organisation for Standardization. (2019). Hoonete energiatõhusus. Hoonete ventilatsioon. Osa 1: Sisekeskkonna lähteandmed hoonete energiatõhususe projekteerimiseks ja hindamiseks, lähtudes siseõhu kvaliteedist, soojuslikust keskkonnast, valgustusest ja akustikast (ISO Standard No. 16798-1). Retrieved from https://www.evs.ee/et/evs-en-16798-1-2019

IPCS. (2006). Carbon Dioxide. International Chemical Safety Cards 0021, International Programme on Chemical Safety, World Health Organization, Geneva.

Itse, B. (2012, June 30). Põhumaja saab ellipsi kuju. *Järva Teataja*. Retrieved from: https://jarvateataja.postimees.ee/892870/pohumaja-saab-ellipsi-kuju

Itse, B. (2018, March 26). Huvi põhumajade vastu püsib suurena. *Järva Teataja*. Retrieved from: https://jarvateataja.postimees.ee/4450613/huvi-pohumajade-vastu-pusib-suurena

Jaakkola, M.S., Jaakkola, J.J. (2004). Indoor Molds and Asthma in Adults. Advances in Applied Microbiology, 309–338. Doi:10.1016/s0065-2164(04)55012-8

Johansson, P., A. Ekstrand-Tobin, T. Svensson., G. Bok. (2012). Laboratory Study to Determine the Critical Moisture Level for Mould Growth on Building Materials. International Biodeterioration & Biodegradation, 73: 23–32. Doi:10.1016/j.ibiod.2012.05.014.

Kalamees, T., Alev, Ü., Arumägi, E., Ilomets, S., Just, A., Kallavus, U. (2011). Maaelamute sisekliima, ehitusfüüsika ja energisääst I. Retrieved 28. July, 2020 from: https://kredex.ee/sites/default/files/2019-03/Maaelamute%20sisekliima,%20ehitusf%c3%bc%c3%bcsika%20ja%20energias%c3%a4%c3%a4st.pdf.

Kalamees, T., Kõiv, T-A., Liias, R., Õiger, K., Kallavus, U., Mikli, L., Ilomets, S., Kuusk, K., Maivel, M., Mikola, A., Klõśeiko, P., Agasild, T., Arumägi, E., Liho, E., Ojang, T., Tuisk. T., Raado, L-M., Jõesaar, T. (2010). Eesti eluasemefondi telliskorterelamute ehitustehniline seisukord ning prognoositav eluiga. Retrieved 28. July, 2020 from: https://www.mkm.ee/sites/default/files/ suurpaneelelamute_uuringu_loppraport_trukk.pdf.

Karakosta, C., Doukas, H., Psarras, J. (2010). Technology transfer through climate change: Setting a sustainable energy pattern. *Renewable and Sustainable Energy Reviews*, 14(6), 1546–1557. Doi:10.1016/j.rser.2010.02.001

Katsoyiannis, A., Cincinelli, A. (2019). 'Coctails and dreams': the indoor air quality that people are exposed to while sleeping. *Journal of Environmental Science Health*, 8, 6–9. Doi:10.1016/j.coesh.2018.12.005

Khan, H., Karuppayil, S.M. (2012). Fungal pollution of indoor environments and its management. *Saudi journal of biological sciences.* 19. 405–426. Doi:10.1016/j.sjbs.2012.06.002.

Khoshnava, S.M., Rostami, R., Zin, R.M., Steimikiene, D., Mardani, A., Ismail, M. (2020). The Role of Green Building Materials in Reducing Environmental and Human Health Impacts. *International Journal of Environmental Research and Public Health.*17(7), 2589. Doi:10.3390/ijerph17072589

King, B. (2003). Load bearing straw bale construction: a summary of worldwide testing and experience. Ecological Building Network (EBnet). Retrieved from: https://www.ecobuildnetwork.org/images/straw_bale_papers/Load-Bearing_SB_Construction_King_2003.pdf

King, B., Aschheim, M. (2007). *Design of straw bale buildings: the state of the art*. San Rafael, CA: Green Building Press.

Kivi, K. (2008, March 13). Hallitus hävitab kipsmajad. *Eesti Ekspress.* Retrieved from: https://ekspress.delfi.ee/kuum/hallitus-havitab-kipsmajad?id=27675709

Kivi, K (2015, July 31). Lahemaal valmib esimene põhust ridaelamu. *Maaleht*. Retrieved from: https://maaleht.delfi.ee/arhiiv/lahemaal-valmib-esimene-pohust-ridaelamu?id=72036067&url=%2Fnews%2Feestielu%2Farhiiv%2Farticle.php

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., Haberl, H. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences,* 114(8), 1880–1885. Doi: 10.1073/pnas.1613773114

Krueger, J.M., Frank, M.G., Wisor, J.P., Roy, S. (2016). Sleep function: Towards elucidating an enigma. *Sleep Medicine Reviews, 28*, 46–54. Doi: 10.1016/j.smrv.2015.08.005

Krus, M, Kilian, R, Sedlbauer, K. (2007). Mould growth prediction by computational simulation on historical buildings. In: Padfield, T, Borchersen, K (Ed.), *Museum Microclimates* (pp.185–189). Copenhagen, DK: The National Museum of Denmark.

Kubba, S. (2012). Green Building Materials and Products. In: Jardim, P (Ed.), *Handbook of Green Building Design and* Construction (pp. 227–311). Boston: Butterworth-Heinemann.

Köbbing, J., Thevs, N., Zerbe, S. (2013). The utilisation of Reed (*Phragmites australis*) – a review. *Mires and Peat*. 13. 1–14.

Laborel-Préneron, A., Magniont, C., Aubert, J.-E. (2018). Characterization of Barley Straw, hemp shiv and corn cob as resources for bioaggregate based building materials. *Waste Biomass Valorization,* 9, 1095–1112. Doi:10.1007/s12649-017-9895-z.

Lacinski, P., Bergeron, M. (2004). *Serious Straw Bale A Home Construction Guide for All Climates.* White River Junction, VT: Chelsea Green Publishing.

Larone, D.H. (2002). Medically Important Fungi, A Guide to Identification, fourth edition., American Society for Microbiology, WA: ASM Press.

Larran, S., Perelló, A., Simón, M.R., Moreno, V. (2006). The endophytic fungi from wheat (*Triticum aestivum L.*). *World Journal of Microbiology and Biotechnology,* 23(4), 565–572. Doi:10.1007/s11274-006-9266-6

Lawrence, M., Heath, A., Walker, P. (2009). Determining moisture levels in straw bale construction. *Construction and Building Materials*, 23(8), 2763–2768. Doi: 10.1016/j.conbuildmat.2009.03.011

Legard, D., Mcquilken, M., Whipps, J., Fenlon, J., Fermor, T., Thompson, I., Lynch, J. (1994). Studies of seasonal changes in the microbial populations on the phyllosphere of spring wheat as a prelude to the release of a genetically modified microorganism. *Agriculture, Ecosystems & Environment*, *50*(2), 87–101. Doi:10.1016/0167-8809(94)90128-7

Lelumees, M. (2016). *Ehitusniiskuse mõju lisasoojustamise moodulelementide niiskustehnilisele toimivusele* [Master´s thesis, Tallinn University of Technology]. Estonian Wooden Houses Cluster. http://woodhouse.ee/static/07_Magnus_Lelumees_l%C3%B5put%C3%B6%C3%B6.pdf

Li, C.S., Hsu, C.W., Tai M.L. (1997). Indoor pollution and sick building syndrome symptoms among workers in day-care centers. Archives of Environmental Health: *An International Journal*. 52 (3), 200–207. Doi:10.1080/00039899709602887

Liao, C., Luo, W., Chen, S., Chen, J., Liang, H. (2004). Temporal/seasonal variations of size-dependent airborne fungi indoor/outdoor relationships for a wind-induced naturally ventilated airspace. *Atmospheric Environment*, 38(26), 4415–4419. Doi:10.1016/j.atmosenv.2004.04.029

Liblik, J., Just, A. (2016). Performance of Constructions with Clay Plaster and Timber at Elevated Temperatures. *Energy Procedia*, 96, 717–728. Doi:10.1016/j.egypro.2016.09.133

Lima, J., Faria, P. (2016). Eco-Efficient Earthen Plasters: The Influence of the Addition of Natural Fibers. *RILEM Bookseries Natural Fibres: Advances in Science and Technology Towards Industrial Applications*, 315–327. Doi:10.1007/978-94-017-7515-1_24

Liuzzi, S., Rubino, C., Martellotta, F., Stefanizzi, P., Casavola, C., Pappalettera, G. (2020). Characterization of biomass-based materials for building applications: The case of straw and olive tree waste. Industrial Crops and Products, 147, 112229. Doi: 10.1016/j.indcrop.2020.112229

Lõiveke, H. (2008, October 25). Hallitusseened ja mükotoksiinid teraviljas. *Ajaleht Nädaline eriväljaanne Talu Leht.* Retrieved from: https://dea.digar.ee/cgi-bin/dea?a=d&d=nadaline20081025.1.9

Lõiveke, H., Ilumäe, E., Akk, E. (2008). Teravilja mikrobioloogiast ja ohutusest. Agraarteadus, XIX, 2, 38–45.

Lymath, A. (2016, June 15). Guide to straw bale construction. Retrieved July 28, 2020, from https://www.thenbs.com/knowledge/guide-to-straw-bale-construction

Maddison, M., Mauring, T., Kirsimäe, K., Mander,M. (2010). The humidity buffer capacity of clay-sand plaster filled with phythomass from treatment wetland. *Building and Enviroment*, 44, 1864–1868. Doi:10.1016/j.buildenv.2008.12.008

Magwood, C. (2004) Straw Bale Building, On the Cusp of the Mainstream. Retrieved July 28, 2020, from http://www.homepower.com/files/HP101 14.pdf

Marks, L.R. (2005). *Straw-bale as a viable, cost effective, and sustainable building material for use in southeast Ohio* (Document No. ohiou1125775864) [Master´s thesis, Ohio State University]. OhioLINK Electronic Theses & Dissertations Center.

Marques, B., Tadeu, A., Almeida, J., António, J., Brito, J.D. (2020). Characterisation of sustainable building walls made from rice straw bales. *Journal of Building Engineering*, 28, 101041. Doi:10.1016/j.jobe.2019.101041

Marschner, P., Umar, S., Baumann, K. (2011). The microbial community composition changes rapidly in the early stages of decomposition of wheat residue*. Soil Biology and Biochemistry*, 43(2), 445–451. Doi:10.1016/j.soilbio.2010.11.015

Maskell, D., Thomson, A., Walker, P., Lemke, M. (2018). Determination of optimal plaster thickness for moisture buffering of indoor air. *Building and Environment*, *130*, 143–150. Doi:10.1016/j.buildenv.2017.11.045

Medrela-Kuder, E. (2003). Seasonal variations in the occurrence of culturable airborne fungi in outdoor and indoor air in Craców. *International Biodeterioration & Biodegradation,* 52(4), 203–205. Doi:10.1016/s0964-8305(02)00167-1

Mendell, M.J. (2007). Indoor residential chemical emissions as risk factors for respiratory and allergic effects in children: A review*. Indoor Air*, 17(4), 259–277. Doi:10.1111/j.1600-0668.2007.00478.x

Milutiene, E., Staniškis, J.K., Kručius, A., Augulienė, V., Ardickas, D. (2012). Increase in buildings sustainability by using renewable materials and energy. *Clean Technologies and Environmental Policy*, 14(6), 1075–1084. Doi: 10.1007/s10098-012-0505-2

Minke, G. (2013). *Building with Earth*. Basel: Birkhäuser Verlag AG.

Minke, G., Mahlke, F. (2005). *Building with straw: design and technology of a sustainable architecture*. Basel, DE: Birkhäuser.

Moon, H.J. (2005). *Assessing mold risk in buildings uncertainty*. [Doctoral dissertation, Georgia Institute of Technology]. Georgia Tech Theses and Dissertations Repository. https://smartech.gatech.edu/bitstream/handle/1853/7279/moon_hyeun_j_200508_phd.pdf?sequence=1&isAllowed=y

Moon, H., Augenbroe, G. (2004). Towards a practical mould growth risk indicator. *Building Services Engineering Research and Technology*, 25(4), 317–326. Doi:10.1191/0143624404bt101oa

Nielsen, K., Holm, G., Uttrup, L., Nielsen, P. (2004). Mould growth on building materials under low water activities. Influence of humidity and temperature on fungal growth and secondary metabolism. *International Biodeterioration & Biodegradation*, 54(4), 325–336. Doi:10.1016/j.ibiod.2004.05.002

Niroumand, H., Zain, M., Jamil, M. (2013). The Role of Nanotechnology in Rammed Earth Walls and Earth Buildings. *Procedia - Social and Behavioral Sciences*, 89, 243–247. Doi:10.1016/j.sbspro.2013.08.842

Nwakanma, C., Unachukwu, M. (2017). Molds. In: Bevilacqua, A., Corbo, M.A., Sinigaglia, M. (Ed.), *The Microbiological Quality of Food* (pp. 133–148). Duxford, UK: Woodhead Publishing.

Ojanen, T., Viitanen, H. (2016, December 4). VTT mold model – Equations, parameters, performance criteria. Retrieved July 28, 2020 from: https://web.ornl.gov/sci/buildings/2016/docs/presentations/workshops/workshop-5/Workshop5_OjanenViitanen_Eqs.pdf

Ojanen, T; Viitanen, H; Peuhkuri, R; Lähdesmäki, K; Vinha, J; Salminen, K. (2010). Mould growth modeling of building structures using sensitivity classes of materials. Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference; (Buildingx XI), December 5-9, 2010, Clearwater Beach, Florida. Proceedings of Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference (CD). DOE, BETEC, ASHRAE, Oak Ridge National Laboratory (ORNL) (2010), 10 p.

Paist, A., Kask, Ü., Kask, L., Vrager, A., Muiste, P., Padari, A., Pärn, L. (2005). Potential of biomass fuels to substitute for oil shale in energy balance in Estonian energy sector. *Oil Shale*, 22, 369–379.

Pasanen, A.-L., Niininen, M., Kalliokoski, P., Nevalainen, A., Jantunen, M. (1992). Airborne Cladosporium and other fungi in damp versus reference residences. Atmospheric Environment. Part B. *Urban Atmosphere*, 26(1), 121–124. Doi:10.1016/0957-1272(92)90044-s

Pasanen, A.-L., Pasanen, J.-P., Rautiala, S., Ikäheimo, M., Rantamäki, J., Kääriäinen, H., Kalliokoski, P. (2000). Fungal growth and survival in building materials under fluctuating moisture and temperature conditions. *International Biodeterioration & Biodegradation*, *46*(2), 117–127. Doi:10.1016/s0964-8305(00)00093-7

Pata, A. (2016). *Põhupakkseinte sobivus passiivmaja välispiireteks Eesti kliimas* [Barchelor's thesis, University of Tartu]. The University of Tartu digital archive. https://dspace.ut.ee/bitstream/handle/10062/53582/pata_artur.pdf?sequence=1&isAllowed=y

Paterson, E., Osler, G., Dawson, L.A., Gebbing, T., Sim, A., Ord, B. (2008). Labile and recalcitrant plant fractions are utilised by distinct microbial communities in soil: Independent of the presence of roots and mycorrhizal fungi. *Soil Biology and Biochemistry*, *40*(5), 1103–1113. Doi:10.1016/j.soilbio.2007.12.003

Pilt, K. (2017). Hallitusseened meie ümber. *Pööning*, 3 (8), 81–85.

Pomponi, F., Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment – What does the evidence say? *Journal of Environmental Management*, 181, 687–700. Doi:10.1016/j.jenvman.2016.08.036

Portnoy, J.M., Kwak, K., Dowling, P., Vanosdol, T., Barnes, C. (2005). Health effects of indoor fungi. *Annals of Allergy, Asthma & Immunology*, 94(3), 313–320. Doi: 10.1016/s1081-1206(10)60982-9

Raamets, J., Kutti, S., Ruus, A., Ivask, M. (2017). Assessment of indoor air in Estonian straw bale and reed houses. *WIT Transactions on Ecology and the Environment*, 211, 193−196. Doi:10.2495/AIR170191

Raamets, J., Kutti, S., Vettik, A., Ilustrumm, K., Rist, T., Ivask, M. (2016). The antimicrobial effect of three different chemicals for the treatment of straw bales used in housing projects. *Sustainable Housing 2016. Proceedings of the International Conference on Sustainable Housing Planning, Management and Usability*: Sustainable Housing 2016, Porto, Portugal 16-18.11.2016. Ed. R. Amoêda, C. Pinheiro. Green Lines Institute for Sustainable Development, 537−545.

Raamets, J., Ruus, A., Ivask, M., Nei, L., Muoni, K. (2020). Siseõhu kvaliteet põhu- ja pilliroopakkidest seintega elumajades. *Agraarteadus*, 31(1), 84–95. Doi: 10.15159/jas.20.05

Rahman, M.M., Flory, E., Koyro, H.-W., Abideen, Z., Schikora, A., Suarez, C., Cardinale, M. (2018). Consistent associations with beneficial bacteria in the seed endosphere of barley (*Hordeum vulgare L.). Systematic and Applied Microbiology,* 41(4), 386–398. Doi:10.1016/j.syapm.2018.02.003

Rajasekar, A., Balasubramanian, R. (2011). Asessment of airborne bacteria and fungi in food courts. Building and Environment, 46(10), 2081–2087. Doi: 10.1016/j.buildenv.2011.04.021

Ramos, N.M.M., Delgado, J.M.P.Q., da Freitas, V.P. (2010). Influence of finishing coatings on hygroscopic moisture buffering in building elements. Construction and Building Materials, 24, 2590–2597. Doi:10.1016/j.conbuildmat.2010.05.017

Reis, C., Mestre, C., Canhão, H., Gradwell, D., Paiva, T. (2016). Sleep complaints and fatigue of airline pilots. *Sleep Science, 9*(2), 73–77. Doi:10.1016/j.slsci.2016.05.003

Rode, C., Peuhkuri, R., Time, B., Svennberg, K., Ojanen, T. (2007). Moisture Buffer Value of Building Materials. Journal of ASTM International, 4(5), 1–12. Doi: 10.1520/JAI100369

Rogawansamy, S., Gaskin, S., Taylor, M., Pisaniello, D. (2015). An Evaluation of Antifungal Agents for the Treatment of Fungal Contamination in Indoor Air Environments. *International Journal of Environmental Research and Public Health, 12*(6), 6319–6332. Doi:10.3390/ijerph120606319

Rowan, N.J., Johnstone, C.M., Mclean, R.C., Anderson, J.G., Clarke, J.A. (1999). Prediction of Toxigenic Fungal Growth in Buildings by Using a Novel Modelling System. *Applied and Environmental Microbiology*, 65(11), 4814–4821. Doi: 10.1128/aem.65.11.4814-4821.1999

Ruppert, J. (2013, October 5). Feuillette House. Retrieved July 28, 2020 from: https://thelaststraw.org/feuillette-house/

Samson, R.A., Hoeckstra, E.S., Frisvad, J.C., Filtenborg, O. (1996). Introduction to Food-Borne Fungi, fifth ed. Centraalbureau voor Schimmelcultures Baarn. Wageningen, NL: Ponsen & Looyen.

Sedlbauer, K. (2001). *Vorhersage von Schimmelpilzbildung auf und in Bauteilen* (Doctoral dissertation University of Stuttgart]. Publikationsdatenbank der Fraunhofer-Gesellschaft. http://publica.fraunhofer.de/eprints/urn_nbn_de_0011-b-784954.pdf

Sedlbauer, K. (2002). Prediction of mould growth by hygrothermal calculation. *Journal of Building Physics*, 23, 321–336. Doi:10.1177/0075424202025004093

Sharma, V., Banair, J.S., Kundu, P.P. (2010). Water Sorption and Diffusion Through Linseed Oil Based Polymers and Nano-Composites. *International Journal of Transport Phenomena,* 11, 267–282.

Shon, C.-S., Mukashev, T., Lee, D., Zhang, D., Kim, J. (2019). Can Common Reed Fiber Become an Effective Construction Material? Physical, Mechanical, and Thermal Properties of Mortar Mixture Containing Common Reed Fiber. *Sustainability*, 11(3), 903. Doi:10.3390/su11030903

Sinisalu, R., Kleesment, A. (2002). Purdsetete granulomeetrilisest klassifikatsioonist. Eesti Geoloogiakeskuse Toimetised. 10/1, lk 20–26.

Soumaa, L., Pekuri, H.-M. (2009). Kosteusvauriot työpaikoilla. Retrieved from: https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/72110/URN%3ANBN%3Afi-fe201504224254.pdf?sequence=1

Steen, A.S., Steen, B, Bainbridge, D., Eisenberg, D. (1994). The Straw Bale. House. Vermont, USA: Chelsea Green Publishing Company.

Stenman, H. (2008). *Reed construction in the Baltic Sea Region*. Turku, FIN: Turku University of Applied Sciences.

Strøm-Tejsen, P., Zukowska, D., Wargocki, P., Wyon, D.P. (2015). The effects of bedroom air quality on sleep and next-day performance. *Indoor Air,* 26(5), 679–686. Doi: 10.1111/ina.12254

Summers, M.D., Blunk S.L., Jenkins B.M. (2003). How Straw Decomposes, [Web page]. Retrieved July 28, 2020 from: https://osbbc.memberlodge.org/Resources/Documents/Technical/how_straw_decomposes.pdf

Svennberg, K. (2006). *Moisture Buffering in the Indoor Environment*. [Doctoral dissertation, Lund University]. Lund University Publications. https://lup.lub.lu.se/search/ws/files/4748178/546684.pdf

Zamolyi, F., Herbig, U. (2010). Reed as building material – renaissance of vernacular techniques, In: Csaplovics, E., Schmidt, J. (Ed.) *International Symposium on advanced methods of monitoring reed habitats* (pp. 83.108). Berlin, DE: Rombos Verlag.

Tenwolde, A., Walker, I.S. (2001). Interior moisture design loads for residences. In Proceedings Thermal Performance of Exterior Envelopes of Buildings VIII; ASHRAE: Atlanta, GA, USA

Theis, B. (July 30, 2003). Straw Bale Fire Safety. Retrieved July 28, 2020 from: https://tallerconco.org/wp-content/uploads/2017/05/Fire_safety.pdf

Thomson, A., Walker, P. (2014). Durability characteristics of straw bales in building envelopes. Construction and Building Materials, 68, 135–141. Doi: 10.1016/j.conbuildmat.2014.06.041

Tian, P., Razavi, B.S., Zhang, X., Wang, Q., Blagodatskaya, E. (2020). Microbial growth and enzyme kinetics in rhizosphere hotspots are modulated by soil organics and nutrient availability. *Soil Biology and Biochemistry*, 141, 107662. Doi: 10.1016/j.soilbio.2019.107662

Torvinen,E., Meklin, T., Torkko, P., Soumalainen, S., Reiman, M., Katila, M.-L., Paulin, L., Nevalainen, A. (2006). Mycobacteria and fungi in moisture-damaged building materials. *Applied and Environmental Microbiology*, 72, 6822–6824. Doi: 10.1128/AEM.00588-06

Tran, V.V., Park, D., Lee, Y. (2020). Indoor Air Pollution, Related Human Diseases, and Recent Trends in the Control and Improvement of Indoor Air Quality. *International Journal of Environmental Research and Public Health*, 17(8), 2927. Doi:10.3390/ijerph17082927

Uddin, N., Chakraverty, R. (1996). Pathogenic and non-pathogenic mycoflora in the air and phylloplane of *Triticum aestivum L*. *Aerobiologia*, 12(4), 257–268. doi: 10.1007/bf02446283

Vares, O., Ruus, A., Raamets, J., Tungel, E. (2017). Determination of hygrothermal performance of clay-sand plaster: influence of covering on sorption and water vapour permeability. *Energy Procedia*, 132, 267−272. Doi: 10.1016/j.egypro.2017.09.719

Veenre, T. (2011, May 14). Kuidas põhust ja fantaasiast kantud utoopiad tõelisuseks saavad? *Eesti Päevaleht*. Retrieved July 28, 2020 from: https://epl.delfi.ee/kultuur/kuidas-pohust-ja-fantaasiast-kantud-utoopiad-toelisuseks-saavad?id=51297094

Vereecken, E., Roels, S. (2012). Review of mould prediction models and their influence on mould risk evaluation. *Building and Environment*, 51, 296–310. Doi: 10.1016/j.buildenv.2011.11.003

Verdier, T., Coutand, M., Bertron, A., Roques, C. (2014). A review of indoor microbial growth across building materials and sampling and analysis methods. *Building and Environment*, 80, 136–149. Doi:10.1016/j.buildenv.2014.05.030

Viitanen, H. (1994). Factors affecting the development of biodeterioration in wooden constructions. *Materials and Structures*, 27(8), 483–493. Doi: 10.1007/bf02473453

Viitanen, H, Ojanen, T, Peuhkuri, R. (2011). Mould growth modelling to evaluate durability of materials. In: de Freitas, V.P., Corvacho, H (Ed.) *XII international conference on durability of building materials and components* (pp. 409–416), Porto, Portugal, 12–15 April, FEUP Edicoes.

Viitanen, H., Vinha, J., Salminen, K., Ojanen, T., Peuhkuri, R., Paajanen, L., Lähdesmäki, K. (2009). Moisture and Bio-deterioration Risk of Building Materials and Structures. *Journal of Building Physics*, 33(3), 201–224. Doi: 10.1177/1744259109343511

Viitanen, H., Krus, M., Ojanen, T., Eitner, V., Zirkelbach, D. (2015). Mold Risk Classification Based on Comparative Evaluation of Two Established Growth Models. *Energy Procedia,* 78, 1425–1430. Doi:10.1016/j.egypro.2015.11.165

Wall, K., Walker, P., Gross, C., White, C., Mander, T. (2012). Development and testing of a prototype straw bale house. *Construction Materials*, 165, 377–384. Doi: 10.1680/coma.11.00003

Wanek, C. (2003). The New Strawbale Home. Layton, UT: Gibbs Smith.

Watanabe, T. (2010). Identification of Fungi from: Pictorial Atlas of Soil and Seed Fungi, Morphologies of Cultured Fungi and Key to Species. Boca Raton, FL: CRC Press.

Williams, L.B., Metge, D.W., Eberl, D.D., Harvey, R.W., Turner, A.G., Prapaipong, P., & Poret-Peterson, A.T. (2011). What Makes a Natural Clay Antibacterial? *Environmental Science & Technology*, 45(8), 3768–3773. Doi: 10.1021/es1040688

Winn, W.C., Koneman, E.W. (2006). Koneman's color atlas and textbook of diagnostic microbiology (6th ed.). Philadelphia, PA: Lippincott Williams & Wilkins.

Wirsel, S.G., Runge-Froböse, C., Ahrén, D.G., Kemen, E., Oliver, R.P., Mendgen, K.W. (2002). Four or More Species of Cladosporium Sympatrically Colonize *Phragmites australis*. *Fungal Genetics and Biology*, *35*(2), 99–113. Doi: 10.1006/fgbi.2001.1314

World Meteorological Organization (WMO). (2020). The state of greenhouse gases in the athmosphere based on global observations through 2019. Retrieved July 28, 2020 from: https://reliefweb.int/report/world/wmo-greenhouse-gas-bulletin-state-greenhouse-gases-atmosphere-based-global-0

Yang, C.-H., Crowley, D.E., Borneman, J., Keen, N.T. (2001). Microbial phyllosphere populations are more complex than previously realized. *Proceedings of the National Academy of Sciences*, *98*(7), 3889–3894. Doi: 10.1073/pnas.051633898

Yang, X. (2010). *Investigation on moisture buffering of hygroscopic materials by full-scale experiments and HAM simulations* [Doctoral dissertation, Concordia University]. Concordia University's open access research repository. https://spectrum.library.concordia.ca/979273/1/NR67328.pdf

Acknowledgements

"It always seems impossible until it's done."
Nelson Mandela

I would like to thank my supervisor Dr. Aime Ruus, who introduced me to the interesting world of building physics and guided me. My gratitude belongs to my supervisor and dear friend *Professor Emerita* Mari Ivask, who has been my motivating, driving force since I started studying at Tallinn University of Technology. Special thanks to Prof. Lembit Nei, who gave me valuable feedback and pushed me to sharpen my thinking and brought my work to a higher level.

I am very grateful to the owners of the straw-bale and reed-bale buildings who allowed to take samples in their dwellings.

My special regards go to my wonderful colleagues at Tartu College – Kaie Lehtme, Kai Kalda, Egge Haiba, Laura Lokko, Annely Kuu.

My gratitude belongs to lecturer Karin Muoni for turning my rough expressions into a smoothly flowing harmony and offered support throughout the writing process. I am grateful to my former co-researcher and lab partner Sander Kutti, who gave me the idea to write about straw-bale buildings.

I wish to acknowledge the support and great love of my husband Raimo, my parents, Karin and Arne Peda, my grandmother Koidula Peda and grandparents Hilja-Anita and Juhan Song. My gratitude belongs to my little sister Gerda Lõiv and her wonderful family.

Many thanks to my friends Laura Lokko, Liis Tammesalu, Tiina Niine and Vivika Halapuu, who have been there for me no matter what happens. My gratitude belongs also to my sisters from Estonian Women Students' Society (ENÜS) for inspiring and motivating me during a seemingly endless PhD journey.

Abstract

Indoor air microbiological quality in reed-bale and straw-bale houses in Estonia

Climate change and the depletion of resources create a need for sustainable solutions in construction. Straw and reed, which are widely available materials in Estonia, can replace energy intensive building materials. Red clay is widespread in South Estonia. It does not have toxic properties, it is a biodegradable, antibacterial and reusable material which according to several studies improves indoor climate and creates a healthy living environment. In addition to clay plaster, whitewash and lime plaster are used as well. All these finishing materials are antibacterial disabling the growth of mould and bacteria.

Straw bale houses have been built since the middle of the 19th century when the emigrants in Nebraska, the Unites States had to use straw bales to construct temporary buildings due to lack of building materials and wood. In modern construction, there are buildings with bearing walls and timber frame houses where straw is used as an insulation material. Straw and reed modules and boards are used in construction in temperate climate as well.

Straw and reed are materials which are colonised by microorganisms at the beginning of their life cycle. Both materials consist mainly of cellulose, hemicellulose and lignin, they are a good medium for microorganisms. The main problem with poor quality material is the emergence of mould, and rodents which damage the material.

The aim of the present thesis was to investigate comprehensively the indoor climate of reed and straw-bale dwellings in Estonia, and the factors influencing the indoor climate. Data on the microbial community present was collected from the bedrooms of eight houses from their building boarder construction in 0.2 m depth at two heights (material samples from the wall) and from indoor air (samples with air analysers). The result of the study showed that the genera found (*Cladosporium, Penicillium, Aspergillus, Alternaria*) were similar in outdoor and indoor air. The abundance of microorganisms was smaller in the reed-bale houses than in the straw-bale houses.

The indoor climate indicators (CO_2, RH%, temperature) were similar in the studied bedrooms too, the content of CO_2 varied the most. The boarder indicators were similar to the room indoor climate indicators.

The hygrothermal properties (i.e. sorption and water vapour permeability, mineralogical composition and texture) of different natural materials and natural paints were studied in laboratory conditions. The result showed that the hygrothermal properties of clay plaster differ significantly depending on the composition of plaster – the content of calcite influenced the most. The hygrothermal properties of clay plaster are very good and the material can inhibit the growth of mould and bacteria. Whitewash, which has antibacterial properties, proved to be the best covering material for clay plaster.

A house built of reed-bale or straw-bale is suitable in Estonian climatic conditions. It is a healthy and environmentally sustainable home when it is carefully planned, and suitable material and quality craftsmanship used.

All the studied houses were hygrothermally properly designed. The buildings with moisture damage (e.g. after flood, water accidents) need to be studied separately for a longer time period after the accident.

Lühikokkuvõte

Siseõhu mikrobioloogiline kvaliteet Eesti roo- ja põhupakist elamutes

Kliimamuutus ning ressursside ammendumine loovad vajaduse kestlike lahenduse järele ka ehituses. Põhk ning pilliroog, mis on Eesti tasandil hõlpsasti hangitavad materjalid, on oma omadustelt võimelised asendama energiamahukaid ehitusmaterjale. Lõuna-Eestis on laialt levinud ka punane savi – ilma toksiliste omadusteta, biolagunev, antibakteriaalne ja taaskasutatav materjal, mis erinevate uuringute andmetel parandab sisekliimat ning loob tervisliku elukeskkonna. Lisaks savikrohvile on kasutusel ka lubivärvid ja lubikrohv – kõik need viimistlusmaterjalid on antibakteriaalsed, raskendades hallitusseente ja bakterite kasvu.

Maailmas on põhust maju ehitatud alates 19. sajandi keskpaigast, mil Ameerika Ühendriikidesse Nebraskasse saabunud uusasunikud oli sunnitud ehitusmaterjalide ja puidu nappuse tõttu kasutama ajutiste ehitiste valmistamiseks põhupakke. Kaasaegses ehituses eristatakse nii kandvate seintega maju kui ka puitkarkassil maju, kus põhk on kasutusel soojustusmaterjalina. Üha enam on parasvöötme aladel kasutusel ka ehitamine pilliroost või põhust moodulitest ja plaatidest.

Põhu ja pilliroo puhul on tegemist on materjalidega, mis oma elutsükli algfaasis on koloniseeritud mikroobikoosluse poolt. Kuna mõlemad materjalid koosnevad peamiselt tselluloosist, hemi-tselluloosist ja ligniinist on nad heaks substraadiks mikroorganismidele. Samuti tekitavad probeeme närilised, kes kahjustavad põhu- ja roopakke, mida kasutatakse hoone ehitusel, vähendades oma tegevusega pakkide soojuspidavust ja tihedust.

Põhku ja pilliroogu peetakse üldjuhul ehitusmaterjalina nii keskkonnale kui ka inimtervisele ohutuks. Paraku võib kaasneda nende materjalide kasutamisega hoonete ehitusel hallituse esinemine, mis võib põhjustada nõrgema immuunsüsteemiga inimestel erinevaid haigusnähte (silmade, nina ja kurgu ärritusnähud, allergiline nohu ja silmapõletik, astma). Uuringuid antud teemal Eesti oludele vastavates klimaatilistes tingimustes tehtud ei ole, kuid looduslikest materjalidest ehitatud hooned koguvad üha enam populaarsust.

Antud töö eesmärgiks oli uurida Eesti roo- ja põhumajade sisekliimat ning seda mõjutavaid tegureid.

Töö raames koguti andmeid kaheksa maja magamistubadest nii ehitlusmaterjalil elutseva kui ka siseõhus leiduva mikroobikoosluse kohta. Nii sise – kui ka välisõhus olid leitud perekonnad sarnased (*Cladosporium, Penicillium, Aspergillus, Alternaria*). Roopakkidest ehitatud majades oli mikroobikoosluse arvukus väiksem kui põhumajades.

Kõikide uuritud magamistubade lõikes olid sarnased ka sisekliima näitajad (CO_2, RH%, temperatuur), enim varieerus süsihappegaasi sisaldus. Piirete näitajad olid vastavuses toa sisekliima näitajatega.

Laboritingimustes uuriti erinevate looduslike viimistlusmaterjalide (savi- ja lubikrohv paberkrohv, looduslikud värvid) niiskustehnilisi omadusi. Leiti, et looduslike materjalide niiskustehnilised omadused erinevad oluliselt sõltuvalt krohvi koostisest. Savikrohvi niiskustehnilised omadused on väga head ning materjal on võimeline inhibeerima hallitusseente ja bakterite kasvu.

Pilliroost või põhust ehitatud maja on Eesti klimaatilistesse tingimustesse sobiv hoone, mis põhjaliku planeerimise, ehituseks sobiva materjali kasutamise ja kvaliteetse ehitustegevuse tulemusena on inimese tervisele sõbralik ja keskkonna mõistes kestlik eluase.

Appendix

Publication I

Raamets, J., Kutti, S., Ruus, A., Ivask, M. (2017). Assessment of indoor air in Estonian straw bale and reed houses. *WIT Transactions on Ecology and the Environment*, 211, 193−196. Doi:10.2495/AIR170191

ASSESSMENT OF INDOOR AIR IN ESTONIAN STRAW BALE AND REED HOUSES

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ABSTRACT
Fungi play an important role in the decomposition process of organic matter. They are able to grow almost in all organic substrates – as well on straw and reed. In Estonia, there is a growing interest in building with green materials due to their low embodied energy and insulation value. The most common understanding is that living in a house built of straw or reed blocks can be also beneficial for human health – people with asthma, allergies and acute environmental sensitivities would suffer less. The aim of this study was to evaluate indoor air in sleeping areas in Estonian straw bale and reed houses. Samples were collected once every season between October 2014 and October 2016, from 8 households (4 straw bale houses, 4 reed houses). Occupants were asked not to air the houses 6 h prior to measurements. For each sample, the corresponding outdoor air was measured as a reference value. In order to determine fungal spore concentrations in the air, Microbio MB2 air samplers were used. Malt extract agar and dichloran glycerol agar plates were used as culture media. The total colony forming units per m^3 were determined. The microorganisms were identified from the isolated colonies. The most abundant bacterial and fungal genes isolated from samples were *Alternaria*, *Aspergillus*, *Cladosporium* and *Penicillum*.
Keywords: straw bale buildings, reed buildings, indoor air, airborne fungi.

1 INTRODUCTION

To reduce carbon emission and save energy, interest in renewable materials has been increasing [1]. Straw and reed are two of such kinds of materials. Straw is currently produced in surplus to requirements, so it is cheap and easily accessible in most countries [2] as well as in Estonia. Every year approximately 100–150 tons of straw will be produced as a by-product [3]. According to Veski et al. [4], reed stands are also common in Estonia: approximately 26,000 ha in total. Thickets of reed produces 10–40 t/ha biomass per year. [4]

Research has shown that straw-bale construction is a sustainable way for building, from the standpoint of both materials and energy needed for heating and cooling [5]. These buildings can be also a potential risk for the human health if not built and ventilated correctly. These main health risks are all linked to the most common microorganisms like *Aspergillus*, *Penicillum*, *Cladosporium* proliferating in damp buildings (Kuhn et al. [6]; Chapman [7]). All mentioned genera of fungi are also known as allergy causers of respiratory system (Singh [8]).

Spores in a dormant state are commonly present in the air and on the surfaces of objects. In this context, air ventilation is an easy and safe method to control and stabilize relative humidity, temperature, moisture content and consequently, microbial activity rate [9].

The goal of this study was to examine sleeping areas in Estonian straw bale and reed houses Spore concentrations of indoor air were compared with spore concentrations outdoors.

2 MATERIAL AND METHODS

The assessment of indoor air in straw bale and reed houses was carried out in October 2014–October 2016 in the Northern part of Estonia.

WIT Transactions on Ecology and The Environment, Vol 211, © 2017 WIT Press
www.witpress.com, ISSN 1746-448X (on-line)
doi:10.2495/AIR170191

Fungal air sampling was performed four times a year (every season) during a two-year period in sleeping areas of Estonian straw bale ($n = 4$) and reed built households ($n = 4$). Occupants were asked not to air the houses 6 h prior to measurements.

Microbio MB2 air samplers were used, passing 100 l of air per sample. Sampling time was 1 min. A set of four air samples captured in each area was used to obtain average contamination values and representative results. For each sampling, the corresponding outdoor air was measured as reference value. Sampling was carried out inside 1 m above floor level and outside 1.5 m above the ground. The sample plates were incubated at 32°C for 72 hours and the colony forming units (CFU) were counted. Malt extract agar (MEA) and dichloran glycerol agar (DG18) plates were used as culture media. The fungal and bacterial colonies were recultivated periodically. All types of growth media were autoclaved at 120°C and poured to Petri dishes to dry overnight. The isolated microorganisms were plated with a spatula on the agar plates. The cultures were grown on the petri dishes under 32°C. All necessary chemicals and reagents (Fluka) were purchased from HNK Analüüsitehnika.

The identification was performed via sample staining and microscopy. Online databases and Bergey's manuals were used.

Evaluation of data was performed with Statistica Version 10.0 (Kruskal–Wallis H-test) and Excel 2010; $p \leq 0.05$ is considered as significant.

3 RESULTS AND DISCUSSION

Atmospheric air contains spores of certain fungal species. Depending on the environmental and climatic conditions and living conditions of fungi, spore concentrations in outdoor air can vary.

The seasonal variations in the colony counts for both outdoor and indoor air are shown in Tables 1 and 2. As expected and reported before [10], the maximum concentrations of airborne fungi were recorded during the summer months (June–August). The mean indoor and outdoor concentrations were lower, especially in winter (December–February). We found similar concentrations to each other in spring and in autumn (March–May; September–November). Mean values indoors were greater in reed houses. Probably is this so because two of reed houses did not have a decent HVAC system [11].

Table 1: Seasonal variation in culturable airborne fungi indoors shown as mean and in parentheses range of CFU m^{-3} air.

Sampling site	*Winter*	*Spring*	*Summer*	*Autumn*
Straw bale indoor (MEA)	149 (60–240)	298 (110–620)	537 (200–840)	307 (100–610)
Straw bale indoor (DG 18)	14 (0–42)	29 (10–56)	46 (20–88)	20 (0–62)
Reed indoor (MEA)	380 (160–760)	518 (200–900)	858 (560–1060)	548 (120–860)
Reed indoor (DG 18)	22 (0–60)	23 (6–50)	36 (11–62)	22 (8–51)

Table 2: Seasonal variation in culturable airborne fungi outdoors shown as mean and in parentheses range of CFU m^{-3} air.

Sampling site	*Winter*	*Spring*	*Summer*	*Autumn*
Straw bale outdoor (MEA)	94 (50–160)	197 (120–350)	289 (210–380)	168 (100–280)
Reed outdoor (MEA)	118 (80–150)	198 (80–310)	353 (240–420)	212 (140–300)
Straw bale outdoor (DG 18)	18 (0–42)	30 (10–56)	50 (20–88)	22 (2–54)
Reed outdoor (DG 18)	24 (8–51)	27 (10–58)	45 (28–77)	23 (8–48)

There was a very weak ($r = 0.38$, $P < 0.05$) relationship between the house characteristics and the presence of fungal propagules in indoor air. Relative humidity ($r = 0.89$, $P < 0.05$), temperature ($r = 0.86$, $P < 0.05$), season ($r = 0.71$, $P < 0.05$) and pets ($r = 0.88$, $P < 0.05$) inside homes had a statistically significant impact on the presence of fungal propagules in indoor air.

There was no difference between species, which lived in straw bale and reed houses. Outdoor air samples corresponded to indoor ones. The fungal genera identified during this study are common organisms that are regularly present in homes. Some of the species can be harmful to human health by the ability to produce mycotoxins [9].

Most common genus in indoor air during winter was *Penicillum*, on second place was *Aspergillus* and then other fungi. In spring the main genus was *Cladosporium*. We also found fungi from genus *Penicillum*, *Aspergillus*, others and *Alternaia*. In summer was the most abundant genera also *Cladosporium*. We found other genera – *Penicillum* and *Alternaria* as well during the summer time. In autumn was the most abundant *Cladosporium*, followed by *Alternaria*, *Penicillum*, other fungi and *Aspergillus.* Similar seasonal variations have found earlier by Mędrela-Kuder [10].

Average concentration below 500 allergenic spores in air causes only minor symptoms in persons known to react very strongly to allergenic species. Concentrations above 500 or 600 spores m^{-3} induce symptoms of disease in all who suffer from allergy [10].

The fungal kingdom is thought to contain over a million species. About 600 of them cause some form of human disease [12].

In most cases the species of genus *Alternaria* are either obligate or facultative pathogens. It has been estimated that about 70% of atopic sensitive peoples respond to the presence of *Alternaria* spores in air samples [7], [13], [14].

Species of genus *Aspergillus* can cause severe invasive infections in most of major organ system. *Aspergillus* most commonly infects immunocompromised hosts in the respiratory tract [7], [15], [16].

The genus *Cladosporium* has different species, from plant to human pathogens. Most of the species of this genus produce a very distinctive and obnoxious odour (chemical compounds responsible for odour are considered toxic) by what it can be easily identified [16]. Some of these species can cause inflammation of the respiratory system as well as inflammation of eyes and skin as well asthma [8], [16], [17].

The species of the genera *Penicillium* are the most abundant considering spores in outdoor and indoor air. They are commonly found in soil, food, grains and cellulose. Some of the species can produce mycotoxins [8], [16]. The toxicity of the spores does not decrease even when the mould itself is already gone. Most of the species of the genus *Penicillium* are harmless to people with strong immune system [9], [16].

4 CONCLUSION

An experiment to investigate indoor air in straw bale and reed houses was carried out from October 2014–October 2016 in Northern part of Estonia. Samples were taken from 8 test houses.

Mean values of CFU were higher in reed houses. This is probably due the lack of good HVAC systems in two of four houses. There was also seasonal difference. Mean values were highest during summer months and lowest in winter. In spring and in autumn the values were in same range.

The genera of the identified fungi were *Alternaria*, *Aspergillus*, *Penicillium* and *Cladosporium*. Most of these species can present a health risk for humans, especially for those with allergies, asthma and weakened immune systems. Children and the elderly people will also be affected. If there will be any constant “flu-like” symptoms, it is highly recommended to consult the physician as soon as possible.

REFERENCES

[1] Goodhew, S., Griffiths, R. & Woolley, T., An investigation of the moisture content in the walls of a straw-bale building. *Building and Environment*, **39**(12), pp. 1443–1451, 2004.

[2] Milutiene, E., Jürmann, K. & Keller, L., Straw bale building – reaching energy efficiency and sustainability in northern latitudes, 2010. Available online, www.earthzine.org/2010/04/26/straw-bale-building-%E2%80%93-reaching-energy-efficiency-and-sustainability-in-northern-latitudes/. Accessed on: 8 Jan. 2017.

[3] Paist, A., et al., Potential of biomass fuels to substitute for oil shale in energy balance in Estonian energy sector. *Oil Shale*, **22**(4), pp. 369–379, 2005.

[4] Veski, R., Palu, V., Luik, H. & Kruusement, K., Thermochemical liquefaction of reed. *Proceedings of the Estonian Academy of Sciences: Chemistry*, **54**(1), pp. 45–56, 2005.

[5] Milutienė, E., Staniškis, J.K. & Kručius, A., Increase in buildings sustainability by using renewable materials and energy. *Clean Technologies and Environmental Policy* **14**(6), pp. 1075–1084, 2012.

[6] Kuhn, D.M. & Ghannoum, M.A., Indoor mold, Toxigenic fungi, and Stachybotrys chartarum: Infectious disease perspective. *Clinical Microbiology Reviews*, **16**(1), pp. 144–172, 2003.

[7] Chapman, M.D., Challenges associated with indoor moulds. *Medical Mycology*, **44**, pp. 29–32, 2006.

[8] Singh, J., Allergic reactions: occupational hygiene. *Health and Safety*, pp. 14–16, 2000.

[9] Raamets, J., Kutti, S., Vettik, A., Ilustrumm, K., Rist, T. & Ivask, M., The antimicrobial effect of three different chemicals for the treatment of straw bales used in housing projects. *Proceedings of the International Conference on Sustainable Housing Planning, Management and Usability: Sustainable Housing 2016*, pp. 537−545, 2016.

[10] Mędrela-Kuder, E., Seasonal variations in the occurrence of culturable air borne fungi in outdoor and indoor air in Craców. *International Biodeterioration & Biodegradation*, **52**, pp. 203–205, 2003.

[11] Haleem Khan, A.A. & Mohan Karuppayil, S., Fungal pollution of indoor environments and its management. *Saudi Journal of Biological Sciences*, **19**(4), pp. 405–426, 2012.

[12] Woodcock, A., Moulds and asthma: Time for indoor climate change? *Thorax*, **62**(9), pp. 745–746, 2007.

[13] Sanchez, H. & Bush, R.K., A review of Alternaria alternate sensitivity. *Revista Iberoamericana de Micología*, **18**, pp. 56–59, 2001.

[14] de Hoog, G.S. & Horre, R., Molecular taxonomy of the *Alternaria* and *Ulocladium* species from humans and their identification in the routine laboratory. *Mycoses*, **45**, pp. 259–276, 2002.

[15] Ellis, M.E., Al-Abdely, H., Sandridge, A., Greer, W. & Ventura, W., “Fungal endocarditis: Evidence in the world literature 1965-1995. *Clinical Infectious Diseases*, **32**, pp. 50–62, 2001.

[16] Bennett, J.W. & Klich, M., Mycotoxins. *Clinical Microbiology Reviews*, **16**(3), pp. 497–516, 2003.

[17] Bensch, K., Braun, U., Groenewald, J.Z. & Crous, P.W., The genus *Cladosporium*. *Studies in Mycology*, **72**, pp. 1–401, 2012.

Publication II

Vares, O., Ruus, A., Raamets, J., Tungel, E. (2017). Determination of hygrothermal performance of clay-sand plaster: influence of covering on sorption and water vapour permeability. *Energy Procedia*, 132, 267−272. Doi:10.1016/j.egypro.2017.09.719

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 132 (2017) 267–272

Energy Procedia

www.elsevier.com/locate/procedia

11th Nordic Symposium on Building Physics, NSB2017, 11-14 June 2017, Trondheim, Norway

Determination of hygrothermal performance of clay-sand plaster: influence of covering on sorption and water vapour permeability

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Abstract

Indoor finishing materials considerably influence indoor climate because of their moisture buffering ability occurring due to the sorption and diffusion properties of materials. Hygroscopic sorption properties were determined in accordance with the standard EVS-EN ISO 12571 and the principles given in the standard EVS-EN 1015-19:2005 were followed when determining water vapour permeability properties. The same specimens (thickness 2.4 cm) were used for both tests. To describe the dynamics during the first hours, the specimens were weighted at 1, 2, 3, 6, 12, 24, 48, 72 hours after changing the humidity level. Moisture uptake (kg/m^2) and moisture uptake rate kg/(m^{2}h) within the very first hours at 0-30, 30-50 and 50-80%; moisture content at RH level of 30%, 50% and 80%; points (30, 50 and 80%) at sorption curve were monitored. Six different covering materials were used: fine finishing mortar with cellulose, fine finishing mortar without cellulose, casein paint, cellulose base coat, lime paint, casein base coat, clay plaster not covered. The rate of moisture uptake was highest within the first hour after a sudden change in moisture level. Water vapour diffusion equivalent air layer thickness S_d=0.11-0.13 m was recorded.

Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics.

Keywords: water vapour permeability; sorption; clay plaster

1. Introduction

The paper focuses on the influence of finishing materials on the hygrothermal performance of boarders. To describe the situation several different parameters have been worked out. For indoor climate and thermal comfort inside the room besides temperature, relative humidity (RH) is one of the key parameters. Relative humidity is determined by

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Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics
10.1016/j.egypro.2017.09.719

measuring indoor moisture generation, air-change rate, and the release or uptake of moisture by hygroscopic surface materials as well as moisture flow through structures [1]. Necessary ventilation rate of a room depends on several aspects - heat production, CO_2 or other gases, moisture, particles, smoke, body smell etc. Ventilation rates calculated by CO_2 balance could differ from the rate calculated by moisture balance. Several household activities e.g. showering, food cooking increase moisture production significantly and regulating ventilation rate by one criterion results in too high or low relative humidity. The buffering ability of materials is useful in that case.

Moisture buffering performance of the room is the ability of materials within the room to moderate variations in the relative humidity [2]. The moisture buffering value of materials was studied by Rode [2], and a definition scheme for the moisture buffer phenomena in indoor environment divided into three descriptive levels – material level, system level and room level – was offered. Fluctuating variation can be seasonal or diurnal, but in practice attention is paid to the moisture buffering diurnal variations mostly. According to Rode [2, 3] the practical Moisture Buffer Value ($MBV_{practical}$ [kg/(m^2·%RH)]) indicates the amount of water that is transported in or out of material per open surface area during a certain period of time, when it is subjected to variations in relative humity of the surrounding air. Normal case suggested by Rode is RH of 75 and 33% and cyclic change is 8 and 16 hours accordingly [4,5] while air temperature at testing is 23°C. Ramos [6] also added tests/results at air temperature 15°C into testing series. Ge et al [7] used 10/14h and 2/22 h cycles.

Janssen [5] introduced the Nordtest protocol formula for $MBV_{practical}$ [g/(m^2·%RH)] calculations (Formula 1):

$$MBV_{8h} = \frac{m_{\max} - m_{\min}}{A \cdot (\varphi_{high} - \varphi_{low})} \tag{1}$$

Where $m_{min/max}$ is moisture mass (min and max) in finishing sample (g or kg), A – exposed area m^2; $\varphi_{high/low}$ -h igh/low RH (-) levels applied in the measurement.

Using the Moisture buffer values [g/(m^2·%RH)@8/16h] materials can be classified as follows [3]: negligible (0-0.2), limited (0.2-0.5), moderate (0.5-1.0) good (1.0-2.0), excellent (2.0-).

Materials behave differently and also moisture load regimes in the buildings and rooms could be different. Ge et al. [7] studied at 10/14 h (moisture generation of 100 g/h) 1 kg total and 2/22 h (200 g/h) 400 g as total of moisture load and got different results of moisture buffering for different materials (volume of 21.4 m^3). For uncoated gypsum panel and wood panelling the adsorption of moisture for 10 hours was similar. That is an interesting result because a quite fixed list of well-known and popular "breathing" materials like timber, clay and lime plaster is often drawn out, probably because of final sorption values. For example, Ge et al. [7] found the stabilised moisture content 313 g/m^2 (achieved at 342 hours) for wood and 38 g/m^2 (10 h) for gypsum board at environment with RH of 75%). Ge et al. [7] also categorised materials into 3 groups depending on **moisture capacity** and **vapour permeability**. **Group A** materials have high moisture capacities but low vapour permeability **Group B** materials have low moisture capacity and high vapour permeability Materials in **Group C** have both high moisture capacity and high vapour permeability.

Ramos [6] focuses on finishing materials properties that can enhance their moisture buffering performance and can be easily demonstrated to designers and builders. Ramos [6] tested gypsum board, gypsum plaster and gypsum + lime plaster for their sorption and water vapour permeability. He used acrylic and vinyl paints with and without primer and concluded that materials tested with painting schemes including a primer presented much lower vapour permeability. Based on ranges for practical MBV classes, it can be said that the base materials tested have a "moderate class" [0.5–1.0 g/(m^2·%RH)] of moisture buffering efficiency, which can be reduced to a "limited class" [0.2-0.5 g/(m^2·%RH] by the effect of coatings.

The influence of different paints depending on time was studied by Minke [8]. On silty loam substrate lime, casein and cellulose glue paint only slightly reduce the absorption (after a sudden increasing RH from 50-80%), whereas double latex and single linseed oil coating can reduce absorption rates to 38% and 50% respectively. One material can have different properties. Šemjakin [9] studied linseed oil paint made on the basis of different recipes. Water vapour diffusion equivalent air layer thickness S_d was estimated as 0.1 and 0.2 m for 1-layer primers, 0.2 to 0.9 m for 1-layer paints and 0.4 to 0.9 m for 2-layer paints. Maddison [10] studied clay plaster sorption properties dependent on different phytomass additives. The sorption of pure clay sand plaster was 11.3 g/m^2 being 38 % of total water absorbed within 12 h.

A daily hygroscopic inertia index, $I_{h,d}$, was defined by Ramos [6, 11] as function of MBV and taking into account of ventilation and time (Formula 2)

$$I_{h,d} = \frac{\sum_i^n MBV_i \cdot S_i + \sum_j^m MBV_{obj}}{ach \cdot V \cdot t_g} \quad (2)$$

Where MBV_{obj}, MBV_i – Moisture buffering value of objects and elements. S_i – surface of element i m^2 ach- air exchange rate h^{-1}, V – room volume m^3, t_g – vapour production period, h.

Janssen and Roels [5] found out that different interior buffering elements: AAC walls, woollen carpets, book shelves etc. have a positive effect on hygrothermal inertia (increasing) and RH fluctuation (decreasing).

Especially during hot periods [12], dynamic moisture storage in hygroscopic materials reduces the moisture in the air leading to increased comfort and consequently a reduced need for cooling resulting in indirect savings. However, it has been shown that since the indoor air humidity is reduced, the indoor air enthalpy is also reduced and consequently less energy is needed for cooling, which leads to *direct* energy savings. Osanyintola and Simonson [13] find out that using hygroscopic materials enables to save heating energy 2-3% and cooling energy 5-30% in countries with moderate climates but similar to Estonia (Finland - Helsinki) as well. The storage of moisture inside a hygroscopic material such as wood also means thermal storage, which contributes to buffering the indoor temperature variations [14].

2. Materials and methods

The recipe used contains local clay, sand, flax and cattail in the form of solid powder, and water. The total number of specimens was 21 (3*7).Six different covering materials were used and marked on the specimens (with a diameter of 100 mm approx. and thickness of 25 mm) as follows: I - fine finishing mortar with cellulose, II – fine finishing mortar without cellulose, III - casein paint, IV - cellulose base coat V – lime paint VI – casein base coat VII - clay plaster not covered. The same specimens were used for both tests: sorption and water vapour permeability. The average thickness of a specimen was 2.40 (2.23-2.54) mm, volume 192.1 (180.11- 204.58) cm^3, dry weight 338.5 (318.31-358.39) g and dry density 1.77 (1.73-1.85) g/cm^3. Hygroscopic sorption properties were determined by following the principle of the standard [15].

To estimate hygroscopic sorption properties, climate chamber method was used at environment temperature of 23±0.5 °C with three specimens with each type of covering. Three different levels were under estimation: 30%, 50% and 80% of RH. That is not in accordance to the standard, but drawing the whole adsorption curve was not a goal. The aim was to study the properties at levels found in literature [8,10] and present realistic values. RH hardly exceeds RH=80% indoors.

To describe the moisture behaviour during the first hours, the specimens were weighted at 1, 2, 3, 6, 12, 24, 48, 72 hours after changing the humidity level [8]. As moisture flow fluctuates daily and different humidifying regimes can be used, that kind of weighing enables to get an overview of different humidity combinations. The principles of the standard [16] were followed when determining water vapour permeability properties.

The same specimens were used for both tests. Clay plaster was embedded into a plastic cylinder cut from a plastic pipe. A plastic film and silicon hermetic were used for tightening.

The following equipment was used to carry out the tests: climate chamber RUMED 4101 affording RH 20...95%, with accuracy ±2-3%, and temperature 0-+60°C with accuracy ±0.5°C; digital balance Memmert PC440 Delta Range 0.5-400g, with accuracy 0.01g for sorption and Mettler 0-1,200 g and accuracy of 0.01g for water vapour permeability.

3. Results

In the first stage specimens dried to 0% of moisture content were put to the climate chamber supplied with temperature 23°C with RH of 30%. The results were registered after first 1, 2, 3, 6, 12 and 24 hours and afterwards every 24 hours. The sorption properties were monitored in two ways: moisture uptake (kg/m^2) and moisture uptake rate kg/(m^{2}h) behaviour within the very first hours at 0-30, 30-50 and 50-80%; moisture content at RH level of 30%, 50% and 80%.

Sorption RH=0-30%. This situation probably rarely occurs in real life. The rate of moisture uptake (Table 1) was the highest during the first hour (10.4-16.6 g/(m^{2}h) being 11-15% of total moisture content received by stabilization at 72 h. The rate of moisture uptake within the first hours was the highest for uncovered plaster (VII) (total moisture uptake within 3 hours 32.7 g/m^2) and the lowest casein base coat (VI) (total moisture uptake within 3 hours 21.2 g/m^2). At that range RH total uptake and moisture content were equal. The total absorbed moisture content at RH of 30% was from 105.0 (casein base coat) to 111.3 g/m^2 (IV -cellulose base coat) g/m^2. It can be noticed that the most remarkable amount of moisture is absorbed within the first 24 hours (Table 1).

Table 1. Sorption at RH=0-30%. Moisture uptake rate g/(m^{2}h) and total moisture uptake g/m^2

	Sorption								
	1 h	2 h	3 h	72 h		1 h	2 h	3 h	72 h
	g/(m^{2}h)	g/(m^{2}h)/g/m^2	g/(m^{2}h)/g/m^2	g/m^2		g/(m^{2}h)	g/(m^{2}h)/g/m^2	g/(m^{2}h)/g/m^2	g/m^2
I	14.4	8.2/22.6	4.1/26.8	106.7	V	12.8	8.3/21.1	5.8/26.9	108.1
II	12.8	9.1/21.9	3.7/25.7	108.9	VI	10.4	7.9/18.3	2.9/21.2	105.0
III	15.7	10.3/26.0	5.4/31.3	110.1	VII	16.6	9.1/25.7	7.0/32.7	108.1
IV	14.8	9.9/24.7	5.8/30.5	111.3					

Range of **RH=30-50%** corresponds more exactly to ventilated indoor living environment and human needs in real-life situation. Moisture uptake rate varied (Table 1) a lot between time periods and covering materials. During the first hour uncovered clay plaster (VII) and plaster with casein paint (III) and cellulose paint coverings (IV) absorbed at the rate of 8.2-8.7 g/(m^{2}h) while plaster with casein base coat(VI) absorbed only 3.3 g/(m^{2}h). Within the first hour the amount of water absorbed is 5.2-13.4% of the total uptake of range 30-50% (58.4-65.5 g/m^2).

T-test analyses for total moisture uptake of the range showed that only lime paint (V; 58.4 g/m^2) had significant difference from others except fine finishing mortar with cellulose (I) and has the lowest absorption. Total moisture content (RH=0-50%) varies from 158.2 g/m^2 (lime paint) to 178.1 g/m^2 (fine finishing without cellulose).

Table 2. Sorption and desorption at RH=30-50%. Moisture uptake/release rate g/(m^{2}h) and total moisture uptake/release g/m^2

	Sorption				Desorption			
	1 h	2 h	3 h	72 h	1 h	2 h	3 h	72 h
	g/(m^{2}h)	g/(m^{2}h)/g/m^2	g/(m^{2}h)/g/m^2	g/m^2	g/(m^{2}h)	g/(m^{2}h)/g/m^2	g/(m^{2}h)/g/m^2	g/m^2
I	4.5	2.9/7.4	2.5/9.9	61.8	-6.2	-1.6/-7.8	-1.2/-9.1	-72.5
II	5.4	3.7/9.1	1.7/10.8	64.2	-5.4	-1.7/-7.0	-1.2/-8.3	-75.4
III	8.2	2.9/11.1	2.5/13.6	63.9	-4.9	-2.5/-7.4	-2.5/-9.9	-73.8
IV	8.7	3.7/12.4	2.5/14.9	65.5	-7.4	-2.5/-9.9	-2.1/-11.9	-74.6
V	5.4	3.3/8.7	2.5/11.2	58.4	-4.6	-2.5/-7.0	-1.7/-8.7	-73.7
VI	3.3	2.9/6.2	2.9/9.1	63.5	-6.6	-2.5/-9.1	-1.7/-10.8	-75.1
VII	8.3	2.9/11.1	2.1/13.3	61.7	-5.0	-3.3/-8.3	-2.5/-10.8	-73.7

The range of RH=**50-80%** is not common in a ventilated living room, but could occur in rooms with high occupation and inadequate ventilation level. Moisture uptake rate is more uniform than at range of RH=30-50% (Table 3). During the first hour uncovered clay plaster (VII), plaster with casein paint (III) and cellulose paint coverings (IV) moisture absorbed with the rate of 14.9-15.7 g/(m^{2}h) while plaster lime paint (V) and fine finishing with cellulose (I) absorbed 11.5-12.0 g/(m^{2}h). The total moisture uptake within three hours was 23.5-31.1 g/m^2 lining up accordingly. Within the first hour the amount of water absorbed was 6.9-9.0 % of the total uptake of range 50-80% (160.3-180.9 g/m^2). *T*–test analyses showed that only lime paint (V) had significant difference from others except fine finishing mortar with cellulose (I) which has the lowest absorption value. Total moisture content (RH=0 -80%) varied from 318.6 g/m^2 (V - lime paint) to 356.2 g/m^2 (II - fine finishing without cellulose).

Water vapour resistance r of uncovered clay plaster with the thickness of 2.3cm was found as $r=0.6 \cdot 10^9$ m^{2}sPa/kg (Fig. 1).

Table 3. Sorption at RH=50-80%. Moisture uptake/release rate g/(m²h) and total moisture uptake/release g/m²

	Sorption				Desorption			
	1 h	2 h	3 h	120 h	1 h	2 h	3 h	120 h
	g/(m²h)	g/(m²h)/g/m²	g/(m²h)/g/m²	g/m²	g/(m²h)	g/(m²h)/g/m²	g/(m²h)/g/m²	g/m²
I	11.5	7.0/18.5	4.9/23.5	167.3	-10.3	-7.0/-17.3	-4.9/-22.3	-137.6
II	12.8	7.5/20.3	5.4/25.7	177.3	-11.6	-6.6/-18.2	-4.6/-22.8	-143.3
III	15.7	7.4/23.1	6.2/29.3	174.0	-12.8	-8.7/-21.4	-6.2/-27.6	-141.8
IV	15.7	8.2/23.9	6.6/30.5	177.2	-16.1	-7.8/-23.9	-5.4/-29.3	-146.7
V	12.0	6.2/18.2	5.8/24.0	160.3	-10.8	-8.3/-19.1	-5.0/-24.0	-143.7
VI	14.5	9.5/24.1	7.1/31.1	180.9	-15.8	-9.1/-24.9	-6.2/-31.1	-147.7
VII	14.9	7.5/22.4	5.8/28.2	166.1	-14.9	-7.9/-22.8	-5.4/-28.2	-143.4

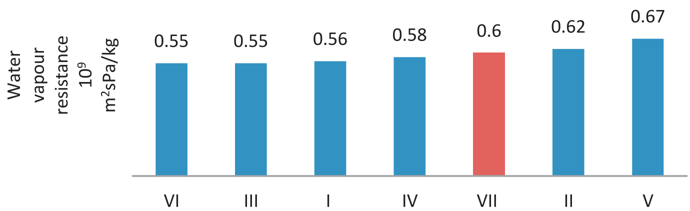

Fig. 1. Water vapour resistance of clay-sand paint with different coverings

Water vapour permeance of 2.3 cm layer was $1{,}660\cdot10^{-9}$ kg/(m²sPa) and water vapour permeability $38\cdot10^{-12}$ kg/(msPa). Water vapour resistance factor μ was found as μ=5.2.Water vapour diffusion equivalent air layer thickness S_d =5.3·0.023=0.12 m. Values are lined up graphically (Fig. 1) and it can be seen that there seems to be tendency that coatings including glue (cellulose - I, III, IV, VI) slightly improve water vapour permeability and mineral covers have some extra resistance comparing with pure naked clay. *T*-test analysis proved only lime paint (V) difference from others except finishing mortar without cellulose. The variance is too big and the number of specimen too small to draw clear relationship. It has been concluded earlier that there are paints and covers reducing water vapour permeability more or less [6, 8]. The current study showed that lime paint increased slightly the resistance of the plaster-coating system, but a lot of coverings like casein paint and base coat, clay finishing mortar, cellulose base coat do not have significant influence on water vapour permeability.

4. Discussion and conclusions

The study carried out concentrated on the initial rate of moisture uptake and release after a sudden change in RH. Also, the total moisture absorbed/desorbed within the RH-range was studied. $MBV_{practical}$ describes the situation in a room. Different cycles could occur. Earlier 8/16, 10/14 and 2/22 cycles and RH-range RH=33-75% have been introduced [7]. Based on the data recorded in the current study $MBV_{practical}$ values can be calculated on the basis of the Formula 1 (Fig. 2).

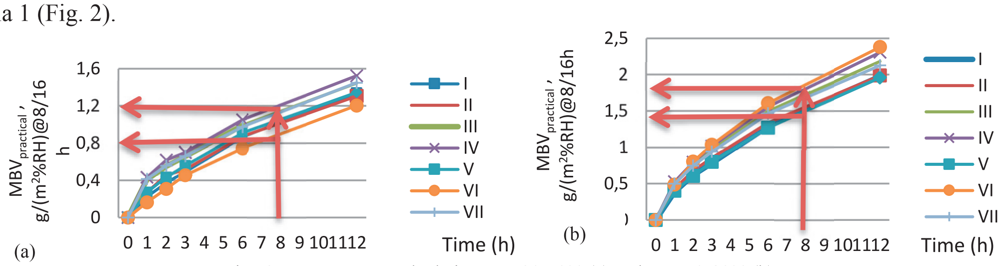

Fig. 2. $MBV_{practical}$ calculation RH=30-50% (a) and RH=50-80% (b)

According to materials practical Moisture Buffering Value classification clay plaster system (plaster about 2.4 cm+covering) could be estimated as "good" ($MBV_{practical}$=1-2g/(m²·%RH)@8/16h). Some coverings can decrease that to "moderate" $MBV_{practical}$=0.5-1 g/(m² ·%RH)@8/16h). $MBV_{prcatical}$ could be a little bit different depending on

RH-range. For RH=50-80%, values 1.5-1.8 are classified as ”good“. The hygrothermal inertia of a room can be calculated with the help of the Formula 2 and an example is presented as follows: Example: room 3m x 4m x 3m, window 1.5m x 2m and door 1m x 2m. Wall area excluding openings is S_i=37m^2, V=36m^3, ach=0.5 1/h, t_g=8h. **RH=30-50%:** min $MBV_{parctical}$=0.9g/(m^2·%RH)@8/16h); $I_{h,d}$=0.23g/(m^3·%RH); max $MBV_{parctical}$=1.2g/(m^2·%RH)@8/16h); $I_{h,d}$=0.31g/(m^3·%RH) and **RH=50-80%:** min $MBV_{parctical}$=1.5g/(m^2·%RH)@8/16h); $I_{h,d}$=0.39g/(m^3·%RH)**;** max $MBV_{parctical}$=2.0g/(m^2·%RH)@8/16h); $I_{h,d}$=0.51g/(m^3·%RH). It seems coverings have some influence on hygrothermal inertia of the room as well.
The stabilisation of moisture content depending on RH range took 72-120 hours and maximum moisture content at RH=80% was from 318.6 g/m^2 (V - plaster+lime paint) to 356.2 g/m^2 (plaster + fine finishing without cellulose). These values are similar to materials group C introduced by Ge et al. [7] - materials having both high moisture capacity and high vapour permeability like wood fibre board, telephone book paper and cotton fibre.

In the current study hygrothermal properties of clay plaster and clay plaster system (plaster + covering) were studied. The measurements carried out provided the data for calculations. Also, material was analysed from practical moisture buffering value $MBV_{practical}$ and Hygrothermal Inertia $I_{h,\,d}$ point of view. These values give us information about system or room level. Cyclic measurements must also be carried out in the future. The influence or behaviour of some coverings could not be explained with that test and must be studied in the future, just preliminary data was gathered in this study. Conclusions can be derived (based on *T*-test results) for lime paint covering as being able to decrease stabilised moisture content and increase water vapour resistance.

Acknowledgements

This study was supported by Tartu College of TUT and Saviukumaja. Special thanks to Marko Kikas.

References

[1] Kurnitski J, Kalamees T, Palonen J, Eskola L, Seppänen, O. Potential effects of permeable and hygroscopic lightweight structures on thermal comfort and perceived IAQ in a cold climate. Indoor Air 2007;17(1):37–49.
[2] Rode C. Moisture buffering of building materials, BYG DTU-126 Report, Department of Civil Engineering, Technical University of Denmark, 2005, http://www.byg.dtu.dk/upload/institutter/byg/publications/rapporter/byg-r126.pdf. (30.01.2017)
[3] Rode C, Peuhkuri R, Time B, Svennberg K, Ojanen T. Moisture Buffer Value of Building Materials. Journal of ASTM International 2007; 4 (5):1-12.
[4]Svennberg K. Moisture Buffering in the Indoor Environment.Thesis Building Physics LTH Lund University 2006.
[5] Janssen H, Roels A. Qualitative and quantitative assessment of interior moisture buffering by enclosures. Energy Build 2009; 41(4):382–394.
[6] Ramos HMM,Delgado JMPQ, de Freitas VP. Influence of finishing coatings on hygroscopic moisture buffering in building elements. Constr Build Mater 2010; 24: 2590–2597
[7] Ge H, Yang XJ, Fazio P, Rao J. Influence of moisture load profiles on moisture buffering potentialand moisture residuals of three groups of hygroscopic materials. Building and Environment 2014;81:162-171.
[8] Minke. G. Building with Earth – Design and Technology of a Sustainable Architecture. Basel: Birkhäuser; 2012.
[9] Šemjakin R, Ruus A, Kirtsi K, Tungel E. Water vapour transmission properties of linseed oil paint. Agronomy Research 2016;14:1107−1115
[10] Maddison M, Mauring T, Kirsimäe K, Mander M. The humidity buffer capacity of clay-sand plaster filled with phythomass from treatment wetland. Building and Enviroment 2010; 44:1864-1868.
[11] Ramos NMM, Freitas VP. Laboratory testing for daily hygroscopic inertia assessment. In: Proceedings of the 8th symposium on building physics in the Nordic countries, Copenhagen, Denmark; 2008:809–16.
[12] Lozhechnikova A, Vahtikari K, Hughes M, Österberg, M. Toward energy efficiency through an optimized use of wood: The development of natural hydrophobic coatings that retain moisture-buffering ability. Energy and Buildings 2015; 105:37-42
[13] Osanyintola OF, Simonson CJ. Moisture buffering capacity of hygroscopic building materials: experimental facilities and energy impact. Energy Build 2006;38:1270–1282
[14] Hameury S, Lundström T. Contribution of indoor exposed massive wood to a good indoor climate: in situ measurement campaign Energy Build 2004;36:281-292.
[15] EVS-EN ISO 12571 Hygrothermal performance of building materials and products – Determination of hygroscopic sorption properties.
[16] EVS-EN 1015-19:2005 Methods of test for mortar for masonry - Part 19: Determination of water vapour permeability of hardened rendering and plastering mortars.

Publication III

Altmäe, E., Ruus, A., Raamets J., Tungel, E. (2019). Determination of Clay-Sand Plaster Hygrothermal Performance: Influence of Different Types of Clays on Sorption and Water Vapour Permeability. In: Johansson D., Bagge H., Wahlström Å. (Ed.) Cold Climate HVAC 2018. CCC 2018. Springer Proceedings in Energy. Springer, Cham

Determination of Clay-Sand Plaster Hygrothermal Performance: Influence of Different Types of Clays on Sorption and Water Vapour Permeability

Erik Altmäe, Aime Ruus, Jane Raamets and Ernst Tungel

Abstract Eight different clay-sand plaster mixtures were studied. Mineral content and particle size distribution were estimated for all specimens. Hygroscopic sorption properties were determined (in climate chamber) at temperature of 23 ± 0.5 °C. The specimens were weighed at 1, 2, 3, 6, 12, 24 h until stabilisation at RH level of 30, 50 and 80% Moisture uptake (kg/m^2) and moisture uptake rate kg/(m^{2}h); moisture content and; points at sorption curve were monitored. There were large differences in sorption properties depending on clay type and plaster recipes. Total uptake of moisture at 30, 50 and 80% of RH for 2.5 cm plaster was 9.4–301.1, 17.5–465.9 and 41.6–744.9 g/m^2 accordingly. Standard (EN 1015-19) procedure was followed. Water vapour diffusion equivalent air layer thickness S_d = 0.08–0.12 m was declared. Strong positive correlation was found between the amount of calcite and sorption properties of plasters.

Keywords Clay plaster · Hygroscopic sorption · Water vapour permeability
Moisture buffering

1 Introduction

The necessary ventilation rate depends on several aspects - heat production, the presence of CO_2 or other gases, body odor, moisture, smoke, airborne particles, etc. Ventilation rates calculated on the basis of CO_2 balance can be different from the rate attained on the basis of moisture balance. Several household activities have influence on moisture production and it can result in too low or high relative humidity.

The buffering ability of indoor finishing materials enables to smooth the peaks of indoor humidity. The Moisture Buffer Value of materials (MBV) was studied by

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D. Johansson et al. (eds.), *Cold Climate HVAC 2018*,
Springer Proceedings in Energy, https://doi.org/10.1007/978-3-030-00662-4_80

several authors [1, 2], and divided into three descriptive levels: material, system and room level. Fluctuating variation of moisture buffering can be diurnal or seasonal, also differences between workdays and weekends can be significant. In real life attention is mostly paid to diurnal variations of moisture buffering like proposed by NORDTEST method [1].

Janssen [3] introduced the formula for $MBV_{practical}$ [g/(m^2 %RH)] calculations including moisture mass (max-min) in sample and range of RH levels. **Thermal effusivity** [3] of material is calculated as the square root of density, thermal conductivity and specific heat capacity, When introducing **moisture effusivity** $\mathbf{b_m}$ [kg/(m^{2}Pa · s½)] in a comparable way, it describes the ability of a material to absorb or release moisture. A daily hygroscopic inertia index, $I_{h,d}$, was introduced by Ramos [5, 6] as a function of MBV which takes ventilation and time into account. All the parameters described above need quite exact numbers for calculation.

McCregor [7] found out that soil selection (minerals and particle size distribution) is more important for the moisture buffering of clay product than changes can be made to a particular soil (density etc.). The clay mineral kaolinite is known as a mineral which absorbs most of water within the first minute and at temperature under 100° C, and it hardly gives up any water [8]. Montmorillonite (Smectite) is known as a mineral easily absorbing water and also its expansion is remarkable. But for example clays in Estonia do not seem to be rich in smectite [9], only illite-smectite and kaolinite can be found.

Schneider and Goss [10] introduced a revised pedotransfer function (PTF) enabling to predict (based on the clay content of the soil) sorption isotherms for dry soils. PTF seems to be suitable to soils containing more than 7% clay and with a clay fraction ratio of 2:1. Soils containing mostly kaolinite as the dominant clay mineral absorb less water than predicted and cannot be described by the log linear function proposed by Campbell and Shiozawa [11]. Arthur [12] studied the possibilities of prediction of clay content from water vapour sorption isotherms considering hysteresis and soil organic matter content. He presented regression relationships for determining clay content from water contents by using the relationship between clay and soil water content (3–93% RH).

The study presented focuses on the possible differences within the "same material" i.e. different products known by the common name "clay plaster". The main components of clay plaster are sand and clay—both of which are mineral resources with very different properties because of their chemical composition or particle size distribution.

2 Materials and Methods

The study focuses on the hygrothermal properties of clay plasters. Eight different clay-sand plaster (6 specimen each) mixtures were used (diameter 100 mm, thickness 25 mm). Mineral content and particle size distribution were estimated for all specimens. All the plaster mixtures tested were produced by manufacturers and the exact content of recipes was not available for study. Only water was added in the laboratory. Short description of mixtures is presented in Table 1. All materials are relevant for indoor use and usually have some surface coating and the influence of coatings must be studied, but separately. The study focuses on plasters but some preliminary data about coatings is gathered by authors already [13].

The consistence of fresh mortar was estimated by standard EVS-EN 1015-3:2004 + A2:2007 [14] and flow table Cooper TCM-0060/E was used. Hygroscopic sorption properties were studied at levels 30, 50 and 80% of RH following standard [15] procedure (in principle). Studied levels were found from literature [16, 17]. RH hardly exceeds value of 80% in living room, but often in bathroom and sometimes in kitchens too.

To describe the dynamics, the specimens were weighed at 1, 2, 3, 6, 12, 24 h during the first day and with a 24-h interval until stabilization [17] at every RH level. The standard [18] procedure was followed when determining plasters properties for water vapour permeability.

The same specimens (embedded into a plastic cylinder and tightened with plastic film and silicon hermetic) were used for both tests. Climate chamber method (RUMED 4101 RH = 20−95%, accuracy ±2 to 3%, temperature 0 to +60 °C, accuracy ±0.5 °C) was used.

Mineralogical composition was estimated at the Institute of Ecology and Earth Sciences of Tartu University by a professor of the Department of Geology Kalle Kirsimäe. X-ray diffraction method with XRD spectrometer Bruker D8 Advance was used. Particle size distribution was estimated by wet sieving analyses by standard EVS-EN1015-1:2004 [19]. The measurement of the 0.063 mm sieve enables only to separate the mixture of silt and clay as a total from sand particles. The calculation formula of fineness modulus for sand was used to describe plasters with one distinguishable number and make results easily comparable.

Table 1 Description and properties of clay plaster specimens

Clay plastr mixture	Specimen group	Fresh mortar specimen on flow table (cm)	Hardened mortar specimen		
			Dry weight (g)	Volume (cm^3)	Dry density (kg/m^3)
Red 0–2 mm cattail	I	19.0	374	200	1864
Brown 0–2 mm cattail	II	18.0	383	203	1892
Dark red 0–2 mm cattail	III	17.5	347	190	1830
Blue 0–2 mm cattail	IV	17.5	363	199	1826
Grey 0–2 mm cattail	V	17.8	374	206	1812
Dark red 0–2 mm	VI	16.5	319	176	1808
White 0–2 mm	VII	16.8	353	202	1748
Dark red 0-2 mm hemp shives	VIII	–	258	190	1357

3 Results

Moulds used are uniform by size. However—dry weight, volume and dry density of specimens have variance (Table 1) because of shrinkage (volume of groups III and VI) and/or additives (dry density of group VIII) (Fig. 1). All mixtures were prepared with a minimum water content indicated in the recipes as first choice. Mixture I received diameter of 19 mm on flow table with minimum water content. Mixture with hemp shives had not flowability. For other recipes some water was added. Shrinkage during the drying was very different and can be seen in photos (Fig. 1) being about 1 mm for white (VII) up to 6 mm for dark red (III, VI).

Sorption. The specimens with 0% of moisture content were placed to the climate chamber with air temperature 23 °C with RH of 30%. A problem occurred—after drying and during cooling there was some water uptake (0.17–0.35 g per specimen).

This has some influence on the results and desiccants must be used more effectively in the future. Moisture uptake rate kg/(m^2h) describes the speed behavior within the first hours and total moisture uptake (kg/m^2) describes water vapour gathered at RH = 0–30, RH = 30–50 and RH = 50-80%.

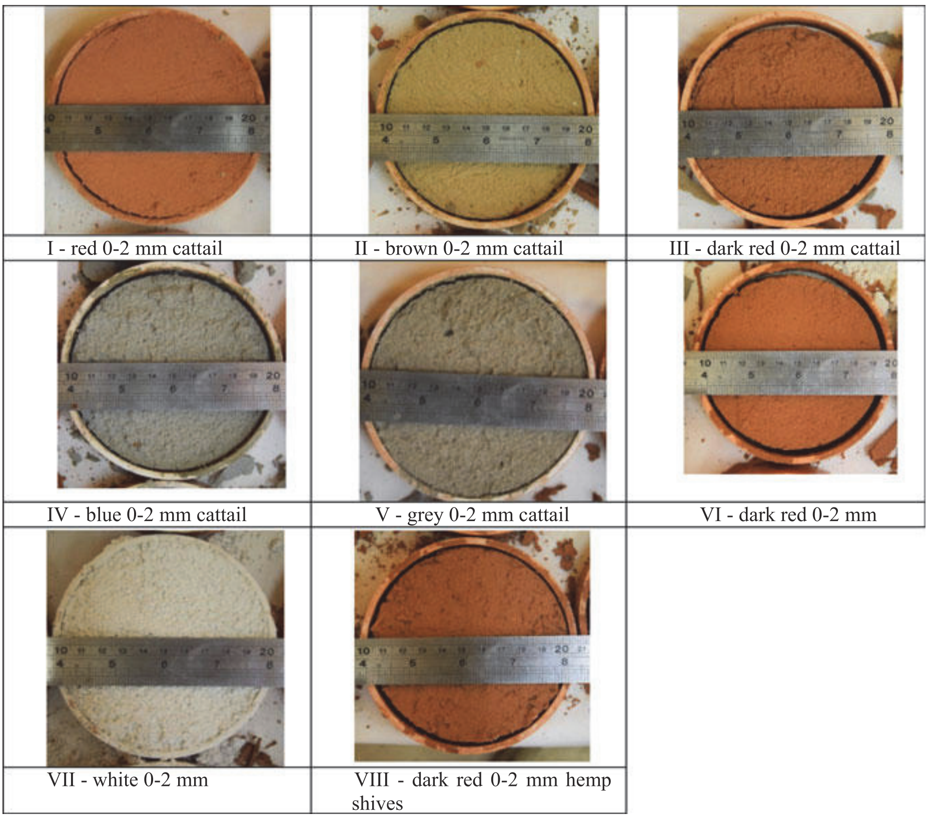

Fig. 1 Examples of specimen groups

Sorption range RH = 0–30%. The moisture uptake rate (Table 2) was highest during the first hour (6.0–14.8 g/(m^2h). Higher was rate for plaster groups I, III, VI, VIII [14.2–14.8 g/(m^2h)] being 5–20% of total moisture uptake.

For group I stabilization time was 48 h and for III, VI and VIII 120 h. The lowest rate was presented by group VII [6.0 g/(m^2h)] being 64% of total moisture uptake (9.4 g/m^2) and stabilizing at 24 h. It can be seen that plasters behave very differently.

The range of **RH = 30–50%** is presenting ventilated indoor living environment most exactly. (Table 3). The range of **RH = 50–80%** but could occur in rooms with high occupation and unsatisfying ventilation rate (Table 4). For both ranges it can be seen that during the first hour the most active is plaster group I and the least active group is VII. There are some negative values of adsorptions during the second and third hour. That is because environments in laboratory (RH = 22–27%) and climate chamber (RH = 50% or RH = 80%) are so different from each other and during weighing time some moisture is already released. On the other hand, it indicates the sensitivity of plasters. The problem must be solved in the future and test must be repeated in a more reliable way. Reliable data used in calculations are total moisture uptake within the given ranges. For desorption results are more adequate. In groups III, VI and VIII the total moisture uptake within the range (RH = 30–50%) was 147.8–164.8 and 250.8–298.9 g/m^2 (RH = 50–80%). In group VII the total moisture uptake within the range (RH = 30–50%) was 8.1 and 24.1 g/m^2 (RH = 50–80%). Results are similar at desorption (Tables 3 and 4). In real life probably 24 h cyclic fluctuation could be more adequate than total moisture uptake or release within 5–6 days.

Anyway, the tendency described above is seen already within the first hours (especially at desorption) and there are large differences between the plasters—up to 20 times (8.1 vs. 164.8 g/m^2 at RH = 30–50%). In Table 5 water uptake per specimens (g) and moisture content of plasters (%)—points on sorption curve are presented.

Diffusion. Difference from standard was thickness of air layer used in calculations—approx. 5 cm instead of 1 ± 0.5. That aspect was taken into account in calculations but as the material is highly water permeable it has some influence on results. The

Table 2 Sorption at RH = 0–30%.

	Sorption								
	1 h	2 h	3 h	120 h		1 h	2 h	3 h	120 h
	g/(m^2h)	g/(m^2h)/g/m^2	g/(m^2h)/g/m^2	g/m^2		g/(m^2h)	g/(m^2h)/g/m^2	g/(m^2h)/g/m^2	g/m^2
I	14.4	7.5/21.7	4.3/25.9	71.9	V	11.8	3.0/14.8	3.6/18.4	89.7
II	8.6	5.0/13.4	4.1/17.5	114.2	VI	14.7	8.8/23.5	6.8/30.3	301.1
III	14.8	6.6/21.4	6.2/27.6	283.7	VII	6.0	2.2/8.2	−1.7/6.5	9.4
IV	7.5	3.6/11.1	4.2/15.3	82.1	VIII	14.2	7.9/22.1	6.9/29.0	269.6

Moisture uptake rate g/(m^2h) and total moisture uptake g/m^2

Table 3 Sorption and desorption at RH = 30–50%. Moisture uptake/release rate g/(m^{2}h) and total moisture uptake/release g/m^2

	Sorption				Desorption			
	1 h	2 h	3 h	120 h	1 h	2 h	3 h	120 h
	g/(m^{2}h)	g/(m^{2}h)/ g/m^2	g/(m^{2}h)/ g/m^2	g/m^2	g/(m^{2}h)	g/(m^{2}h)/ g/m^2	g/(m^{2}h)/ g/m^2	g/m^2
I	9.4	−1.2/8.2	4.1/12.3	45.3	−8.3	−6.3/−14.5	−6.3/−20.8	−53.3
II	4.7	0.5/5.2	1.6/6.8	63.1	−6.5	−4.4/−10.9	−4.0/−14.9	−71.3
III	7.8	3.3/11.1	1.2/12.3	147.8	−11.9	−7.0/−18.9	−4.3/−23.2	−148.2
IV	5.5	0.8/6.3	0.9/7.2	69.5	−6.6	−4.3/−10.9	−2.8/−13.7	−78.0
V	3.9	−0.3/3.6	1.9/5.5	55.7	−6.7	−4.8/−11.5	−2.8/−14.3	−65.1
VI	6.5	7.4/13.9	−0.8/13.1	164.8	−15.3	−6.8/−22.1	−5.9/−28.0	−165.1
VII	3.4	−1.2/2.2	0/2.2	8.1	−3.5	−2.3/−5.8	−1.9/−7.7	−13.7
VIII	7.4	4.3/11.7	0.8/12.5	164.1	−12.7	−6.3/−19.0	−5.1/−24.1	−161.6

Table 4 Sorption at RH = 50–80%. Moisture uptake/release rate g/(m^{2}h) and total moisture uptake/release g/m^2

	Sorption				Desorption			
	1 h	2 h	3 h	120 h	1 h	2 h	3 h	120 h
	g/(m^{2}h)	g/(m^{2}h)/ g/m^2	g/(m^{2}h)/ g/m^2	g/m^2	g/(m^{2}h)	g/(m^{2}h)/ g/m^2	g/(m^{2}h)/ g/m^2	g/m^2
I	9.6	−14.8/−5.2	8.1/2.9	110.7	−23.3	−25.8/−49.1	−4.7/−53.8	−116.2
II	4.7	−3.4/1.3	−0.6/0.7	146.7	−14.5	−11.6/−26.1	−7.3/−33.4	−128.4
III	4.9	0.1/5.0	−6.4/−1.4	250.8	−30.6	−12.1/−43.7	−14.7/−58.4	−209.6
IV	5.0	−1.8/3.2	2.9/1.1	187.3	−26.3	−10.0/−36.3	−9/−45.3	−154.0
V	4.6	−5.7/−1.1	−0.7/−1.8	145.6	−15.6	−13.5/−29.1	−7.9/−37.0	−135.8
VI	5.5	6.9/12.4	−12.8/−0.4	279.0	−30	−11.6/−41.6	−22.3/−63.9	−228.4
VII	2.9	−11.4/−8.5	5.8/0.4	24.1	−8.8	−7.3/−16.1	−1.6/−17.7	−24.2
VIII	5.3	3.7/9.0	8.6/0.4	298.9	−29.9	−11.0/−40.9	17.4/−58.3	−213.8

water vapour permeance of 2.5 cm layer varied between 1680 and 3076 $\times$ 10^{-9} kg/(m^{2}sPa) and water vapour permeability was from 44 to 76 $\times$ 10^{-12} kg/(msPa). Water vapour resistance factor μ was found to be μ = 2.7–4.6. Water vapour diffusion equivalent air layer thickness S_d is presented in Table 7. *T*-test analysis was performed to study water vapour resistance. It proved that group III (r = 0.33 10^9 m^2 s Pa/kg) is significantly different from all other groups. For group VI *p* equalled 0.016. All other values were smaller than that. Groups VI and VIII were also statistically different from other groups (p = 0.014).

Mineralogical composition including sand and additives (e.g. cattail) in clay plaster mixture was estimated The results are presented in Table 6 where “tr” means that the content of the mineral is less than accuracy.

Table 5 Water uptake per specimen (g) and moisture content of plasters (%)

	RH = 0–30% (120 h)			RH = 30–50% (120 h)			RH = 50–80% (120 h)		
	Water uptake		Moisture content RH = 30%	Water uptake		Moisture content RH = 50%	Water uptake		Moisture content RH = 80%
	Range	Aver.		Range	Aver.		Range	Aver.	
	g	g	%	g	g	%	g	g	%
I	0.51–0.68	0.58	0.16	0.35–0.38	0.36	0.25	0.82–0.95	0.89	0.49
II	0.85–0.95	0.92	0.24	0.47–0.54	0.51	0.37	1.11–1.21	1.18	0.68
III	1.96–2.32	2.19	0.63	1.07–1.23	1.14	0.96	1.85–2.05	1.93	1.52
IV	0.61–0.67	0.65	0.18	0.54–0.57	0.55	0.33	1.44–1.54	1.48	0.74
V	0.54–0.91	0.72	0.19	0.42–0.48	0.45	0.31	1.12–1.21	1.17	0.63
VI	2.17–2.32	2.24	0.70	1.19–1.31	1.23	1.09	2.02–2.14	2.08	1.74
VII	0.02–0.11	0.08	0.02	−0.02–0.1	0.07	0.04	0.13–0.23	0.20	0.10
VIII	2.07–2.17	2.13	0.83	1.22–1.38	1.30	1.33	2.32–2.42	2.36	2.24

Table 6 Mineralogical composition of plaster mixture, % of mass

Component	I	II	III	IV	V	VI	VII	VIII
Quartz	54.7	58.7	49.1	52.8	54.7	45.6	55.8	49.8
K-feldspar	9.8	8.4	9.6	7.3	9.8	6.6	10.5	16.2
Plagioclase	9.5	7.5	7.8	8.8	9.5	7.9	5.6	9.1
Chlorite	0.6	1.0	1.0	0.8	Tr	1.5		0.9
Ill./Ill-smect.	13.0	12.0	14.0	16.4	13.0	20.9	8.0	8.0
Kaolinite	5.4	2.8	4.2	3.8	5.4	4.1	15.7	3.6
Calcite	4.2	5.2	8.6	5.7	4.2	8.5		7.2
Dolomite	2.2	3.6	4.2	4.2	2.2	4.0		3.5
Hematite			Tr			0.5		0.5
Amphibole	0.6	0.8	0.9		0.6	0.5	0.9	1.2
Cristobalite							1.9	
Anatase							tr	

Clay mixture VII which had the highest kaolinite content absorbed less water than others—according to data known from literature (Fig. 2a). On the other hand, it can be seen that other mixtures which have similar kaolinite content do not absorb water the same way and no strong correlation can be found $R^2 = 0.42$. From literature data it is known that smectite has a good ability to absorb water.

Table 7 Summarized data collected

Specimen	Specimen moisture content g				S_d m	Kaolinite (%)	Calcite (%)	FM
	0–30%	30–50%	50–80%	0–80%				
I	0.58	0.36	0.89	1.83	0.10	5.47	4.2	1.5
II	0.92	0.51	1.18	2.61	0.11	2.8	5.2	1.6
III	2.19	1.14	1.93	5.26	0.07	4.2	8.6	1.7
IV	0.65	0.55	1.48	2.68	0.12	3.8	5.7	1.7
V	0.72	0.45	1.17	2.34	0.12	5.4	4.2	1.6
VI	2.24	1.23	2.08	5.55	0.08	4.1	8.5	1.2
VII	0.08	0.07	0.20	0.35	0.12	15.7	0	2.9
VIII	2.13	1.29	2.36	5.78	0.08	3.6	7.2	1.2

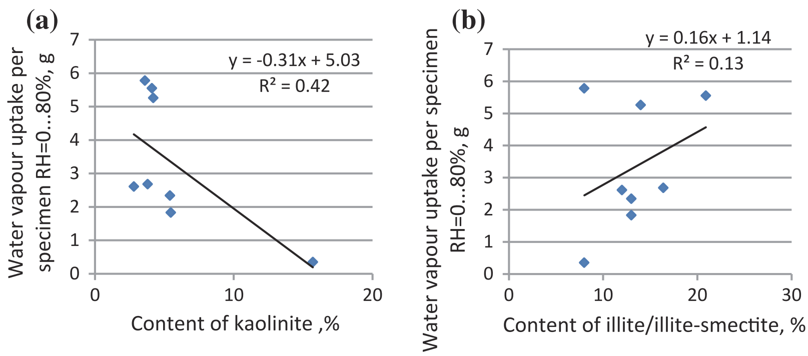

Fig. 2 Water vapour uptake g per specimen depending on the content of kaolinite (**a**) and content of illite/illite-smectite (**b**)

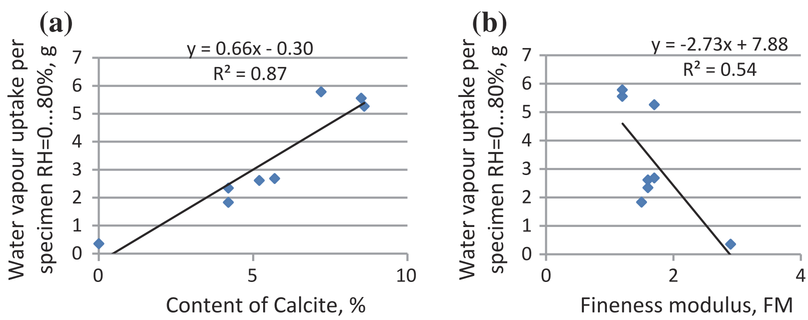

Fig. 3 Water vapour uptake g per specimen depending on content of calcite (**a**) and FM (**b**)

In mixture under investigation there was no smectite separately present. No correlation $R^2 = 0.12$ (Fig. 2b) can be found between illite/illite-smectite content and water vapour uptake. Strong correlation $R^2 = 0.87$ (Fig. 3a) was found—between content of calcite in plaster and water vapour uptake ability.

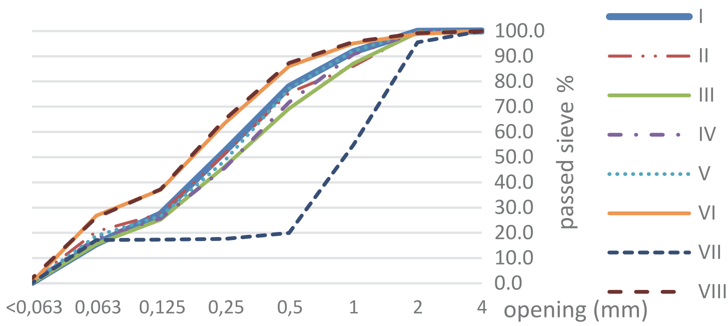

Fig. 4 Particle size distribution curves

Particle size distribution was estimated by wet sieving analyses. Curves can be seen in Fig. 4 where Group VII (FM = 2.9) again has differences with others (FM = 1.2–1.7). In group VII bout ¾ of the material has particle size 0.5–2 mm. In other groups about ½ of material has particle size 0.125–0.5 mm. There was no strong correlation between fineness modulus and water vapour uptake—R^2 = 0.54 (Fig. 3b), but it is clearly seen that the mixture (VII) which has bigger particle size and therefore less specific surface area has the smallest water adsorption ability.

4 Discussion and Conclusions

All the results are summarised in Table 7. Group VII (white clay) differentiates from others in most aspects except water vapour permeability. There kaolinite and FM = 2.9 (e.g. coarse sand) content is the largest. There is no calcite in the clay and almost no ability to absorb water vapour compared to other clay plaster mixtures (0.35 g vs. 1.8–5.8 g per specimen). All other groups having FM = 1.2–1.7 could be compared to fine sand. According to literature smectite is well known because of its good moisture buffering ability. There was no pure smectite in the plasters studied.

By sorption properties clay mixtures can be divided into three groups. The largest amount of water vapour was absorbed by specimen groups III, VI and VIII (>5 g per specimen) all basing on the same dark red clay. There calcite content is 7.2 to 8.6%—clearly bigger than in others and S_d = 0.07–0.08 m vs. S_d = 0.1–0.12 m.

No other positive or negative correlation was found. Similar (medium) sorption properties (1.83–2.68 g per specimen) presented specimen groups I, II, IV and V basing on clays from different sources (brown, grey, blue, red). There calcite content is 4.2–5.7%—clearly smaller than in specimen groups III, VI and VIII.

Moisture uptake rate properties show that group I is very active (Tables 2, 3 and 4) and has almost largest initial moisture uptake rate (1 h). Stabilization time is about 48 h. Group VII has the lowest initial moisture uptake rate and the smallest stabilisation time (6–24 h). Groups III, VI and VIII have the longest stabilization period. Activity within the first hour depends on the range of RH.

Moisture buffering ability of material is strongly related with sorption properties. By using formula introduced by Janssen [3] it can be calculated from data presented that MBV_{8h} at RH = 30–50% range is 0.3 (VII) to 1.9 (VI, VIII) and at RH = 50–80% range is 0.6 (VII) to 2.3 (VI, VIII) g/(m^2 %RH)@8/16 h). According to $MBV_{prcatical}$ classification introduced by Rode [4] different clay plasters could be estimated as “limited” ($MBV_{practical}$ = 0.2–0.5 g/(m^2 %RH)@8/16 h), “moderate” (0.5–1), “good” (1–2) or even “excellent” (2–3.5 g/(m^2 %RH)@8/16 h)).

By water vapour permeability plasters can be divided into two groups, where differences are not as clear as at sorption, but tendency is the same. Groups III, VI and VIII have higher water vapour uptake/release and water vapour permeability.

The study presented proved that there are differences within the “same material” i.e. different products known by the common name “clay plaster”. The main components of clay plaster are sand and clay—both of which are mineral resources with very different properties because of their chemical composition or particle size distribution.

The clearest correlation was found between the calcite content of plaster mixture and water vapour uptake. The properties of products must be monitored carefully. If a plaster is included into hygrothermal calculations of boarders or ventilation rate, the properties must be declared and the user has to be aware of them. Also, the user who just wants to use plaster with good moisture buffering ability must be supplied with relevant information if the product does not have commonly expected properties.

Acknowledgements This study was supported by Tartu College of TUT. Special thanks to Marko Kikas from Saviukumaja and Prof. Kalle Kirsimäe from Tartu University.

References

1. C. Rode, Moisture buffering of building materials, BYG DTU-126 Report, Department of Civil Engineering, Technical University of Denmark, 2005, http://www.byg.dtu.dk/upload/institutter/byg/publications/rapporter/byg-r126.pdf
2. K. Svennberg, Moisture Buffering in the Indoor Environment. Thesis Building Physics LTH Lund University, 2006
3. H. Janssen, A. Roels, Qualitative and quantitative assessment of interior moisture buffering by enclosures. Energy Build. **41**(4), 382–394 (2009)
4. C. Rode, R. Peuhkuri, B. Time, K. Svennberg, T. Ojanen, Moisture buffer value of building materials. J. ASTM Int. **4**(5), 1–12 (2007)
5. H.M.M. Ramos, J.M.P.Q. Delgado, V.P. de Freitas, Influence of finishing coatings on hygroscopic moisture buffering in building elements. Constr. Build. Mater. **24**, 2590–2597 (2010)
6. N.M.M. Ramos, V.P. Freitas, Laboratory testing for daily hygroscopic inertia assessment, in *Proceedings of the 8th Symposium on Building Physics in the Nordic countries*, Copenhagen, Denmark (2008), pp. 809–816

7. F. McGregor, A. Heath, A. Shea, M. Lawrence, The moisture capacity of unfired clay masonry. Build. Environ. **82**, 599–607 (2014)
8. W.A. White, E. Pichler, *Water Sorption Characteristics of Clay Minerals*, USA (1959)
9. M. Palolill, Looduslike savide ja savipinnaste geotehniliste omaduste sõltuvus saviminer-aalsest koostisest: ekvivalentse basaalse distantsi kontseptsioon. Master Thesis, Tartu University Tartu, 2007, (In Estonian) http://dspace.ut.ee/bitstream/handle/10062/2752/palolill_margus.pdf?sequence=1
10. M. Schneider, K.-U. Goss, Prediction of the water sorption isotherm in air dry soils. Geoderma **170**, 64–69 (2012)
11. G.S. Campbell, S. Shiozawa, Prediction of hydraulic properties of soils using particle size distribution and bulk density data, in *International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils*, University of California Press, Berkely (1992) referred by Scheider
12. E. Arthur, M. Tuller, C. Moldrup, D.K. Jens, L.W. De Jong, Prediction of clay content from water vapour sorption isotherms considering hysteresis and soil organic matter Content. Eur. J. Soil Sci. **66**, 206–217 (2015)
13. O. Vares, A. Ruus, J. Raamets, E. Tungel, Determination of hygrothermal performance of clay-sand plaster: influence of covering on sorption and water vapour permeability. Energy Procedia **132**, 267–272 (2017)
14. EVS-EN 1015-3:2004 + A2:2007, *Methods of Test Mortar for Masonry Part 3: Determination of Consistence of Fresh mortar by Flow Table*
15. EVS-EN ISO 12571, *Hygrothermal Performance of Building Materials and Products—Determination of Hygroscopic Sorption Properties*
16. G. Minke, *Building with Earth—Design and Technology of a Sustainable Architecture* (Birkhäuser, Basel, 2012)
17. M. Maddison, T. Mauring, K. Kirsimäe, M. Mander, The humidity buffer capacity of clay-sand plaster filled with phythomass from treatment wetland. Build. Environ. **44**, 1864–1868 (2010)
18. EVS-EN 1015-19:2005, *Methods of Test for Mortar for Masonry—Part 19: Determination of Water Vapour Permeability of Hardened Rendering and Plastering Mortars*
19. EVS-EN1015-1:2004, *Methods of Test for Mortar for Masonry. Part 1: Determination of Particle Size Distribution (by sieve analyses)*

Publication IV

Raamets, J., Ruus, A., Ivask, M., Nei, L., Muoni, K. (2020). Siseõhu kvaliteet põhu- ja pilliroopakkidest seintega elumajades. *Agraarteadus*, 31(1), 84–95. Doi:10.15159/jas.20.05

Agraarteadus
1 ● XXXI ● 2020 84–95

Journal of Agricultural Science
1 ● XXXI ● 2020 84–95

SISEÕHU KVALITEET PÕHU- JA PILLIROOPAKKIDEST SEINTEGA ELUMAJADES

INDOOR AIR QUALITY IN RESIDENTIAL BUILDINGS WITH STRAW- AND REED-BALE WALLS

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Saabunud: Received: 11.02.2020
Aktsepteeritud: Accepted: 08.05.2020

Avaldatud veebis: Published online: 12.05.2020

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Keywords: mould, indoor air, straw-bale walls, reed-bale walls, propagules.

DOI: 10.15159/jas.20.05

ABSTRACT. Straw and reed are natural local insulation- and construction materials, which properties allow them to replace energy intensive building materials. In general, straw and reed as building materials are considered harmless to the environment and human health. Unfortunately, the use of these materials may bring about mould growth in buildings which may result in different diseases (for example irritation of eyes, nose and throat, allergic rhinitis, conjunctivitis, and asthma) in people with weaker immune systems. No research has been carried out on the topic of microbiological community in straw and reed houses in climatic conditions similar to Estonia, although buildings made of natural materials are becoming more and more popular. The aims of the study were to investigate the indoor climate of buildings with straw and reed-bale walls and to determine the factors influencing indoor air quality. In order to fulfil the set aim: (1) air quality was tested in the bedrooms of the studied houses, and the microbial species in air and walls were determined; (2) the indoor air quality parameters (CO_2, RH%, and temperature) in air and at two different heights in the walls were measured. The results enable to conclude that the walls of straw or reed-bale house are suitable in Estonian climatic conditions, which as a result of professional design, usage of materials suitable for building, and high-quality craftsmanship provides a healthy and environmentally friendly housing.

Sissejuhatus

Inimesed veedavad erinevatele uuringutele tuginedes 80–90% oma ajast siseruumides (Horr jt, 2016; Katsoyiannis, Cincinelli, 2019) ning umbes kolmandik inimese eluajast veedetakse magades (Strøm-Tejsen jt, 2015). Viimastel aastatel on publitseeritud hulgaliselt siseõhu kvaliteeti käsitlevaid uuringuid, kuid magamistoad, kus inimesed veedavad 7–8 järjestikust tundi oma päevast, leiavad sellistes uuringutes väga vähe käsitlemist (Strøm-Tejsen jt, 2015, Canha jt, 2019).

Pilliroog ja teraviljapõhk on materjalid, millest ehitamine on viimasel kümnendil järjest enam populaarsust kogunud. Sellistest materjalidest ehitamine on säästlik nii keskkonnale kui võimaldab kokku hoida ka energiat, mida on vaja hoonete kütteks ja jahutamiseks (Milutiené jt, 2012). Olgugi, et põhk ja pilliroog on lihtsasti hangitavad ja naturaalsel kujul ka odavad materjalid, on tegemist materjalidega, mis võivad olla potentsiaalseteks ohuallikateks inimese tervisele. Koosnedes tselluloosist, hemitselluloosist ja ligniinist, on looduslikud materjalid heaks elupaigaks mikroorganismidele. Pidev eksponeeritus hallitusseentele võib põhjustada probleeme nõrgenenud immuunsüsteemiga inimestele, kroonilistele haigetele, lastele ja vanuritele (Portnoy jt, 2005, Hernberg jt, 2014).

Looduslike materjalide kasutamine ehituses kogub üha enam populaarsust. Uuringud näitavad, et võrreldes roopakist elamutega nõuab kivihoonete kütmine ja jahutamine rohkem energiat (Barreca jt, 2019). Pilliroo lisamine betoonisegule vähendab oluliselt materjali soojusjuhtivust (Shon jt, 2019). Rooehitised olid tuntud juba Sumeri kultuuris 5000 aastat tagasi ja Iraagi aladel on nad laialdaselt kasutusel ka tänasel päeval (Al-Jumeily jt, 2018). Need paistavad silma tervisliku sisekliima poolest ja roo kõrge ränisisaldus muudab selle materjali ebaatraktiivseks putukatele ning teistele loomadele (Al-Jumeily jt, 2018). Puudustena tuleb aga välja tuua tuletundlikkust ja madalat survetugevust, mistõttu saab ehitada kandvate seintega ainult ühekordseid hooneid (Al-Jumeily jt, 2018). Kui roog on lõigatud valel aastaajal, siis võib see kaasa tuua materjali lagunemise (Al-Jumeily jt, 2018). Seentel on oluline roll orgaaniliste ehitusmaterjalide lagundamisel (Raamets jt, 2017). 20–40% Euroopa ja Põhja-Ameerika hoonete sisekliima on mõjutatud hallitusest, millega kaasnevad erinevad terviseprobleemid (Laborel-Préneron jt, 2018). On leitud, et roog on tundlik mädaniku suhtes, kuid lagunemisprotsessi on võimalik olulisel määral alla suruda termilise töötlemise abil (Brischke, Hanske, 2016).

Mitmed autorid on oma uurimustes näidanud, et hallitusseened põhul võib jagada vee vajaduse järgi kolme rühma. Primaarsed koloniseerijad kuuluvad perekondadesse *Wallemia, Penicillium, Aspergillus* ja *Eurotium*, sekundaarsed koloniseerijad perekondadesse *Cladosporium, Ulocladium ja Alternaria* ning tertsiaarsed koloniseerijad perekondadest *Stachybotrys, Chaetomium, Trichoderma* ja *Auraeobasidium* (Grant jt, 1989; Gravesen jt, 1994, Nielsen jt, 2004). Eesti päritolu teravilja tüüpilised hallitusseened kuuluvad perekondadesse *Cladosporium, Alternaria, Aspergillus, Fusarium, Penicillium, Helminthosporium, Mucor ja Rhizopus* (Lõiveke jt, 2008). Perekonda *Aspergillus* kuuluvate liikide esinemine on iseloomulikum just Lõuna-Eestile (Lõiveke, 2008). Ka siseõhus on seeneperekonnad *Alternaria, Aspergillus, Cladosporium* ja *Penicillium* levinuimad (Zorman, Jeršek, 2008, Bernasconi jt, 2010).

Esimesed teadaolevad põhupallidest hooned püstitati 19. sajandi lõpul Nebraskas, põhjuseks eelkõige elanike vaesus (Henderson, 2007). Üks vanemaid sealseid põhupallidest hooneid, pärineb aastast 1903 (King, 2006). Sellist pikaealisust põhjendatakse kuiva kohaliku kliimaga (Henderson, 2007). Tänapäeval leidub põhupallidest tehtud maju Ameerika Ühendriikides, Euroopas, Kanadas, Austraalias ja Aasias (Holzhueter, Itonaga, 2010). Holzhueter ja Itonaga väidavad, et hallituse tekkimise oht on põhuelamute korral ülepaisutatud. Hallituse tekke vältimisel annavad eriliselt positiivset efekti vihmatõkked (Holzhueter, Itonaga, 2017). Siiani ei ole meie kliimavöötmes tehtud arvestatavaid uuringuid selle kohta, millised mikroobid põhul ja pillirool kui ehitusmaterjalil elutsevad, milline on siin ehitatud põhu- ja roopakkidest seintega elamute sisekliima ning käesoleva töö eesmärgiks uurida kompleksselt Eesti roo- ja põhuelamute sisekliimat ning seda mõjutavaid tegureid.

Materjal ja metoodika

Püstitatud eesmärgi saavutamiseks:

- Võeti õhuproovid uuritavate elamute magamistubadest ning välisõhust ja materjaliproove välispiiretest. Määrati nii sise- kui ka välisõhus ning piiretes leiduvad seened perekonna tasemeni;
- Määrati sisekliima näitajad (RH% ja temperatuur) elamute siseõhust (määrati lisaks ka CO_2) kui ka kahelt erinevalt kõrguselt (0,2 ja 1,2 m) välisseintes;
- Hinnati välisseinte niiskuskoormust ja hallituse ohtu.

Ülevaade uuritud objektidest

Uuringu käigus võeti proove ja koguti andur-andmesalvestitega andmeid neljast põhu- ja neljast roopakkidest ehitatud seintega elamust. Osa elamutest (kaks põhu- ja üks roopakkidest seintega) oli ehitatud Nebraska stiilis, osa karkassiga (üks põhu- ja kolm roopakkidest seintega), ühe põhupakkidest seintega elumaja puhul on ehitusel kasutatud tehases valmistatud mooduleid. Kõik uuritud elamud on projekteeritud ja ehitatud vastava kogemusega projekteerijate ja ehitusettevõtete poolt. Visuaalsel vaatlusel niiskuskahjustusi ja hallituse kasvu ei tuvastatud. Uuritud elamute vanus jäi 2–7 aasta vahele.

Elamute keskmine välisseina paksus oli 50 ± 5 cm, erandiks oli elumaja, mille seina paksus oli 100 cm. Kõik seinad olid krohvitud nii seest kui ka väljast. Krohvikihi paksus oli enamasti nii sees kui ka väljas 5 cm, erandiks olid kaks elamut. Ühe elamu seinte krohvikihi paksus oli nii seest kui ka väljast 7 cm (lubikrohv), teisel elamul oli välisseina sisepinnal 10 cm krohvi, välisseinas 12 cm krohvi. Krohvimiseks oli kasutatud enamasti savikrohvi, kahe elamu puhul oli kasutusel nii sise- kui ka välisviimistlusel lubikrohv. Kõigil uuritud elamutel oli küllaltki kõrge sokkel, lai räästas (joonis 1), mis on oluline abinõu vähendamaks seinte niiskuskoormust.

Vundamendina kasutati nii madalvundamenti (viis elamut) kui ka postvundamenti (3). Kõikide põrandate konstruktsioon oli puidust. Katusekattematerjaliks on kolme elamu puhul laast, kolme elamu puhul rullmaterjal/PVC, ühel elamul kivi ja ühel elamul on rohekatus.

Kasutatud metoodika

Töös peeti oluliseks uurida elamuid kompleksselt, katsed viidi läbi perioodil oktoober 2014 – oktoober 2016, kogudes paralleelselt sisekliima parameetrite (temperatuur, RH, CO_2) ning mikrobioloogia andmeid (pesa moodustavate ühikute arv ja taksonoomiline koosseis) nii õhust kui ka välispiirde (seinte) materjalist.

Elanikel paluti kuus tundi enne proovide võtmist magamistube mitte tuulutada. Söötmed (linnasesööde (MEA) ja dikloraan 18% sööde (DG18)) valmistati ja proovivõtuprotseduur viidi läbi ISO standardist 16000-18 juhindudes (ISO 16000-18:2011). Söötmekomponendid kaaluti analüütilise kaaluga (ABJ 120-4M, Kern & Sohn, Balingen, Saksamaa). Söötmed autoklaaviti, kasutades HMT 260 MB autoklaavi (HMC Europe, Tüssling, Saksamaa). Proovid koguti õhuanalüsaatoritega Mirobio MB2 (Cantum Scientific, Dartford, Ühendkuningriik) 9 cm Petri tassidele neli korda aastas (kevadel, suvel, sügisel ja talvel) magamistubadest ühe meetri kõrguselt põrandapinnast. Proovivõtu aeg oli üks minut ja õhu kogus 100 liitrit proovi kohta. Igalt alalt koguti kokku neli paralleelproovi mõlema söötmega. Referentsina koguti õhuproovid nelja paralleelina ka välisõhust 1,5 m kõrguselt maapinnast. Kogutud proove töödeldi, lähtudes EVS-ISO standardist 16000-17 (EVS-ISO 16000-17:2012.). Proove inkubeeriti 25 ^{o}C juures seitse päeva, peale mida loeti pesa moodustavad ühikud (PMÜ). Puhaskultuuride saamiseks teostati edasised külvid. Seened määrati morfoloogiliste tunnuste alusel mikroskoobi abil (SP100, Brunnel Microscopes LTD, Chippenham, Ühendkuningriik). Värvimiseks kasutati laktofenool-puuvillasinist. Väljakülvid identifitseeriti perekondadeni, kasutades selleks erinevaid määrajaid (Domsch jt, 1980; Kilch, 1988; Samson jt, 1996; Bergey jt, 2000; Larone, 2002; Winn, Koneman, 2006; Watanabe, 2010).

Joonis 1. Näited uuritud elamute soklist (vasakpoolne pilt) ja räästast (parempoolne pilt)
Figure 1. *Examples of plinths (left image) and eaves (right image) of the studied buildings*

Välispiiretest (seinast) võeti ka põhu- ja roomaterjali uurimiseks proove, kasutades selleks varem välja töötatud metoodikat (Raamets jt, 2016). 10-grammise mahuga proovid plaaditi otse linnaseagarile (MEA), kuhu oli lisatud klooramfenikooli. Proove inkubeeriti 32 °C juures 72 tundi ning seejärel loendati kokku pesa moodustavad ühikud (PMÜ).

Lisaks koguti taustandmeid ühe andur-andmesalvestiga süsihappegaasi sisalduse, temperatuuri ja õhuniiskuse kohta uuritavate elamute magamistubadest (andur paiknes 1,2 m kõrgusel põrandapinnast, salvestades 30-minutilise intervalliga). Andmeid koguti ka temperatuuri ja õhuniiskuse kohta piiretes 20 cm sügavusel sisepinnast. Selleks puuriti piiretes kahele kõrgusele (0,2 ja 1,2 m) 7 mm läbimõõduga augud. Aukudesse asetati 20 cm sügavusele andur-andmesalvestitega mõõtepead ning automaatmõõtmisi teostati 10-minutilise intervalliga. Aukude sulgemiseks kasutati krohvi ja mingil määral vajus kinni ka kõrreline materjal ise.

Väliskliima andmetena kasutati Riigi Ilmateenistuse poolt mõõdetud andmeid uuritud elamutele lähimast automaatjaamast (Tallinna, Lääne-Nigula, Türi, Väike-Maarja). 2014. aasta november oli tavaliselt soojem (2,4 °C (norm 1,2 °C)). Nii 2014–2015 kui ka 2015–2016 aasta talv oli normist soojemad. 2015. aasta oli viimase poole sajandi kõige soojem aasta (keskmine õhutemperatuur 7,6 °C (norm 6,0 °C)) (Riigi Ilmateenistus, 2020).

Piirete niiskuskoormuse hindamiseks kasutati valemit 1, mis pärineb standardist EVS-EN ISO 13788 (EVS-EN ISO 13788:2012). Niiskuslisa Δv (g $m^{3\,-1}$) arvutati valemist:

$$\Delta v\ (g\ m^{-3}) = v_i - v_e \quad (1)$$

kus:
v_i – siseõhu veeaurusisaldus / *water vapour content (indoor air)*, g $m^{3\,-1}$;
v_e – välisõhu veeaurusisaldus / *water vapour content (outdoor air)*, g $m^{3\,-1}$.

Hallituseohu hindamiseks kasutati Hukka ja Viitaneni (1999) poolt avaldatud matemaatilist mudelit, mis kasutab nii suhtelise niiskuse kui ka temperatuuriandmeid hallitusindeksi arvutamiseks.

Kemikaalid ja töövahendid

Kõik tööks vajalikud kemikaalid ja reagendid osteti ettevõttest HNK Analüüsitehnika OÜ (Tallinn, Eesti). Soja baasil toodetud peptoon (≥99%, Fluka), kaaliumdivesinikfosfaat (KH_2PO_4) (puhtusaste ≥99%, Sigma Aldrich), magneesiumsulfaat heptahüdraat ($MgSO_4$ $7H_2O$) (puhtusaste ≥99,5%, Sigma Aldrich), D-(+)-glükoos (≥99,5%, Sigma Aldrich), dikloraan (2,6-dikloro-4-nitroaniliin) (puhtusaste ≥96%, Sigma Aldrich), klooramfenikool (puhtusaste ≥98%, Sigma Aldrich), glütserool (puhtusaste ≥99,96%, Sigma Aldrich), vesi (deioniseeritud, Sigma Aldrich). Agar (Sigma Aldrich), linnaseekstrakt (Sigma Aldrich), laktofenool-puuvillasinise (hallitusseente värvimiseks, Sigma Aldrich) vastasid standardis (ISO, 2011). Mikrobioloogilisteks külvideks vajalikud vahendid (Petri tassid (9 cm), inokulatsiooninõelad, alus- ja katteklaasid) osteti KRK OÜ (Tartu, Eesti).

Söötmekomponendid kaaluti analüütilise kaaluga ABJ 120-4M (mõõtetäpsus ±0,2 mg, tootja: Kern & Sohn, Balingen, Saksamaa). Söötmed autoklaaviti, kasutades HMT 260 MB autoklaavi (HMC Europe, Tüssling, Saksamaa). Söötmeplaadid valati tõmbekapi all (vastab ISO 13150 standardile, Retent AS, Nõo, Eesti). Proovid koguti õhuanalüsaatoritega Mirobio MB2 (Cantum Scientific, Dartford, Ühendkuningriik). Laboris valmistati destilleeritud vett seadmega RO01033 (ROWA, Heimsheim, Saksamaa).

Andmeid koguti igas magamistoas ka süsihappegaasi (CO_2) sisalduse, õhutemperatuuri ja niiskusnäitajate kohta andur-andmesalvestitega Green-Eye mudel 7798 (mõõtetäpsus süsinikdioksiidi mõõtmisel ±50 ppm, temperatuuri mõõtmisel ±0,6 °C, õhuniiskuse mõõtmisel ±3% (10–90%), tootja: TechGrow, Haag, Holland). Piiretest temperatuuri ja niiskusandmete kogumiseks kasutati Hobo UX100-023 andur-andmesalvesteid (mõõtevahemik –20°C kuni +70 °C, 5 kuni 95% RH, täpsus vastavalt ±0,35 °C ja ±2,5% RH, tootja Onset Computer Corporation, Bourne, Ameerika Ühendriigid).

Tulemused

Hallitusseente arvukus ja dünaamika sise- ja välisõhus aastaaegade lõikes ning hallitusseente koosseis perekondade lõikes

Sesoonne pesa moodustavate ühikute dünaamika on nii põhust kui ka roopakist ehitatud elamute magamistubade puhul sarnane (tabelid 1 ja 2). Erinevused esinevad moodustavate ühikute arvus. Kõige arvukam oli siseõhu mikroobikooslus põhupakkidest seintega elamutes suvel (tabel 1) (juuni–august), mil siseõhust kultiveeritavaid kolooniaid linnaseagarilt (MEA) oli keskmiselt 537 ± 102 PMÜ m^{3-1}. Sama seos esines ka roopakkidest seintega elamute puhul, mil suvel siseõhust kultiveeritavaid kolooniaid linnaseagarilt oli keskmiselt 858 ± 106 PMÜ m^{3-1}. Välisõhus (tabel 2) registreeriti samal ajal põhupakkidest seintega elamutel linnaseagarilt 289 ± 32 PMÜ m^{3-1} ja roopakkidest seintega elamutel 353 ± 41 PMÜ m^{3-1}. Kevadel ja sügisel jäid nii sise- kui ka välisõhust linnaseagarile võetud proovide puhul tulemused võrreldavale tasemele. Diglütserool 18% söötmele (DG18) võetud proovid olid samuti kõrgemad nii sise- kui ka välisõhus just suveperioodil ning madalaimad talvel.

Uuringu käigus identifitseeriti siseõhu hallitusseeni perekonna tasemeni (tabel 3). Talveperioodil kuulus kõige enam identifitseeritud seentest põhupakkidest seintega elamutes perekonda *Penicillum* (74%), järgnesid perekondadesse *Aspergillus* (17%), *Alternaria* (1%) ja *Cladosporium* (1%) kuuluvad hallitusseened, 7% hallitusseentest ei kuulunud eelnevalt mainitud perekondadesse. Roopakkidest seintega elamute puhul oli järgnevus perekondade lõikes sama ning erinevused esinesid osakaaludes *Penicillum* – 70%, *Aspergillus* – 19%, *Cladosporium* – 6%, *Alternaria* – 1%; 4% leitud hallitusseentest ei kuulunud eelnimetatud perekondadesse.

Tabel 1. Sesoonsed muutused pesa moodustavate ühikute (PMÜ) arvukuses siseõhus näidatuna aastaaja keskmisena elamute lõikes koos keskmise veaga (±SE) proovide lõikes m^{3-1} õhu kohta

Table 1. *Seasonal variation in culturable airborne fungi indoors shown as mean with standard error (±SE), range of CFU m^{-3} air*

Proovivõtu koht *Sampling site*	Talv *Winter*	Kevad *Spring*	Suvi *Summer*	Sügis *Autumn*
Põhk (MEA) *Straw (MEA)*	149 ± 29	298 ± 100	537 ± 102	307 ± 99
Roopakk (MEA) *Reed (MEA)*	380 ± 136	518 ± 145	858 ± 106	548 ± 155
Põhk (DG18) *Straw (DG18)*	14 ± 8	29 ± 9	46 ± 12	20 ± 11
Roopakk (DG18) *Reed (DG18)*	22 ± 13	23 ± 9	36 ± 11	22 ± 10

MEA – linnaseagari sööde / *Malt Extract Agar media;* DG18 – diglütserool 18% sööde / *18% Dichloran glycerol agar (DG18) media*

Tabel 2. Sessoonsed muutused pesa moodustavate ühikute (PMÜ) arvukuses välisõhus näidatuna aastaaja keskmisena elamute lõikes koos keskmise veaga (±SE) proovide lõikes m^{3-1} õhu kohta

Table 2. *Seasonal variation in culturable airborne fungi outdoors shown as mean with standard error (±SE), range of CFU m^{-3} air*

Proovivõtu koht *Sampling site*	Talv *Winter*	Kevad *Spring*	Suvi *Summer*	Sügis *Autumn*
Põhk (MEA) *Straw (MEA)*	94 ± 19	197 ± 43	289 ± 32	168 ± 34
Roopakk (MEA) *Reed (MEA)*	118 ± 15	198 ± 48	353 ± 41	212 ± 34
Põhk (DG18) *Straw (DG18)*	18 ± 7	30 ± 9	50 ± 11	22 ± 10
Roopakk (DG18) *Reed (DG18)*	24 ± 9	27 ± 11	45 ± 12	23 ± 9

MEA – linnaseagari sööde / *Malt Extract Agar media;* DG18 – diglütserool 18% sööde / *18% Dichloran glycerol agar (DG18) media*

Kevadel kuulus põhupakkidest seintega elamutes kõige enam identifitseeritud hallitusseeni perekonda *Cladosporium* (79%). Järgnesid perekonnad *Penicillum* (8%), *Aspergillus* (8%) ja *Alternaria* (3%). 2% hallitusseentest ei kuulunud eelnevalt mainitud perekondadesse. Roopakkidest seintega elamutes oli perekondade järjestus kevadel sama mis põhuelamutes: erinevused esinesid vaid esinemisprotsentide lõikes – *Cladosporium* (81%), *Penicillium* (7%), *Aspergillus* (7%) ja *Alternaria* (3%). 2% leitud seentest ei kuulunud eelnevatesse perekondadesse.

Tabel 3. Perekonna tasemeni identifitseeritud hallitusseente jaotumine perekondadesse aastaegade ja ehitusmaterjali lõikes. Esimene näitaja tähistab pesa moodustavate ühikute (PMÜ) arvu ja teine protsenti koguhulgast

Table 3. *Distribution of molds identified by genus, by season and building material. The first figure represents the number of colony forming units (CFU) and the second percentage of the seasonal total*

Hallitusseened *Molds*	Talv / *Winter*		Kevad / *Spring*		Suvi / *Summer*		Sügis / *Autumn*	
	põhk / *straw*	roopakk / *reed*	põhk / *straw*	roopakk / *reed*	põhk / *straw*	roopakk / *reed*	põhk / *straw*	roopakk / *reed*
Alternaria	1 (1)	4 (1)	9 (3)	16 (3)	32 (6)	43 (5)	25 (8)	49 (9)
Aspergillus	25 (17)	72 (19)	24 (8)	36 (7)	11 (2)	9 (1)	71 (23)	110 (20)
Cladosporium	1 (1)	23 (6)	235 (79)	420 (81)	451 (84)	738 (86)	92 (30)	142 (26)
Penicillum	110 (74)	266 (70)	24 (8)	36 (7)	38 (7)	51 (6)	95 (31)	203 (37)
Teised / *Others*	10 (7)	15 (4)	6 (2)	12 (2)	5 (1)	15 (2)	25 (8)	44 (8)

Suvel kuulus kõige enam identifitseeritud seentest põhupakkidest seintega elamutes siseõhus perekonda *Cladosporium* (84%), järgnesid *Penicillium* (7%), *Alternaria* (6%), *Aspergillus* (2%); 1% leitud hallitusseentest ei kuulunud eelnevalt mainitud perekondadesse. Roopakkidest seintega elamute siseõhu puhul oli järgnevus sama: kõige enam leiti perekonda *Cladosporium* (86%) kuuluvaid hallitusseeni, järgnesid perekonnad *Penicillum* (6%), *Alternaria* (5%) ja *Aspergillus* (1%). 2% leitud hallitusseentest ei kuulunud eelnevalt mainitud perekondadesse.

Sügisel kuulus kõige enam põhuelamute siseõhus identifitseeritud hallitusseentest perekonda *Penicillum* (31%), järgnesid perekonnad *Cladosporium* (30%), *Aspergillus* (23%) ja *Alternaria* (8%). 8% põhuelamutest leitud seentest ei kuulunud eelnevalt mainitud perekondadesse. Roopakist elamute siseõhu puhul kuulus kõige enam hallitusseeni sügisel perekonda *Penicillium* (37%), järgnesid perekondadesse *Cladosporium* (26%), *Aspergillus* (20%) ja *Alternaria* (9%) kuuluvad hallitusseened. 4% hallitusseentest ei kuulunud ühegi eelnevalt mainitud perekonna hulka. Välisõhust võetud proovidest identifitseeritud hallitusseente perekondade jaotus oli vastavuses elamute siseõhust võetud proovidega.

Materjaliproovid seintest ning identifitseeritud hallitusseened perekondade lõikes

Uuringu käigus koguti materjaliproove välispiiretest (seinast) sügisel. Kogutud proovidest kasvatati välja vaid üksikuid kolooniaid (min 6 PMÜ, max 14 PMÜ). Kolooniate perekondadesse jaotumine oli sarnane siseõhust kultiveeritud proovide perekondadesse jaotumisega sügisesel perioodil. 36% identifitseeritud hallitusseentest kuulus perekonda *Cladosporium,* 32% perekonda *Penicillium*, 25% perekonda *Aspergillus*, 2% perekonda *Alternaria*. 3% hallitusseentest ei kuulunud eelpoolmainitud perekondadesse.

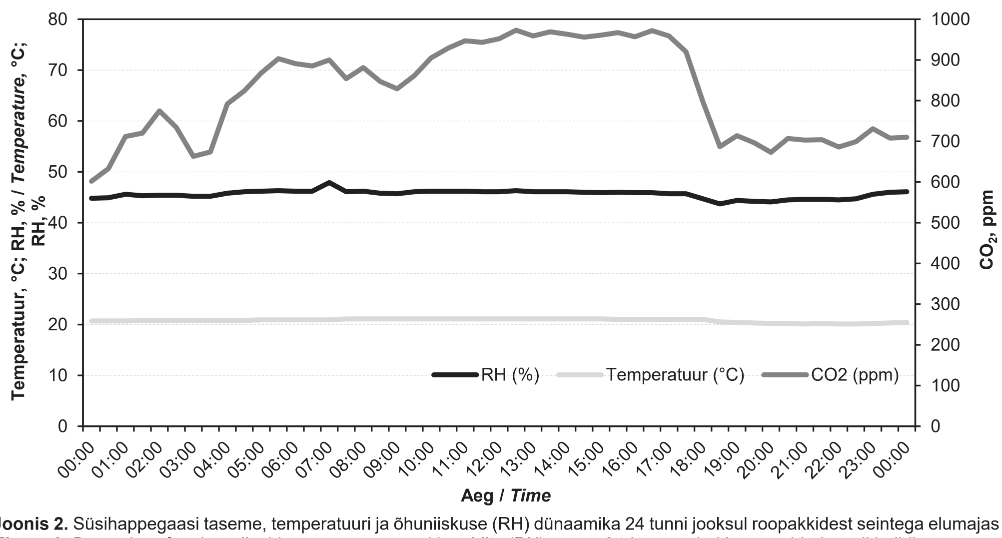
Sisekliima näitajad (CO_2, RH% ja temperatuur) elamute siseõhus ja kahel erineval kõrgusel piiretes

Kogu uuritud perioodi jooksul oli nii põhu- kui ka roopakkidest seintega elamute süsihappegaasi keskmine tase (tabel 4) madalaimal tasemel suveperioodil (põhupakkidest seintega elamutes 607 ± 26 ppm, roopakkidest seintega elamutes 568 ± 48 ppm). Kõige kõrgem oli süsihappegaasi keskmine tase põhupakkidest seintega elamutes kevadel (636 ± 26 ppm) ja roopakkidest seintega elamutes sügisel (626 ± 65 ppm).

Ühte juhuslikult valitud päeva roopakkidest seintega elamus kirjeldab joonis 2. Joonisel toodud päeva keskmine süsihappegaasi tase oli 822 ± 17 ppm. Vastavad väärtused olid madalamad öösel, maksimumväärtus (973 ppm) registreeriti päeval. Antud tuba oli kasutusel nii magamistoana kui ka laste mängutoana.

Tabel 4. Sisekliima keskmised näitajad näitajad (CO_2, RH% ja temperatuur) põhu- ja roopakist seintega elamut magamistubades esitatuna koos standardveaga (±SE)
Table 4. *Average parameters describing indoor climate (CO_2, relative humidity to temperature) in the bedrooms of buildings with straw-bale and reed-bale walls shown as a mean with standard error (±SE)*

Näitajad / *Parameters*	Talv / *Winter*		Kevad / *Spring*		Suvi / *Summer*		Sügis / *Autumn*	
	põhk *straw*	roopakk *reed*	põhk *straw*	roopakk *reed*	põhk *straw*	roopakk *reed*	põhk *straw*	roopakk *reed*
Süsihappegaas (CO_2), ppm *Carbon dioxide (CO_2), ppm*	618 ± 28	574 ± 46	636 ± 26	573 ± 55	607 ± 26	568 ± 48	616 ± 27	626 ± 65
Temperatuur, °C / *Temperature, °C*	19,0 ± 0,5	19,0 ± 0,5	19,0 ± 0,4	19,3 ± 0,9	19,0 ± 1,3	20,6 ± 1,8	20,4 ± 0,6	20,7 ± 0,9
RH, %	36 ± 2	41 ± 2	36 ± 2	42 ± 2	36 ± 2	43 ± 2	39 ± 2	44 ± 3



Joonis 2. Süsihappegaasi taseme, temperatuuri ja õhuniiskuse (RH) dünaamika 24 tunni jooksul roopakkidest seintega elumajas
Figure 2. *Dynamics of carbon dioxide, temperature and humidity (RH) over a 24-hour period in a reed-bale wall building*

Keskmine õhutemperatuur (tabel 4) jäi uuritud elamute magamistubades 19–21 °C vahele. Vastavad näitajad olid ühtlased, olles talvel ja kevadel mõlema elamutüübi korral keskmiselt 19,0–19,3 °C. Suvel oli roopakist elamute siseõhutemperatuur keskmiselt 1,6 °C võrra kõrgem kui põhust seintega elamutes. Keskmine õhutemperatuur oli kõige kõrgem nii põhupakkidest seintega elamutes (20,4 ± 0,6 °C) kui ka roopakkidest seintega elamutes (20,7 ± 0,9 °C) sügisel.

Uuritud magamistubades (tabel 4) jäi keskmine õhuniiskus 36–44% vahele, olles madalam põhupakkidest seintega elamute (36–39%) ja kõrgem roopakkidest seintega elamute magamistubades (41–44%) Roopakkidest seintega elamute puhul oli niiskusnäitaja kevadel 41 ± 2%, nii suvel kui ka sügisel oli see protsendi võrra eelnenud aastaaja väärtusest kõrgem (vastavalt 42 ± 2% ja 43 ± 2%).

Keskmine temperatuur piiretes 1,2 meetri kõrgusel (tabel 5) oli põhupakkidest seintega elamutes madalaim talvel (17,5 ± 1,3 °C), roopakist seintega elamutes aga kevadel (15,6 ± 1,5 °C). Kõrgeimad olid keskmised temperatuurinäitajad 1,2 meetri kõrgusel välispiirdes nii põhust (20,6 ± 0,8 °C) kui ka roopakist seintega elamutes suvel (19,3 ± 1,1 °C). Põhupakkidest seintega elamute puhul oli 1,2 m kõrgusel temperatuur välispiirdes (17,3–20,6 °C) kõrgem kui roopakkidest seintega elamutes (15,6–19,3 °C). Erinevus oli palju suurem 0,2 m kõrgusel, kus põhupakkidest seintega elamute keskmine õhutemperatuur varieerus vastvavalt 14,4–19,2 °C ja roopakkidest seintega elamute temperatuur vastavalt 7,3–16,3 °C. 0,2 meetri kõrgusel välispiirdes oli keskmine temperatuur madalaim nii põhu- kui ka roopakkidest seintega elamutes talvel (vastavalt 14,4 ± 2,4 °C ja 7,3 ± 2,5 °C). Kõrgeim oli keskmine temperatuur suveperioodil – põhupakkidest seintega elamutes 19,2 ± 1,0 °C ja roopakkidest seintega elamutes 16,3 ± 1,6 °C.

RH% keskmised näitajad olid 1,2 meetri kõrgusel piiretes nii põhu – kui ka roopakkidest seintega elamutes madalaimad talvel (vastavalt 33 ± 12% ja 33 ± 14%), kõrgeimad aga suveperioodil (põhupakkidest seintega elamutes 53 ± 7%, roopakkidest seintega elamutes 57 ± 1%). Üldiselt on suhtelise õhuniiskuse väärtused sarnased – vastavalt 33–53% ja 33–57%.

Keskmine RH% oli 0,2 m kõrgusel piiretes madalaim talvel (vastavalt 38 ± 4% põhupakkidest seintega elamutes ja 45 ± 6% roopakkidest seintega elamutes), kõrgeimad olid keskmised näitajad suveperioodil (põhupakkidest seintega elamutes 54 ± 2%, roopakkidest seintega elamutes 58 ± 1%). Roopakkidest seintega elamutes on tendets, et suhteline õhuniiskus on 0,2 m kõrgusel kõrgem (42–58%), kui põhupakkidest seintega elamutes (38–54%).

Välispiirde niiskuskoormus ja hallituse ohu hindamine

Temperatuuri ja niiskusenäitajaid piiretes iseloomustab joonis 3. Piirdes registreeriti ka kõrgemaid õhuniiskuse ja temperatuuri väärtusi kui siseõhus, kuid tõenäosus, et tingimused on hallitusseente kasvuks piirdes sobilikud, on väga madal.

Siseõhu niiskuslisa hinnati nii talve- kui ka suveperioodil ühe konkreetse päeva põhjal. Roopakkidest seintega elamute niiskuslisa varieerus suvel 0,46 g m^{3-1} kuni 3,42 g m^{3-1} ja talvel 0,62 g m^{3-1} kuni 2,73 g m^{3-1}. Põhupakkidest seintega elamute niiskuslisa varieerus suvel 2,1 g m^{3-1} kuni 1,99 g m^{3-1}, talvel – 0,06 g m^{3-1} kuni 1,43 g m^{3-1}. Negatiivne oli niiskuslisa päevasel ajal, mil elanikud ruumides ei viibinud. Tulenevalt Hukka ja Viitaneni (1999) poolt loodud mudeliga võrdlemisest, oli hallituse oht kõikides uuritud elamutes madal.

Hoonete kompleksne hindamine

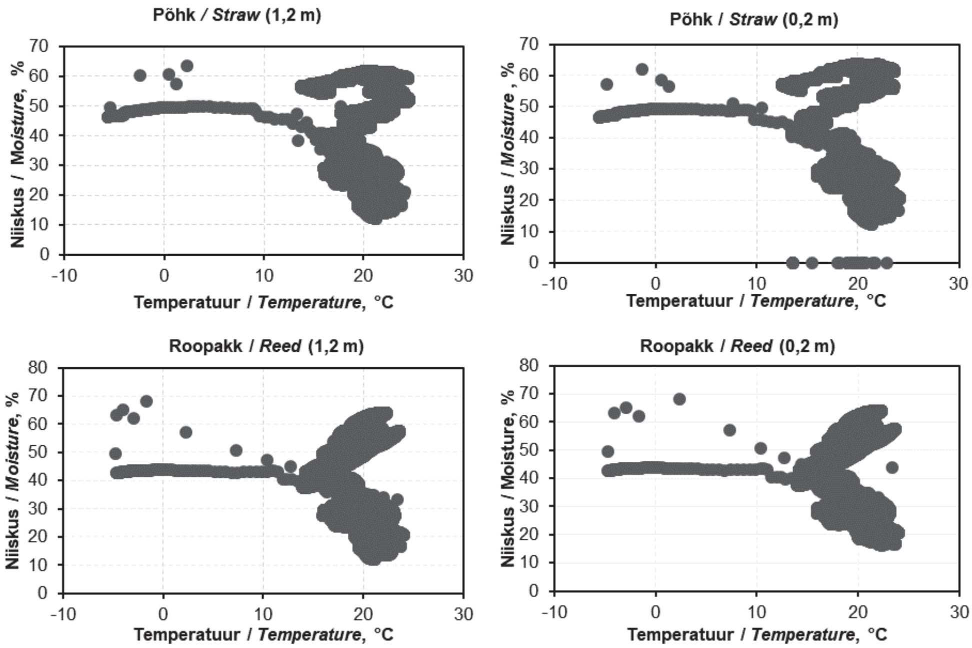
Töös uuriti elamute siseõhu kvaliteeti komplekselt, kogudes paralleelselt sisekliima parameetrite (õhutemperatuur, RH, CO_2) ning mikrobioloogia andmeid (pesa moodustavate ühikute arv ja taksonoomiline koosseis) nii õhust kui ka välispiirde (seinte) materjalist. Interdistsiplinaarses uuringus vaadati komplekselt põhu- ja roopakkidest seintega elamute sisekliimat, kasutades selleks andur-andmesalvesteid, õhu- ja materjaliproove. Kaks andur-andmesalvestit paiknesid piirdes ligikaudu 20 cm sügavusel – üks 0,2 m kõrgusel põrandast, et tuvastada võimalikke probleemkohti sõlme lähedal (kapillaartõus, vundamendi ehitusvead, võimalikud külmasillad) ja teine 1,2 m kõrgusel põrandast stabiilses seinaosas.

Tuginedes andur-andmesalvestitega kogutud teabele ning õhu- ja materjaliproovide tulemustele leiti, et nii põhust kui ka pilliroost elamute seintes on hallituseoht väike. Roopakkidest seintega elamute puhul väärib märkimist erakordselt madal temperatuur (7,3 ± 2,5 °C) piirdes 0,2 m kõrgusel põrandast talvisel perioodil, mis viitab roopakkide madalale tihedusele. Korstnaefekti tõttu on alumises sõlmes sissetõmme ning niiskustase ei ole kõrge.

Tabel 5. Keskmine õhutemperatuur ja õhuniiskuse (RH) piiretes 1,2 ja 0,2 m kõrgusel põhu – ja roopakist elumajade magamistubades esitatuna koos standardveaga (±SE)

Table 5. *Average air temperature and humidity (RH) within the ranges of 1.2 and 0.2 m for straw bale and reed buildings, shown with standard error (±SE)*

Näitajad / *Parameters*	Talv / *Winter*		Kevad / *Spring*		Suvi / *Summer*		Sügis / *Autumn*	
	põhk *straw*	roopakk *reed*	põhk *straw*	roopakk *reed*	põhk *straw*	roopakk *reed*	põhk *straw*	roopakk *reed*
Temperatuur (°C) 1,2 m kõrgusel *Temperature (°C) at 1.2 m*	17,3 ± 2,2	16,3 ± 4,6	17,5 ± 1,3	15,6 ± 1,5	20,6 ± 0,8	19,3 ± 1,1	18,2 ± 1,2	17,0 ± 1,8
Temperatuur (°C) 0,2 m kõrgusel *Temperature (°C) at 0.2 m*	14,4 ± 2,4	7,3 ± 2,5	15,7 ± 1,0	11,3 ± 3,7	19,2 ± 1,0	16,3 ± 1,6	16,7 ± 1,5	13,9 ± 2,6
RH (%) 1,2 m kõrgusel *RH (%) at 1.2 m*	33 ± 12	33 ± 14	41 ± 7	47 ± 2	53 ± 7	57 ± 1	41 ± 4	45 ± 4
RH (%) 0,2 m kõrgusel *RH (%) at 0.2 m*	38 ± 4	45 ± 6	42 ± 3	47 ± 1	54 ± 2	58 ± 1	42 ± 2	51 ± 2



Joonis 3. Temperatuur (°C) ja niiskusnäitaja (%) piiretes 1,2 ja 0,2 meetri kõrgusel nii põhu- ja roopakkidest elamute välisseintes
Figure 3. *Temperature (°C) and humidity (%) in outer boarders at 1.2 and 0.2 meters in buildings with straw- and reed-bale walls*

Arutelu

Ehitussektor on suurim ressursside tarbija kogu maailmas, mis aitab olulisel määral kaasa kliimamuutusele (Dutil jt, 2011; Iacovidou, Purnell, 2016). Kasvav nõudlus ehitiste ja infrastruktuuri järele suurendab nii materjalide kaevandamist kui ka emissioone (Krausmann jt, 2017). Süsiniku emisoonide vähendamiseks kogu olelustsükli jooksul on võimalik kasutada leevendusmeetmeid nii projekteerimisel kui ka ehitamisel (Pomponi, Moncaster, 2016), kasutada saab aga ka süsinikneutraalseid materjale (Chel, Kaushik, 2018). Looduslikel materjalidel on keskkonnale väike mõju, samuti pakuvad sellised materjalid elanikele/kasutajatele tervislikku elukeskkonda (Brojan jt, 2013).

Põhk ja pilliroog on materjalid, mis kasvamise käigus kasutavad fotosünteesiprotsessis süsihappegaasi ning nende kasutamine ehituses on kasvutrendis. Kuna tegemist on biolagunevate materjalidega, on oluline olla informeeritud selliste materjalide ehitamisel kasutamisega kaasas käivast mikroobipopulatsioonist ja selle võimalikust ohtlikkusest nii siseõhule kui ka piirdetarinditele.

Mikroorganismid, kes elavad suure niiskustasemega keskkonnas, vajavad oma elutegevuseks sobivat temperatuuri. Lawrence jt (2009) toovad välja, et sobiv temperatuurivahemik on 20–70 °C, madalam kui 10 °C temperatuur aga pärsib mikroorganismide elutegevust. Köetavates ruumides peab inimese pikemaajalisel ruumis viibimisel temperatuur olema vähemalt 18 °C, optimaalne, luues inimesele soojatunde ning aidates kaasa tervisliku ja nõuetele vastava sisekliima tekkimisele ja püsimisele (Kalamees jt, 2011). Keskmine siseõhu temperatuur jäi mõõteperioodil 19–21 °C vahele vastates standardi EVS-EN 16798-1:2019 (EVS-EN 16798-1:2019) alusel sisekliimaklassile III. Suveperioodil, mil temperatuurid ja niiskustase on hoonetes kõrgem, on ebasoodsate olude kokkulangemisel (kõrge temperatuur, piisav suhteline niiskus (üle 75%)) võimalik mikroobne kasv (Hukka, Viitanen, 1999; Johansson jt, 2012). Otseselt materjali hallitus ei kahjusta, kuid see viitab liiga kõrgele niiskustasemele konstruktsioonis ning võimalikele sellest põhjustatud riskidele (kõdunemine) (Lelumees, 2016).

Lisaks sobivatele temperatuuridele on mikroorganismide kasvu seisukohalt oluline roll ka ruumi õhuniiskusel ning toitainetel (Rajasekar, Balasubramanian, 2011). Eluruumide kohta kehtiva määruse kohaselt võiks optimaalne niiskus olla 40–60% (Arundel jt, 1986). Kriitiline õhuniiskuse tase mikrobioloogilise kasvu seisukohalt on 75–95%, sõltudes nii temperatuurist kui ka ehitusmaterjalist (Johansson jt, 2012). Hukka ja Viitanen (1999) toovad oma hallituse kasvu iseloomustavas mudelis välja keskkonnatingimuste ajalise kestuse, mis on vajalik mikrobioloogilise kasvu alguseks. Uuritud elamutes jäi õhuniiskus 36–44% piiridesse ja temperatuur 19–21 °C vahele. Süsihappegaasi taseme näitajad jäid soovitatud piiridesse (ühes liitris ruumiõhus on lubatud CO_2 kontsentratsioon kuni 1000 ppm (RT I, 2011)) kuuludes kõikide uuritud magamistubade puhul ISO standardi EVS-EN 16798-1:2019 (EVS-EN 16798-1:2019) alusel sisekliima klassi II (≤800ppm). Käesoleva töö raames uuritud elumajade magamistubade puhul on õhu niiskuse ja temperatuurinäitajad liiga madalad, et eeldada hallitusseente kasvu.

Roopakkidest seintega elamutes olid pesa moodustavate ühikute (PMÜ) väärtused kõrgemad kui põhupakkidest seintega elamutes ning see võib viidata võimalikule mikrobioloogilisele kasvule ülemise sõlme läheduses.

Õhu suhteline niiskus mõjutab nii hoonepiirete niiskusrežiimi kui ka hoone sisekliimat (Kalamees jt, 2011). Kui niiskuskoormus on suur, võib see halvendada nii sisekliimat kui ka põhjustada niiskusprobleeme piirdetarinditele (Kalamees jt, 2010). Siseõhu niiskuslisa oli üsna madal, olles kõrgem roopakkidest seintega elamute puhul (0,46 g m^{3-1} kuni 3,42 g m^{3-1} suvel ja talvel 0,62 g m^{3-1} kuni 2,73 g m^{3-1}) ning kuuludes standardi EVS-EN ISO 13788 alusel II klassi (EVS-EN ISO 13788:2012). Põhupakkidest seintega elamud kuulusid oma niiskuslisa poolest standardi EVS-EN ISO 13788 alusel I klassi (EVS-EN ISO 13788:2012). Põhupakkidest seintega elamute puhul oli niiskuslisa negatiivne talveperioodil tööpäevadel päevasel ajal, mil elanikud kodus ei viibinud.

Talveperioodil oli roopakkidest seintega elamute puhul keskmine temperatuur 0,2 meetri kõrgusel vaid 7,3 ± 2,5 °C. Sellises olukorras eeldame, et suhteline õhuniiskus on kõrge, kuid antud olukorras oli see keskmiselt 41 ± 2%. See viitab võimalikule hõredusele ehitussõlmede puhul, ning tänu korstnaefektile toimub selles piirkonnas külma õhu sissevool. Kuna piirdes teostati mõõtmisi ainult kahel kõrgusel (0,2 ja 1,2 m), siis korstnaefekti tõttu on oht, et piirde ülemises servas on tõenäoline ülerõhu tõttu (sooja niiske) õhu väljavool, mis on otsene oht hallituse tekkeks. Antud leid on murettekitav, sest piirdetarind on ohustatud niiskumisest ja roopakk sobivate tingimuste korral ka mikrobioloogilisest kasvust. Linnaseagarile (MEA) siseõhust võetud proovid näitavad kõrgemaid väärtusi kõikide aastaaegade lõikes, võrreldes välisõhust võetud proovidega.

Erinevatel riikidel on kasutusel erinevad standardid pesa moodustavate ühikute lubatud tasemete suhtes, kuid ühtne rahvusvaheline standard puudub (Jyotshna, Helmut, 2011). WHO ekspertrühma uurimuses leiti, et pesa moodustavate ühikute kogus sisetingimustes ei tohiks ületada 1000 PMÜ m^{3-1} (Nevalainen, Morawaska, 2009). Eestis puuduvad hallitusseentele sisekeskkonnas piirnormid. Soovituslikud piirnormid on kehtestatud Soomes ning seal tuuakse välja, et talveperioodil on soovituslik kuni 500 PMÜ m^{3-1}, suveperioodil kuni 2500 PMÜ m^{3-1} (Kosteusvauriot työpaikoilla, 2009). Antud uuringu puhul jäid siseõhus pesa moodustavate ühikute kogu uuringuperioodi hõlmavad keskmistatud kontsentratsioonid põhust seintega elamute puhul tasemele 323 ± 80 PMÜ m^{3-1} ning roopakkidest seintega elamute puhul tasemele 576 ± 94 PMÜ m^{3-1}. Ühest roopakkidest seintega elamust 2015. aasta suvel võetud proovid (1060 ± 8 PMÜ m^{3-1}) ületasid sisetingimustesse sobivaid WHO ekspertrühma poolt toodud soovituslikku kontsentratsiooni (1000 PMÜ m^{3-1}), kuid jäid alla Soome soovituslike piirnormide (kuni 2500 PMÜ m^{3-1}).

Hallitusseente kontsentratsioonid olid kõikidel aastaaegadel siseõhus kõrgemad kui välisõhus. Elamute siseõhust võetud proovidelt identifitseeritud hallitusseente perekonnad ei erinenud välisõhust võetud proovidelt identifitseeritud seeneperekondadest. Varasemad uuringud on näidanud, et välisõhust kultiveeritavad seeneliigid on kultiveeritavad ka siseõhust (Hoseini jt, 2012; Kalawasinska jt, 2012; Raamets jt, 2019). Piirdes olid kontsentratsioonid mõõdetud piirkondades väga madalad ning hallitusseente perekondlik jaotus oli sarnane sise- ja välisõhust identifitseeritud perekondadega. Olulisi erinevusi hallitusseente perekondlikus ja protsentuaalses jaotuses ei leitud, sügisesed konsentratsioonid olid kõrgemad kui talvised kontsentratsioonid (Hameed jt, 2012). Põhjuseks on hallitusseente kasvuks ja arenguks sobiv temperatuuri ja õhuniiskuse tase, samuti hulgaliselt taimset materjali, mis on substraadiks (Awad jt, 2018). Sarnast dünaamikat siseõhuproovide puhul aastaaegade lõikes, nagu leiti selle uuringu tulemusena, on leitud ka varasemates hoone sisekliimat puuduta¬vates uuringutes (Medrela-Kuder, 2003; Haas jt, 2007; Frankel jt, 2012).

Kompleksne lähenemine põhu- ja roopakkidest seintega elamute sisekliima uurimisele aitas tuvastada probleemse koha roopakkidest seina konstruktsioonis, mis on ilmselt tingitud ebapiisavast roopakkide tihedusest. Kahtluse kontrollimiseks on vajalik teostada edasised uuringud ning andur-andmesalvesti tuleks paigaldada ka piirdesse lae (ülemise sõlme) lähedale.

Järeldused

Töös uuriti ja mõõtmised viidi läbi põhu- ja roopakkidest elumajades, mis olid vastava eriala spetsialistide poolt projekteeritud ja ehitatud. Lahendusi töös lähemalt ei analüüsitud, kuid näiteks võib tuua nii laiad räästad, mis kaitsevad seinu vihma eest, kui ka hästi isoleeritud ja üsna kõrge sokliosa. Üheski hoones ei tuvastatud niiskuskahjustusi ega nähtavat hallituse kasvu. Kõiki elamuid uuriti kompleksselt. Sisekliima andmetest nähtub, et õhutemperatuur oli küll pigem mõnevõrra madalam, kui eluruumides tavaliselt (21 °C). Suhteline õhuniiskus oli optimaalses vahemikus ning silma ei registreeritud ka väga madalaid temperatuuriväärtusi, mis on talvisel ajal tavaline probleem keskküttega ja hästiventileeritud hoonetes. CO_2 kontsentratsioon ei ületanud soovituslikku piirväärtust.

Siseõhu niiskuslisa oli väike, siseõhust ega piiretest ei leitud hallituse arenguks sobivaid tingimusi vastavalt hallitusindeksile.

Kõrgemad pesa moodustavate ühikute (PMÜ) väärtused registreeriti mõõtmisperioodi jooksul roopakkidest seintega elamutes. Põhupakkidest seintega elamutes olid vastavad väärtused madalamad. Sesoonsed muutused esinesid mõlemal juhul. Läbiviidud uuringute põhjal võib öelda, et põhu- ja roopakkidest seintega elamute siseõhus esineb rohkem kolooniaid võrreldes välisõhuga. Uuringu käigus ei tuvastatud visuaalsel vaatlusel hallituse koldeid.

Töö käigus määrati nelja perekonda kuuluvaid hallitusseeni (*Alternaria, Aspergillus, Penicillium* ja *Cladosporium*), mis on leivnuimad teraviljal leiduvad hallitusseente perekonnad. Eelmainitud perekondadesse kuuluvad hallitusseened võivad kujutada endast riski inimestele (allergia, krooniline nohu, köha, hingamisteede haigused).

Kompleksne lähenemine võimaldas tuvastada ühe probleemse koha roopakkidest hoonete puhul. Nendes hoonetes oli ka hallitusseente hulk mõnevaõrra suurem. Vastavat lähenemist võib soovitada ka teiste analoogsete uuringu puhul, mis võiks anda aluse selle meetodiks arendamisele.

Uuritavate elamute sisekliima hindamisel saadud tulemused lubavad järeldada, et roo- või põhupakkides seintega ehitatud elamu on Eesti klimaatilistesse tingimustesse sobiv ehitis, mis asjatundliku planeerimise, ehituseks sobiva materjali kasutamise ja kvaliteetse ehitustegevuse tulemusena on tervislik ja keskkonnasõbralik eluase. Kindlasti tuleks läbi viia vastavad uuringud hoonetes, kus on mingil põhjusel niiskuskahjustused tekkinud. Kuivõrd niiskuskahjustusi hoonetes ikka esineb kasvõi veeavariide tõttu, siis on tarvis välja selgitada, milline on olukord ja töötada välja taastamiseks vajalikud meetmed.

Tänuavaldused
Autorid tänavad põhu- ja roopakist seintega elamute omanikke, kes lubasid oma eluruumides vajalikke mõõtmisi teostada.

Huvide konflikt / *Conflict of interest*

Autorid kinnitavad artikliga seotud huvide konflikti puudumist.
The authors declare that there is no conflict of interest regarding the publication of this paper.

Autorite panus / *Author contributions*

JR, AR – uuringu kava ja planeerimine / *study conception and design;*
JR – Proovide kogumine ja analüüs / *acquisition of data*;
JR, AR, MI, LN, KM – andmete analüüs ja interpretatsioon / *analysis and interpretation of data;*
JR, AR, MI, LN, KM – käsikirja koostamine / *drafting of manuscript;*
AR, MI, LN – käsikirja ülevaatamine ja lõplik heaks kiitmine / *critical revision and approve the final manuscript*.

Indoor air quality in straw bale and reed buildings

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Summary

Straw and reed buildings are item or synonyms for "ecological building" from healthy, reusable and renewable materials and energy efficient buildings. On the ohter hand there are legends about mould and asthma problems as common problem in straw and reed buildings.

To describe the indoor environment and building boarders (wall) long term studies (over 2 years) were carried out in the bedrooms of eight buildings (4 straw bale and 4 reed houses). This interdisciplinary study focuses to building as whole system. Air temperature, relative humidity (RH) and CO_2 concentration, temperature and RH inside the boarders (walls) at two heights (0.2 and 1.2 m) from floor level were measured. Holes were closed with plaster. To describe the microbiology in buildings and find out microbiological problems two kinds of tests were performed. Microbiological samples from indoor air and outdoor air (reference value) were collected in every season with air samplers. Residents were asked not to ventilate the houses at least 6h prior to measurements. Sampling media and procedure was designed according to ISO standard 16000-18: Detection and enumeration of moulds – Sampling by impaction. Malt Extract Agar (MEA) and 18% Dichloran glycerol agar (DG18) media were used. The sample plates were incubated at 25 °C for seven days, colony forming units (CFU) were counted and fungi were determined morphologically and microscopically following staining with lactophenol blue. For the identification to the genus level standardized identification keys were used.

Microbiological samples from building materials mounted in boarders (walls) were collected at two heights (0.2 and 1.2 m) by hand at the same points, where the holes for the temperature and RH loggers were made. Malt Extract Agar (MEA) and 18% Dichloran glycerol agar (DG18) media were used for direct plating. The sample plates were incubated at 32 °C for 72 hours, colony forming units (CFU) were counted and fungi were determined morphologically and microscopically following staining with lactophenol blue. For the identification to the genus level standardized identification keys were used.

Higher values of Colony Forming Units (CFU) were recorded during the measurement period in reed houses. The values were lower in straw houses. Seasonal changes occurred in both cases. Studies have shown that there are more colonies in the indoor air of straw and reed buildings compared to outdoor air. No mold growth was identified during this study. A complex approach to indoor climate of straw and reed habitats helped to identify a problematic site in reed buildings,

probably due to inadequate density of reed bales. Further investigations are needed to verify the suspicion and the data recorder should also be installed in the enclosure near the ceiling.

In the course of the work, four families of molds (*Alternaria, Aspergillus, Penicillium* and *Cladosporium*) were identified that may pose a risk to human health (allergy, chronic rhinitis, cough, respiratory disease). The results of the indoor climate assessment of the buildings under investigation allow us to conclude that a house made of reed or straw is a building suitable for Estonian climatic conditions, which, as a result of expert planning, use of building materials and quality construction, is a healthy and environmentally friendly housing solution.

Kasutatud kirjandus

Al-Jumeily, D., Hashim, K., Alkaddar, R., Al-Tufaily, M., Lunn, J. 2018. Sustainable and Environmental Friendly Ancient Reed Houses (Inspired by the Past to Motivate the Future). – In: 11th International Conference on Developments in E Systems Engineering. DOI: 10.1109/dese.2018.00032.

Arundel, A.V., Sterling, E.M., Biggin, J.H., Sterling, T.D. 1986. Indirect health effects of relative humidity in indoor environments. – Environ. Health Perspect, 65:351–361. DOI:10.1289/ehp.8665351.

Awad, A.H., Saeed, Y., Hassan, Y., Fawzy, Y. Osman, M. 2018. Air microbial quality in certain public buildings, Egypt: a comparative study. – Atmos. Pollut. Res., 9:617–626. DOI: 10.1016/j.apr.2017.12.014.

Barreca, F., Gabarron, A.M., Yepes, J.A.F., Pérez, J.J.P. 2019. Innovative use of giant reed and cork residues for panels of buildings in Mediterranean area. – Resour. Conserv. Recy., 140:259–266. DOI: 10.1016/j.resconrec.2018.10.005.

Bergey, D.H., Holt, J.G. (Eds.). 2000. Bergey's manual of determinative bacteriology. – Philadelphia : Lippincott Williams & Wilkins, USA. 787 p.

Bernasconi, C., Rodolfi, M., Picco, A.M., Grisoli, P., Dacarro, C., Rembges, D. 2010. Pyrogenic activity of air to characterize bioaerosol exposure in public buildings: a pilot study. – Letters in Appl. Microbiol., 50(6):571–577. DOI: 10.1111/j.1472-765X.2010.02831.x.

Brischke, C., Hanske, M. 2016. Durability of untreated and thermally modified reed (*Phragmites australis*) against brown, white and soft rot causing fungi. – Ind. Crops and Prod., 91:49–55. DOI: 10.1016/j.indcrop.2016.06.031.

Brojan, L., Petric, A., Clouston, P.L. 2013. Comparative study of brick and straw bale wall systems from environmental, economic and energy perspectives. –ARPN J. Eng. Appl. Sci., 8:980–926. DOI: 10.1016/ j.applsci.2013.8.008.

Canha, N., Lage, J., Coutinho, J.T., Alves, C., Almeida, S.M. 2019. Comparison of indoor air quality during sleep in smokers and non-smokers' bedrooms: A preliminary study. – Environ. Pol., 249:248–256. DOI: 10.1016/j.envpol.2019.03.021.

Chel, A., Kaushik, G. 2018. Renewable energy technologies for sustainable development of energy efficient building. – Alex. Eng. J., 57(2):655–669. DOI: 10.1016/j.aej.2017.02.027.

Domsch, K.H., Gams, W., Anderson, T.H. 1980. Compendium of Soil Fungi, Vol. 1. – Academic Press, London. 860 p.

Dutil, Y., Rousse, D., Quesada, G. 2011. Sustainable buildings: An ever evolving target. – Sust., 3:443–464. DOI: 10.3390/su3020443.

Frankel, M., Bekö, G., Timm, M., Gustavsen, S., Hansen, E.W., Madsen, A.M. 2012. Seasonal variations of indoor microbial exposures and their relation to temperature, relative humidity, and air exchange rate. – App. Environ. Microbiol, 78(23):8289–8297. DOI: 10.1128/AEM.02069-12.

Grant, C., Hunter, C., Flannigan, B., Bravery, A. 1989. The moisture requirements of moulds isolated from domestic dwellings. – Int. Biodeter., 25(4):259–284.

Gravesen, S., Frisvad, J.C., Samson, R.A., 1994. Microfungi. – Munksgaard, København, Denmark 1994, 168p. (In Danish)

Haas, D., Habib, J., Galler, H., Buzina, W., Schlacher, R., Marth, E., Reinthaler, F. 2007. Assessment of indoor air in Austrian apartments with and without visible mold growth. – Atmos. Environ., 41(25):5192–5201. DOI: 10.1016/j.atmosenv.2006.07.062.

Hameed, A.A.A., Khoder, M.I., Ibrahim, Y.H., Saeed, Y., Osman, M.E., Ghanem, S. 2012. Study on some factors affecting survivability of airborne fungi. – Sci. Total Environ., 414:696–700. DOI: 10.1016/j.scitotenv.2011.10.042.

Henderson, K. 2007. Achieving legitimacy: visual discourses in engineering design and green building code development. – Build. Res. Inf., 35(1):6–17. DOI: 10.1080/09613210600979780.

Hernberg, S., Sripaiboonkij, P., Quansah, R., Jaakkola, J.J., Jaakkola, M.S. 2014. Indoor molds and lung function in healthy adults. – Respir Med., 108(5):677–684. DOI: 10.1016/j.rmed.2014.03.004

Holzhueter, K., Itonaga, K. 2010. The Hygrothermal Environment and Potential for Mold Growth within a Straw Bale Wall. – J. Asian. Archit. Build. Eng., 9(2):495–499. DOI: 10.3130/jaabe.9.495.

Holzhueter, K., Itonaga, K. 2017. An Evaluation of WUFI-Bio to Predict Mold Growth in Straw Bale Walls in Japan. – J. Asian. Archit. Build. Eng., 16(2):357–362. DOI: 10.3130/jaabe.16.357.

Horr, Y.A., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A., Elsarrag, E. 2016. Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. – Int. J. Sustain. Built. Environ., 5(1):1–11. DOI: 10.1016/j.ijsbe.2016.03.006.

Hoseini, M., Jabbari, H., Naddafi, R., Nabizadeh, M., Rahbar, M., Yunesian, M., Jaafari, J. 2012. Concentration and distribution characteristics of airborne fungi in indoor and outdoor air of Tehran subway stations. – Aerobiol., 29:355–363. DOI: 10.1007/s10453-012-9285-8.

Hukka, A., Viitanen, H. 1999. A mathematical model of mould growth on wooden material. – Wood Sci. Technol., 33:475–485. DOI: 10.1007/s0022600 50131.

Iacovidou, E., Purnell, P. 2016. Mining the physical infrastructure: Opportunities, barriers and interventions in promoting structural components reuse. – Sci. Total Environ., 557:791–807. DOI: 10.1016/j.scitotenv. 2016.03.098.

EVS-EN 16798-1:2019. Hoonete energiatõhusus. Hoonete ventilatsioon. Osa 1: Sisekeskkonna lähteandmed hoonete energiatõhususe projekteerimiseks ja hindamiseks, lähtudes siseõhu kvaliteedist, soojuslikust keskkonnast, valgustusest ja akustikast. – Tallinn: Eesti Standardikeskus. (In Estonian)

EVS-ISO 16000-17:2012. Siseõhk. Osa 17: Hallitusseente avastamine ja loendamine. Külvipõhine meetod. – Tallinn: Eesti Standardikeskus. (In Estonian)

ISO 16000-18:2011. Detection and enumeration of moulds -- Sampling by impaction. – Bruxelles: European committee for Standardisation.

EVS-EN ISO 13788:2012. Hoone elementide ja piirdetarindite soojus- ja niiskustehniline toimivus. Kriitilise pinnaniiskuse ja elemendisisese kondenseerumise vältimine. Arvutusmeetodid. – Tallinn: Eesti Standardikeskus. (In Estonian)

Johansson, P., Ekstrand-Tobin, A., Svensson., T., Bok, G. 2012. Laboratory Study to Determine the Critical Moisture Level for Mould Growth on Building Materials. – Int. Biodeter. Biodegr., 73:23–32. DOI: 10.1016/j.ibiod.2012.05.014.

Jyotshna M, Helmut B. 2011. Bioaerosols in Indoor Environment - A Review with Special Reference to Residential and Occupational Locations. – The Open Envir. & Biol. Mon. J., 4:83–96. DOI: 10.2174/ 1875040001104010083.

Kalamees, T., Alev, Ü., Arumägi, E., Ilomets, S., Just, A., Kallavus, U. 2011. Maaelamute sisekliima, ehitusfüüsika ja energisääst I. – https://kredex.ee/ sites/default/files/2019-03/Maaelamute%20 sisekliima,%20ehitusf%c3%bc%c3%bcsika%20ja% 20energias%c3%a4%c3%a4st.pdf. Viimati külastatud 04.02.2020. (In Estonian)

Kalamees, T., Kõiv, T-A., Liias, R., Õiger, K., Kallavus, U., Mikli, L., Ilomets, S., Kuusk, K., Maivel, M., Mikola, A., Klõšeiko, P., Agasild, T., Arumägi, E., Liho, E., Ojang, T., Tuisk. T., Raado, L-M., Jõesaar, T. 2010. Eesti eluasemefondi telliskorterelamute ehitustehniline seisukord ning prognoositav eluiga. – https://www.mkm.ee/sites/ default/files/suurpaneelelamute_uuringu_loppraport _trukk.pdf. Viimati külastatud 05.02.2020. (In Estonian)

Kalawasinska, A., Burkowska, A., Wilk, I. 2012. Microbial air contamination in indoor environment of a University library. – Ann. Agric. Environ. Med., 19:25–29.

Katsoyiannis, A., Cincinelli, A. 2019. ´Coctails and dreams´: the indoor air quality that people are exposed to while sleeping. – J. Environ. Sci. Health., 8:6–9. DOI: 10.1016/j.coesh.2018.12.005.

Kilch, M.A. 1988. A Laboratory Guide to Common Aspergillus Species and their Teleomorphs. – Commonwealth Scientific and Industrial Research Organization, Division of Food Processing, North Ryde, Australia. 116 p.

King, B. 2006. Design of Straw Bale Buildings. – The State of the Art, Green Building Press, San Rafael. 296 p.

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., Haberl, H. 2017. Global socioeconomic material stocks rise 23-fold over the 20th Century and require half of annual resource use. – Proc. Natl. Acad. Sci., 114(8):1880–1885. DOI: 10.1073/pnas.1613773114.

Kosteusvauriot työpaikoilla. 2009. Kosteusvauriotyöryhmän muistio. Sosiaali- ja terveysministeriön selvityksiä: 18. – Yliopistopaino, Helsinki. 82 p. (In Finnish)

Laborel-Préneron, A., Ouédraogo, K., Simons, A., Labat, M., Bertron, A., Magniont, C., Aubert, J.-E. 2018. Laboratory test to assess sensitivity of bio-based earth materials to fungal growth. – Build. Environ., 142:11–21. DOI: 10.1016/j.buildenv. 2018.06.003.

Larone, D.H. 2002. Medically Important Fungi. A Guide to Identification, 4th ed. ASM Press, American Society for Microbiology, Washington, 409 p.

Lawrence, M., Heath, A., Walker, P. 2009. Determining moisture levels in straw bale construction. – Const. Build. Mat., 23(8):2763–2768. DOI: 10.1016/j.conbuildmat.2009.03.011.

Lelumees, M. 2016. Ehitusniiskuse mõju lisasoojustamise moodulelementide niiskustehnilisele toimivusele. – Magistritöö. Tallinna Tehnikaülikool, Tallinn, Eesti, 10/06/2016, 117 lk. (In Estonian)

Lõiveke, H. 2008. Hallitusseened ja mükotoksiinid teraviljas. – Nädaline, 124:9. (In Estonian)

Lõiveke, H., Ilumäe, E., Akk, E. 2008. Teravilja mikrobioloogiast ja ohutusest. – Agraarteadus, 19(2):38–45. (In Estonian)

Medrela-Kuder, E. 2003. Seasonal variations in the occurrence of culturable airborne fungi in outdoor and indoor air in Craców. – Int. Biodeter. Biodegr., 52(4):203–205. DOI: 10.1016/s0964-8305(02)00167-1

Milutiené, E., Staniškis, J.K., Kručius, A. 2012. Increase in buildings sustainability by using renewable materials and energy. – Clean. Technol. Envir., 14(6):1075–1084. DOI: 10.1007/s10098-012-0505-2.

Nevalainen, A., Morawaska, L. (Eds.). 2009. Biological Agents in Indoor Environments. Assessment of Health Risks. – Work conducted by a

WHO Expert Group between 2000–2003. WHO, QUT.

Nielsen, K., Holm, G., Uttrup, L., Nielsen, P. 2004. Mould growth on building materials under low water activities. Influence of humidity and temperature on fungal growth and secondary metabolism. – Int. Biodeter. Biodegr, 54(4):325–336. DOI: 10.1016/j.ibiod.2004.05.002.

Pomponi, F., Moncaster, A. 2016. Embodied carbon mitigation and reduction in the built environment – What does the evidence say? – J. Environ. Manage., 181:687–700. DOI: 10.1016/j.jenvman.2016.08.036

Portnoy, J.M., Kwak, K., Dowling, P., Vanosdol, T., Barnes, C. 2005. Health effects of indoor fungi. – Ann. Allergy Asthma Immunol., 94(3):313–320. DOI: 10.1016/s1081-1206(10)60982-9.

Raamets, J., Kutti, S., Vettik, A., Ilustrumm, K., Rist, T., Ivask, M. 2016. The antimicrobial effect of three different chemicals for the treatment of straw bales used in housing projects. – Proceedings of the International Conference on Sustainable Housing Planning, Management and Usability: Sustainable Housing 2016, Porto, Portugal 16-18.11.2016. Eds. R. Amoêda, C. Pinheiro. Green Lines Institute for Sustainable Development, 537−545.

Raamets, J., Kutti, S., Ruus, A., Ivask, M. 2017. Assessment of Indoor Air in Estonian Straw Bale and Reed Houses. – WIT Trans. Ecol. Envir., 211:193–196. DOI: 10.2495/AIR170191.

Raamets, J., Ruus, A., Ivask, M. 2019. Assessment of indoor air quality and hygrothermal conditions of boarders during autumn, winter and spring in two of Estonian straw-bale houses. – Cold Climate HVAC 2018: Sustainable Buildings in Cold Climates: Cold Climate HVAC 2018 The 9th International Cold Climate Conference, Sustainable new and renovated buildings in cold climates, Kiruna, Sweden 12-15, March 2018. Eds. D. Johansson, H. Bagge, Å. Wahlström. Springer, 815−823. (Springer Proceedings in Energy) DOI: 10.1007/978-3-030-00662-4_68.

Rajasekar, A., Balasubramanian, R. 2011. Asessment of airborne bacteria and fungi in food courts. – Build. Environ., 46(10):2081–2087. DOI: 10.1016/j.buildenv.2011.04.021.

Riigi Ilmateenistus. 2020. Ilmaülevaated. – http://www.ilmateenistus.ee/kliima/ulevaated/. Viimati külastatud 30.01.2020. (In Estonian)

RT I. 11.10.2011. Tervisekaitsenõuded koolieelse lasteasutuse maa-alale, hoonetele, ruumidele, sisustusele, sisekliimale ja korrashoiule, Vabariigi Valitsuse määrus nr. 131. – https://www.riigiteataja.ee/akt/111102011003. Viimati külastatud 30.01.2020. (In Estonian)

Samson, R.A., Hoeckstra, E.S., Frisvad, J.C., Filtenborg, O. 1996. Introduction to Food-Borne Fungi, 5th ed. – Centraalbureau voor Schimmel-cultures Baarn, Delft, Wageningen, Ponsen & Looyen. 322 p.

Shon, C.-S., Mukashev, T., Lee, D., Zhang, D., Kim, J. 2019. Can Common Reed Fiber Become an Effective Construction Material? Physical, Mechanical, and Thermal Properties of Mortar Mixture Containing Common Reed Fiber. – Sustain., 11(3):903. DOI: 10.3390/su11030903.

Strøm-Tejsen, P., Zukowska, D., Wargocki, P., Wyon, D.P. 2015. The effects of bedroom air quality on sleep and next-day performance. – Ind. Air., 26(5):679–686. DOI: 10.1111/ina.12254.

Zorman, T., Jeršek, B. 2008. Assessment of Bioaerosol Concentrations in Different Indoor Environments. – Indoor Built Environ., 17(2):155–163. DOI: 10.1177/1420326X08089251.

Watanabe, T. 2010. Identification of Fungi from: Pictorial Atlas of Soil and Seed Fungi, Morphologies of Cultured Fungi and Key to Species. – CRC Press. 426 p.

Winn, W.C., Koneman, E.W. 2006. Koneman's color atlas and textbook of diagnostic microbiology. 6th ed. – Philadelphia: Lippincott Williams & Wilkins. 1565 p.

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Language skills

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