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Mould growth in buildings

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April 2010

Jonas Holme

Summary

Many studies around the world have reported that moisture-related problems in buildings (i.e., dampness) increase the risk of health effects such as respiratory symptoms, asthma and allergy in both adults and children. However, there is only limited knowledge about which agents in indoor air or dust cause the reported health effects. Biological pollutants such as moulds is one of the explanations that has been suggested. The principal objective of this PhD study has been to increase the knowledge about mould growth in buildings and possible links between mould growth and health effects in humans.

In this PhD study, moisture-acceptance criteria concerning mould growth have been developed for several building materials. In general it would seem that spruce and chipboard have a greater resistance to mould growth compared to plywood and gypsum. Wind-breaking materials based on wood-fibre and gypsum had an even greater resistance to mould growth compared to the other materials. As the RH increased, germination of the spores was faster, and the development and strength of the mould growth increased for all materials tested. The experiments also showed that an increase of 1% RH had a greater influence on the mould growth than an increase in temperature of 8 ºC when the RH was above 85%. Exposure of building materials to high temperatures (up to 60 ºC) decreases, or inhibits, mould growth. But when the temperature exposure is discontinued, growth continues as if nothing had happened.

In this study we have carried out a close examination of low-slope compact roofs as a possible “risk construction” with regard to mould growth. The drying-out potential and the risk of mould growth were examined in roofs exposed to large amounts of water. The results showed that the drying-out potential for the water-damaged roofs were higher than expected, and increased with substantially more ventilation. The observed mould growth was relatively small compared to what was expected. In conclusion, flat or low-slope compact roofs would seem to represent a more robust construction regarding the risk of mould growth than first expected.

In this study, data from two field investigations in Norwegian and Swedish houses concerning different building characteristics, indicators of a moisture damage and indoor relative humidity in accordance to the risk of mould growth have been analysed. The results given in this study show that moisture supply is not a constant value throughout the year, but is dependent on the outdoor temperature. According to our measurements, it would seem that the design curves given in EN ISO 13788 need to be modified if they are to be used in hygro-thermal analysis, both with regard to shape and deflection points, and with regard to the level of varied occupancy and room types. It was also found that the variation of RH and moisture supply generally followed the expected daily variation of moisture production due to the use of the house and the rooms. It was also found that the moisture supply, when calculated on an hourly basis, is highly sensitive to changes in the outdoor air water-vapour content during the day and week. As a general conclusion, therefore, measurements of indoor air humidity should be made on a long-term basis, i.e. minimum one week of measurements.

No link was found between water supply and rooms with registered mould growth. Neither were there any links between indicators of dampness and mould growth indoors (as indoor culturable mould spores). This shows that reliance on measurements of mould spores in the indoor air, whether there is a moisture problem in the building or not, is too unpredictable. Reported or observed data concerning water staining and measurements of indoor air humidity are also necessary to verify an indoor moisture problem.

In this study there was a link between a higher percentage share of houses with one or more moisture indicators and types of ventilation, types of foundation and building period. There were more cases of registered mould growth in houses with no ventilation / natural ventilation compared to houses with mechanical ventilation, and in houses with basement cellars compared to those with slab on ground. There was also a link between greater registered mould growth in older houses compared to newer ones. In a risk-reducing strategy it might be useful to improve the ventilation and carry out improvements to the foundations in order to avoid potential moisture damage.

Knowledge about which agent is causing the reported health problems in buildings with moisture-related problems is limited. In this study there was no link between mould-spore concentrations (CFU) in the children's bedrooms and asthma/allergy among the children. Based on these results, there is no reason to carry out one-time air sampling of mould CFU in indoor air of homes in order to identify risk factors for asthma/allergy in children living in Scandinavian countries. These results might also indicate that there could be agents other than mould spores that are the cause of the health effects in damp buildings.

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I. **Holme**, J. (2009) Mould growth on board-based wind-barrier products *Energy Efficiency and New Approaches – Proceedings of the Fourth International Building Physics Conference* (Bayazit N.T. *et al*. eds), Beysan Matbaacilik ve Reklamcilik, Istanbul, 75-82.

II. **Holme**, J. and Kvande, T. (2010) Mould growth on building materials and the effect of periodical exposure to "higher" temperatures. *International Biodeterioration and Bio-degradation*, (submitted).

III. **Holme**, J., Noreng, K., and Kvande, T. (2008) Moisture and Mould Growth in Compact Roofs – Results from a Three-Stage Field Survey *Proceedings of the 8th Symposium on Building Physics in the Nordic Countries* (Rode C. eds), Report R-189, Dept. of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, 1221-1228

IV. Geving, S. and **Holme**, J. (2010) The drying potential and risk of mould growth in compact wood-frame roofs with built-in moisture *International Journal of Building Physics* 33(3): 249-269.

V. Geving, S., **Holme**, J., and Jenssen, J. (2008) Indoor air humidity in Norwegian houses*, Proceedings of the 8th Symposium on Building Physics in the Nordic Countries* (Rode C. eds), Report R-189, Dept. of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, 801-808

VI. Geving, S. and **Holme**, J. (2009) Diurnal variations of indoor air humidity in Norwegian houses, *Energy Efficiency and New Approaches – Proceedings of the Fourth International Building Physics Conference* (Bayazit N.T. *et al*. eds), Beysan Matbaacilik ve Reklamcilik, Istanbul, 807-814.

VII. **Holme**, J., Geving, S., and Jenssen, J. (2008) Moisture and Mould Damage in Norwegian Houses*, Proceedings of the 8th Symposium on Building Physics in the Nordic Countries* (Rode C. eds), Report R-189, Dept. of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, 1213-1220

VIII. **Holme**, J., Haghered-Engman, L., Mattsson, J., Sundell, J., and Bornehag, C.G. (2010) Culturable mould in indoor air and its association with moisture-related problems and asthma and allergy among Swedish children. *Indoor Air* 20: 329-340.

These papers will be referred to by their Roman numerals.

1 Introduction

1.1 General

Much attention has been focused in recent years on the negative effects moist materials have on indoor air quality and human health. The link between dampness and health has been scientifically demonstrated by numerous epidemiological surveys. Such surveys have been summarised in a Nordic research project (Bornehag *et al.*, 2001). Moreover, the Technical Regulations (TEK, 1997) under the Planning and Building Act clearly state that moisture problems in buildings and poor indoor climate are unacceptable.

From the perspective of the occupants of a building, an indoor environment that satisfies all the occupants is the ideal situation. The indoor climate should not increase the risk or severity of illness or injury. According to the World Health Organization (WHO): "Health is a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity." An unhealthy indoor environment will lead to decreased productivity, and increased sick leave, among employees as well as losses in work efficiency. The economic losses are self-evident. With regard to dwellings, asthma and allergy-related illnesses result in increased medical costs.

1.2 Moisture and Dampness in Buildings

Almost all buildings sustain excessive moisture, leaks, or flooding at some point in time. If dampness-related problems are to be prevented, it is essential to understand their causes. From a technologic viewpoint, one must understand the source and transportation of moisture in buildings, which depend on the design, operation, maintenance, and use of buildings in relation to external environmental conditions such as climate, soil properties, and topography. From a societal viewpoint, it is necessary to understand how construction, operation, and maintenance practices might lead to dampness problems. The interactions between moisture, materials, and environmental conditions inside and outside a building determine whether the building may become a source of potentially harmful dampness-related microbial and chemical exposure (Institute of Medicine, 2004).

Dampness is used to denote a wide range of signs indicating moisture damage of variable spatial extent and severity. This may represent visual observations of current or earlier moisture (such as water stains or condensation on windows), observed microbial growth, measurement of high moisture content of building materials, measurement of high relative humidity (RH) in the indoor air, mouldy or musty odours, and other signs that can be associated with excess moisture in a building (Institute of Medicine, 2004).

The amount of water present in a substrate is expressed in relation to its volume (kg/m^3), or its oven-dry weight (kg/kg). The former is referred to as moisture content (MC), and the latter as percentage-moisture content (%-MC). MC is directly proportional to %-MC and to the density of the substance (Geving and Thue, 2002)

Relative humidity (RH) is the existing water-vapour pressure of the air, expressed as a percentage of the saturated water-vapour pressure at the same temperature. RH reflects both the amount of water vapour in the air and the air temperature. For example if the temperature of a tract of air is decreased but no water is removed, the RH will increase. If the air is cooled sufficiently, a portion of the gaseous water vapour in the air will condense, producing liquid water.

The temperature of air and materials in a building vary spatially; therefore RH also varies spatially. In the winter for example, the temperature of the interior surface of a window or a wall will normally be less than the temperature of the centre of a room. Air in contact with the window or wall will cool to below the central-room temperature, increasing the local relative humidity. If the surface has a temperature below the dew-point temperature of adjacent air, water vapour will condense on the surface, producing liquid water.

Without a source to continuously moisten building materials, the MC of the material depends on temperature and the RH of the surrounding air. The RH of the atmosphere in equilibrium with a material that has a particular MC is known as the equilibrium relative humidity (ERH) (Oliver, 1997). Different materials have a different distribution of pore size and degrees of hygroscopicity, thus materials that have the same ERH may have different MC. For example at an ERH of 80%, the MC for mineral wool is about 0.3 kg/m^3, for concrete it can be 80 kg/m^3, and for wood it is about 90 kg/m^3 (Geving and Thue, 2002).

Sources of moisture in buildings include rainwater, groundwater, plumbing, construction moisture, water use, condensation, and indoor and outdoor humidity (Lstiburek, 2001, Straube, 2002). The first three are sources of liquid-water problems, while construction moisture may result in both liquid-water and vapour-water problems. Condensation associated with humidity involves water vapour as well as liquid water. Moisture problems begin when materials remain wet sufficiently long for microbial growth, physical deterioration, or chemical reactions to occur. This may occur due to continual moistening, or intermittent moistening that happens often enough to keep materials from drying.

In Scandinavian countries most of the moisture problems are hidden within the building structure. Such moisture damage is generally caused by precipitation, leakage from pipes, built-in moisture or moisture from the ground, and rarely by condensation on indoor surfaces which is the common case in warmer climates (Lisø *et al.*, 2006, Jaakkola *et al.*, 2005, Hall *et al.*, 2006).

Building inspection in large-scale studies are basically conducted using non-destructive methods. Exposure-assessment methods used to characterise moisture and mould include the following: (1) physical measurements (e.g., humidity, temperature); (2) sampling and analysis to detect microbes indicative of moisture;

(3) visual inspections for moisture and mould; or (4) questionnaires (individual or interviewer-administered reports) (ACGIH, 1989).

One common way of expressing the indoor air-humidity load is by the moisture supply (the difference in water-vapour content between the indoor and exterior air). The moisture supply is used when the relative humidity is not controlled but allowed to undergo wide variations due to factors such as weather conditions, building characteristics, moisture generation and ventilation. Knowing the typical variation of indoor air humidity in a specific type of building, it is also possible to compare measurements in one specific building to assess the risk of moisture problem.

Typical indicators of dampness could be (1) visible mould or damp/discoloured stains on the ceiling, walls or floor; (2) Discoloured or blackened parquet or cork flooring, or bubbly and loosening or discoloured vinyl or linoleum floor covering; (3) Mouldy or "earth cellar" odour; (4) Condensation on the inside of windows.

1.3 Mould Growth

Fungi are eukaryotic organisms that lack chlorophyll and depend on other organisms for their supply of nutrients. Most fungi are saprophytic, i.e. live on dead organic material. Fungi play an important role in the ecosystem in the recycling of nutrients. However, as fungi can exploit all organic materials, they may also damage food, wood and textiles as well as building materials in buildings with moisture problems (Eduard, 2006).

Moulds are filamentous fungi that grow with branched multi-cellular filamentous structures (hyphae) that collectively form the mycelium. Moulds need organic material, oxygen and water for growth. As oxygen and organic materials are readily available in most environments, access to water is usually the limiting factor (Hyvärinen, 2002, Eduard, 2006). On the other hand, too much free water will inhibit growth, while free water can hinder the availability of oxygen (McGinnis, 2007). The time it takes for fungi to grow depends on the material's characteristics, the fungal species and the amount of water available (Doll, 2002).

The minimum moisture needed for microbial growth may be characterised in terms of the water activity of the substrate, $a_{w,}$ which is the ratio of the moisture content of the material in question to the moisture content of the same material when it is saturated. In a situation where the material is in equilibrium with surrounding air that has a RH of 100%, $a_w = 1$ (Institute of Medicine, 2004).

Moisture demands depend on fungal species. The lowest a_w at which the most tolerant xerophilic fungi may grow is 0.7, which corresponds to an RH of 70% (Grant *et al.*, 1989). In general, most mesophilic moulds can grow at a_w of 0.95-0.99, while the range for xerophilic moulds and for yeast are 0.70-0.90 and 0.88-0.99, respectively (Gravesen *et al.*, 1994).

Moreover, water moulds need adequate nutrition and temperatures in order to grow. Nutrition may be carbohydrates, proteins, lipids or other biological molecules. Nutrients occurs in house dust and water as well, therefore the availability of nutrients does not generally limit mould growth (McGinnis, 2007). Prevailing temperatures in living spaces and other sections of buildings are usually 0-55°C, that is greater than freezing and less than the temperature at which the denaturalisation of proteins would start. This range permits the growth of most moulds even if the temperature is not optimal for a particular genus or species. Most of the moulds are mesophilic and show optimal growth at 15-30°C. Psychrophilic and psychrotolerant species grow at lower temperatures, e.g. *Cladosporium herbarum* can grow at temperatures down to -5°C. Thermophilic species have their growth optima above 30°C. Temperatures above 50°C might kill the organisms (Eduard, 2006, Hyvärinen, 2002).

Although few moulds grow below pH 3 or above pH 9, condition for growth are often broad with optima around pH 6 (Eduard, 2006).

Time is another integral element when assessing microbial growth in buildings. Growth may be slowed by decreasing or increasing temperatures or other limiting factors, and the time window that must be considered in building microbiology is weeks, months or even years (Institute of Medicine, 2004). If growth conditions are favourable, the germination could start within an hour (McGinnis, 2007).

Conidia (asexual), spores (asexual or sexual), and hyphal fragments are reproductive propagules that can establish growth at a nutrient source. Each fungal propagule is an independent viable unit that has the potential to initiate a new colony. Once the conidium, spore or hyphal fragment lands and becomes anchored on a substrate having sufficient moisture, growth can commence (McGinnis, 2007). Moisture in the substrate rather than moisture in the air is important for the germination process (Armolik and Dickson, 1956). High relative humidity is required for spore germination. A low RH can induce conidia ore spores to go into dormancy. The vegetative growth form of moulds is hyphae, and during growth many hyphae form a mycelium. The hyphae grow and secrete enzymes at their apices into the substrate to obtain nutrient (McGinnis, 2007).

Almost any damp or wet material, such as carpeting, upholstered furniture, gypsum wallboard, ceiling tiles, wood products, shower walls and curtains, and potted plants, can colonize mould growth (Horner *et al.*, 2008).

1.4 Mould Growth in buildings

Many fungi can amplify indoors; among the most commonly identified are species of *Cladosporium*, *Penicillium* and, *Aspergillus*. In addition several species are known to be associated with extensive water damage, including *Aspergillus versicolor*, *Sthacybotrus charatum*, *Chaetomium globsum*, and *Ulocladium charatum*. The last 3 are especially common on cellulose-based materials (Flannigan *et al.*, 2002).

Concentrations of viable airborne fungi vary between 10^1-10^5 cfu/m^3. This wide range is partly explained by the impact of outdoor air. Mean levels are, however, typically 10^2-10^3 cfu/m3. In two studies, lower indoor levels have been reported in winter; this was noted not only in a cold climate (Reponen *et al.*, 1992) but also in a subtropical climate (Kuo and LI, 1994).

In some studies, the association between elevated fungal levels and moisture damage or observed mould growth has been investigated. The observations of concentrations of viable fungi in moisture-damaged dwellings have tended to be contradictory. In general, fungal concentrations have been higher in moisture damaged buildings than in buildings without such problems (Verhoeff *et al.*, 1992, Dharmage *et al.*, 1999, Klanova, 2000). Hunter *et al.* (1988) also showed that there were higher levels of fungi in a room with visible growth than in those rooms where mould was absent (Hunter *et al.*, 1988). On the other hand, there are many studies where no difference in concentrations of viable fungi between mouldy and non-mouldy buildings has been observed (Strachan *et al.*, 1990, Nevalainen *et al.*, 1991, Dill and Niggemann, 1996, Garrett *et al.*, 1998) or between dwellings with severe and mild mould damage (Miller *et al.*, 2000).

In most studies, the classification of dwellings is based on reported or observed visible mould. There are only a few studies that have investigated levels in buildings with no moisture or mould damage. The range or average of the fungal concentrations in dwellings with or without mould or moisture damages has not always been reported, which makes comparison difficult. In general, the distributions of fungal levels in mouldy and non-mouldy buildings overlap. In a study showing the association between mould damage and fungal levels, some extremely high levels (e.g. 23 000 cfu/m^3) have been reported, even in dwellings with no visible mould (Hunter *et al.*, 1988). There is no fungal level that always indicates moisture or mould damage, even though several attempts to set such limits have been reported (Rao *et al.*, 1996). In order to use fungal levels in source characterisation, the conclusion must be based on the knowledge of what is considered normal in the environment and climate of interest.

Although differences in mean fungal levels between moisture-damaged and reference buildings have not always been found, differences in microbial composition of air samples have commonly been noted. For example, higher concentrations of *Aspergillus, Cladosporium*, *Penicillium*, non-sporulating fungi (including basidiomycetes) or yeasts have been observed in buildings with moisture damage or with visible mould growth than in reference buildings (Strachan *et al.*, 1990, Dekoster and PS, 1995, Garrett *et al.*, 1998). In the study of Miller *et al.*, the total concentrations of viable fungi were similar in dwellings with severe and mild mould damage, but the presence of severe damage could be seen in the higher prevalence of fungal species not present in the outdoor air (Miller *et al.*, 2000). Occurrence of certain fungi in air has also been associated with dampness or mould growth in buildings. Typically higher concentrations of *Aspergillus, Cladosporium*, *Penicillium*, non-sporulating fungi (including basidiomycetes) or yeasts have been observed in buildings with moisture damage or with visible mould growth than in reference buildings (Garrett *et al.*, 1998, Haas *et al.*, 2007). Garrett *et al.* studied associations between house dampness, airborne fungal spore levels, and health consequences among 149 children from 80

households in Australia. These investigators found a link between several conditions of damp housing including musty odour, water intrusion, high humidity, limited ventilation, and indoor fungal growth along with high spore concentrations (Garrett *et al.*, 1998). Haas *et al.* found that Austrian apartments with mould odour had significantly higher mould loads than apartments without odour. Rooms with water damage due to dampness were significantly more affected by moulds than rooms without damage (Haas *et al.*, 2007). Indoor spaces with visible mould frequently show very high concentrations of airborne fungal spores (Morey, 1999). In addition, several other genera different from outdoor air have been found, but their occurrence has not been reported to indicate moisture damage. In general, the dominant genera in air have usually been reported, but the value of rare findings as indicators of moisture damage has not been emphasised. Nevertheless, a list of damage-associated fungi and bacteria has been published as a result of an expert meeting (Samson *et al.*, 1994). This is based on empirical observations, but little published data are available about the frequencies or other characteristics of these microbes in building environments. The list of "indicator microbes", or microbes that do not belong to the normal flora, but the presence of which may indicate mould growth, is as follows: *Trichoderma, Exophiala, Phialophora, Ulocladium, Stachybotrys, Fusarium, Wallemia, Aspergillus versicolor, Aspergillus fumigatus,* actinobacteria, gram-negative bacteria and yeasts (e.g. *Rhodotorula* and *Sporobolomyces*) (Samson *et al.*, 1994).

1.5 Mould Growth and Health

Many studies worldwide have reported that moisture-related problems in buildings (i.e. dampness) increase the risk of health effects such as respiratory symptoms, asthma and allergy in both adults and children (Bornehag *et al.*, 2001, Bornehag *et al.*, 2004). Other health symptoms such as tiredness, headaches, mucous-membrane irritation and airway infections have also been reported in association with dampness in buildings. However, there is limited knowledge about which agents in indoor air or dust that causes the reported health effects. Both chemical and biological pollutants besides house-dust mites have been suggested.

Indoor conditions are important for exacerbation of allergic diseases, such as existing asthma, as well as allergenic sensitisation (Dharmage *et al.*, 2002). It is a well-known fact that house-dust mites and animal allergens are important allergens in indoor environments. However, less research has been carried out on the effect of fungal material. Garret *et al.* studied association between house dampness, airborne fungal spore levels, and health consequences in 149 children from 80 households. They concluded that indoor exposure to certain fungal genera was a risk factor for asthma, atopy, and respiratory symptoms in children (Garrett *et al.*, 1998). Several other studies in the US have found that allergy to fungi correspond with asthma. Persons with asthma were 5.1 times more likely to react to *Alternaria* than were non-asthmatics. When both asthma and allergic rhinitis were considered, *Alternaria* remained strongly associated with these disorders (Gergen and Turkeltaub, 1992, O'Connor G *et al.*, 2004). In another study on the relationship between production of fungal-specific IgE and development of asthma in adults with newly diagnosed asthma, it was found that the risk of developing asthma

increased in a dose-dependent manner as the total and fungus specific IgE increased (Jaakkola *et al.*, 2006).

In 2004 the Institute of Medicine (IOM) published a report entitled Damp Indoor Spaces and Health (Institute of Medicine, 2004). This evidence-based document listed several health conditions for which various degrees of scientific evidence seem to exist between the condition and exposure to mould in a damp environment. The IOM report found sufficient evidence of a link between exposure to fungi in a damp environment and development of upper respiratory-tract (nasal and throat) symptoms and asthma (eg, wheezing and coughing) symptoms in already sensitised asthmatic persons. The report did not find any evidence of a link between fungal exposure and the initial development of asthma or its symptoms in otherwise healthy children.

1.6 Principal Objectives and Scope

The principal objective of the present work has been to increase the knowledge about mould growth in buildings and possible links between mould growth and health effects in humans.

Mould growth is primarily dependent on water availability and temperature. Links between relative humidity and temperature and mould growth have been examined through laboratory experiments on various building materials (board-based wind-breaking barriers and typical materials used in constructions such as walls and roofs) as well as through field experiments and research on flat, compact roofs. One of the goals in this survey has been to develop acceptance criteria for moisture safety levels on building materials, and gain more knowledge of the effect of higher temperatures on mould growth.

Moisture problems in flat or low-slope compact roofs have received a great deal of attention in the last 10 years. This is a type of construction with a small potential for built-in moisture to dry out, compared to ventilated slanting roofs and external walls, and thereby a construction with a potential for mould growth. It has been a goal in this study to investigate the robustness regarding mould growth in flat or low-slope compact roofs.

There is also an urgent need for a better understanding of mould growth and physical measurements as they relate to the micro-environment (associations between building characteristics and mould growth). In this study, data from two field investigations in Norwegian and Swedish houses have been analysed concerning different building characteristics, indicators of a moisture damage and indoor relative humidity in accordance to the risk of mould growth. One goal has been to identify constructions in a building, and factors associated to the use of buildings, which could give an increased risk for moisture damage and mould growth. This important knowledge could subsequently be used in a risk-reducing strategy related to moisture damage and mould growth.

Mould growth has been suggested as being one of several possible explanations to health problems among humans living in damp buildings. One goal in this study has been to investigate such a link by comparing indoor mould-spore concentrations in the houses of healthy and ailing children.

2 Main findings

2.1 Introduction

The first two papers have investigated the risk of mould growth on building materials. Basic requirement for mould growth concerning available water and temperature have been investigated on wind-breaking barriers based on wood fibre and gypsum (Paper I) and spruce, gypsum, chipboard and plywood (Paper II). The effect of exposure to periodically "higher" temperatures (40ºC, 50ºC and 60ºC) on the germination and development of mould growth are investigated in Paper II.

Low-sloped compact roofs as a possible "risk construction" with regard to mould growth have been investigated both in a field study (Paper III) and in a controlled field experiment (Paper IV). In both studies the drying-out potential and the risk of mould growth was examined in roofs exposed to large amounts of water.

Knowledge of indoor air humidity is important when assessing the risk for internal surface condensation, and the potential for mould growth. In Paper V and VI the indoor air humidity levels in Norwegian houses were analysed. There are several factors that might influence the level of indoor air humidity. The dependence of factors such as outdoor temperature, occupancy, type of building, type of room, age of houses and ventilation were investigated in Paper V. The typical diurnal amplitudes of relative humidity, temperature and moisture supply and the effect of influencing factors such as type of basic ventilation of the house, type of building, time of the year and the level of average indoor air humidity were also investigated (Paper VI).

As studies increasingly support the presence of health risks associated with moisture related agents (microbes and/or chemicals), there is a strong need for understanding fungal concentrations and physical measurements as they relate to the micro-environment (links between building characteristics and mould growth). Links between measurements of relative humidity in the indoor air, and reported and observed indicators of visible moisture problems, and registered mould growth, and the influence of some building characteristics were investigated in Paper VII. In Paper VIII the link between indoor air-spore concentration and parental reports and inspectors' observation of mouldy odour and visible signs of dampness were investigated.

There is no established method for measuring exposure to moisture-related indications (i.e. dampness) in houses which would be suitable for epidemiological research. In most studies questionnaire are used to classify whether or not the house is affected by dampness or fungal contamination. Such classification has been useful in identifying moisture problems, but more specific methods are needed to quantify the specific fungal exposure which is relevant to health. Air sampling for spore concentrations has been used in many previous studies to

measure fungal exposure. Most studies using this method have not included either a health assessment of the exposed subjects nor environmental factors such as dampness. In Paper VIII the mould-spore concentration and distribution in the indoor air of the 390 Swedish dwellings have been investigated to see if there is any link between indoor air-spore concentrations and parental reports and inspector observations of mouldy odour and visible signs of dampness in the homes, and if there is any link between spore concentrations indoors and asthma/allergy in children.

2.2 Methodology Overview

The following research methods have been applied to obtain the present results

- Laboratory experiments with building materials (*Paper I, Paper II*)
- Field experiment in compact frame roof (*Paper IV*)
- Field investigation of water-damaged compact roofs (*Paper III*)
- Field investigation and analysis of water damage, physical measurements, and mould growth in buildings (*Paper V, Paper VI, Paper VII, Paper VIII*)
- Epidemiological study on relationship between indoor spore concentration and asthma/allergy in children. (*Paper VIII*)
- Statistical analysis (*Paper V, Paper VI, Paper VII, Paper VIII*)
- Literature surveys (*All papers*)

2.3 Mould growth on board-based wind barriers (Paper I)

The time when board-based wind-barriers are exposed to the heaviest climatic loads is during the construction period before the external cladding has been installed. In exposed locations, materials will also be subject to moisture later on due to rain being driven through the cladding and onto the wind barrier. A wind-barrier layer must therefore be both water-repellent and sufficiently watertight to prevent the wall within becoming damp.

In order to predict and prevent attacks in building structures, knowledge about the properties of various materials regarding resistance to mould attacks is most important, and the main purpose of this laboratory investigation has been to chart the criteria for mould growth on various board-based wind-barrier products.

Four different board-based wind barriers were tested during the experiments (both front and reverse sides). Two were plasterboard based and two were wood-fibre based (hardboard). The material samples were sterilised, conditioned, infected and incubated in climate boxes representing six differing environments with different temperatures and RH (15ºC and 85.9%, 95.4%, ~100%, and 32.5ºC and 83.7%, 91.5%, ~100%). The incubation periods were six weeks (samples at 32.5ºC) and eleven weeks (samples at 15ºC). The mould growth was checked during weeks 3, 4, 5 and 6 for samples at 32.5ºC, and during weeks 3, 4, 5, 6 and 11 for samples at 15ºC. Three replicas were utilised for each test.

The results of these experiments show that wood-fibre (hardboard) based wind-barrier boards have a comparatively greater resistance to mould growth than plasterboard-based wind-barrier boards. This is reflected both in the length of time until proof of visible growth (detectable with the naked eye), and the extent of growth after incubation periods of 6 and 11 weeks. The difference applies to growth at approx. 100% RH and temperature 15°C and 32.5°C. After 11 weeks at lower RH (< 95.4%) and 15°C there is a relatively similar degree of proof and degree of growth between the plasterboard and wood-fibre (hardboard) products.

2.4 Mould growth on building materials and the effect of periodically exposure to “higher” temperatures (Paper II)

The most common construction materials used in timber houses are spruce, plywood, chipboard and gypsum. All these materials have a potential for mould growth. In this study, we have investigated the levels by which constant relative humidity and constant temperature mould growth will develop on these four materials. The effect of periodically “higher” temperature on the growth was also tested.

This investigation was conducted as two different experiments. In the first experiment plywood, gypsum board, spruce and chipboard were all tested for mould growth at eight different climatic conditions of constant temperature and RH (15ºC and 75.61%, 15ºC and 85.9%, 15ºC and 95.4%, 15ºC and ~99, 23ºC and

75.4%, 23ºC and 84.7%, 23ºC and 94.0%, 23ºC and ~99%) for 32 weeks. In the second experiment the same materials were exposed to "higher temperatures" (40ºC, 50ºC, 60ºC) for two hours three days a week for 12 weeks. These samples were all placed in climate boxes at 21ºC and ~ 99% RH for 15 weeks.

The test pieces were infected by means of a spore suspension comprising three mould species (*Aspergillus versicolor, Cladosporium cladosporioides, Penicillium chrysogenum).* Each test piece had 1×106 sp (0.5 ml) sprayed onto the upper side during testing. Three replicas were utilised for each test. The mould growth was checked visually once every week and by microscope (40X with down light).

The degree of mould growth on all the building materials tested in this project, showed an increasing growth according to the level of relative humidity to which the test pieces had been exposed. It would also seem that the temperature difference between 15 and 23ºC is less important than a difference in relative humidity between 95.4 and 94.0% and 85.6 and 84.7%. At ~75% RH no growth was registered on any of the materials.

Plywood is the material in this test with the best potential for mould growth. Visual growth was first registered at 85.6% RH and 15ºC after 21 weeks of exposure. At ~99% RH visible visual growth was registered after 3 weeks, with maximum growth after 9 weeks.

Gypsum had the second best potential for mould growth, but at a level in RH above ~95%. At ~99% RH visual growth was registered after 2 weeks, and maximum growth was reached after 4 weeks when the temperature was 23ºC.

Spruce had less mould growth compared to plywood and gypsum. At 95.4% RH and 15ºC visual growth was registered after 17 weeks, and the growth did not reach higher than level 5, thin visible layer with 66% coverage. When the RH was ~99% spruce was the material with the least growth of the materials tested.

Chipboard had only microscopic growth at RH less than ~99 (both at 15ºC and 23ºC). Above ~99% RH chipboard had visible growth after 2 weeks, with maximum growth after 19 weeks.

In these experiments there was no difference in mould growth between samples exposed to 40ºC and 50ºC for two hours three times a week compared to the reference samples not exposed to "higher" temperatures." The samples exposed to 60ºC started to grow later, and the growth was less compared to the other samples. However when the temperature exposure stopped after 12 weeks, these samples too started to grow like the reference samples.

2.5 Mould growth in compact roofs – a field investigation (Paper III)

Flat or low-slope compact-roof systems that have been built correctly, using materials that are not mould-prone between a correctly installed vapour barrier and the roof waterproofing membrane, have typically been regarded as being not especially moisture sensitive. Moisture in such roofs has therefore perhaps not received sufficient attention. With large amounts of precipitation in southern Norway in the autumn of 2000, the topic of built-in moisture in flat or low-slope compact roofs once again became relevant. In connection with roof work executed during periods of heavy precipitation and e.g. due to leakage, relatively large amounts of moisture can become trapped within the roof. This paper summarises some of the results from a field study that was performed in order to investigate how flat or low-slope compact roofs behave over time when moisture had been trapped inside the construction. The investigation included 12 roofs inspected in 2002. 10 of the 12 roofs were chosen among roofs which had considerable problems with built-in moisture during the building period (autumn 2000). Two of the roofs did not have any previously known moisture problems, and were therefore intended to act as reference roofs. Nine of the roofs were inspected again in 2004 and 2007.

Even though the majority of compact roofs covered by this field investigation had moisture problems during manufacturing, the extent of moisture problems are decreasing. Compared to what was assumed beforehand, measurements in several of the roofs showed that dehydration was so extensive that mechanisms other than pure diffusion through the roofing or inward diffusion had possibly been a predominant factor in several instances. Other mechanisms contributing towards drying out may be convection currents in the roof and outward diffusion via the parapet, as well as less incidental air currents through all, or portions of, the roof's surface.

Microbiological growth observed inside the compact roofs was limited, confirming a small potential for growth in such constructions. This is most probably due to the general robustness of the thermal insulation regarding growth and unfavourable maximum temperature amplitude (> 60°C).

2.6 Mould growth in compact roofs – a field experiment (Paper IV)

Built-in moisture in the insulation layer of a compact roof will generally dry out very slowly, compared to the drying rate in a ventilated roof construction. Intentional or unintentional leakages of outdoor air through the insulation layer may however speed up the drying rate.

In this investigation the drying potential of various configurations of compact wood-frame roofs with a high level of built-in moisture was investigated, through test house measurements and hygro-thermal simulations (WUFI 1D software). Compact wood-frame roof elements were soaked in water, and mould spores were

added to the elements. The hygrothermal conditions of the elements were monitored over a two-year period, and the microbial conditions were also registered. In order to investigate the effect of the two-dimensional vapour diffusion and air leakage/ventilation through the eaves, various modifications were introduced at the roof elements. For all elements except for the control element the lower parts of the eaves (cornices) were left open, to increase the possibility for air leakage/ventilation through the insulation layer of the elements and sideways vapour diffusion. In two of the elements, a few addition holes were drilled through the reinforcement beam thereby ensuring a leakage of outdoor air through the insulation layer under windy conditions. The drilled holes had an area equivalent to an approx. 1 mm continuous opening along the edge of the roof.

The measurements and the hygrothermal simulations showed a significantly faster rate of drying for roof elements with a higher degree of ventilation (with small ventilation holes drilled at the edge of the roof). The measurements also showed that the predominately windward side of the roof dried faster than the leeward and middle parts of the roof.

The measured moisture content was also of such a magnitude, one would perhaps have expected extensive mould growth in the roof. However, the observations showed relatively little mould growth. One possible explanation for this could be the high temperature levels (above 40ºC) occurring during sunny periods, which may have inhibited mould growth.

2.7 Indoor air humidity in Norwegian houses (Paper V)

Large-scale measurements of indoor air humidity levels in buildings are required for many purposes. One of the most important input parameters when doing a hygrothermal analysis of the building envelope using a simulation models is knowledge about typical levels of indoor air humidity. With knowledge of the typical variations of indoor air humidity in a specific type of buildings, it is also possible to compare measurements in one specific building, e.g. to assess the risk of moisture problems and mould growth.

One common way of expressing the indoor air humidity load is by the moisture supply. The moisture supply (Δv), is defined as the difference between indoor (v_i) and outdoor (v_e) air water-vapour content (in g/m^3). The moisture supply is used when the relative humidity is not controlled but allowed to undergo wide variations due to several factors such as weather conditions, building characteristics, moisture generation and ventilation. It is generally accepted that the moisture supply tends to be relatively constant in a house during the colder part of the heating season (outdoor temperature < 0 - +5ºC), whereas it decreases when the outdoor temperature increases.

In this study indoor air humidity levels and temperature have been measured in 117 houses in Trondheim, Norway. The measurements were taken at 15 min. intervals over a period of seven days. The moisture supply (Δv) was calculated on an hourly basis. Mean weekly values for the moisture supply were calculated from these hourly values. Most of the measurements took place during the heating season. In

each house, measurements were made in a children's bedroom, the main living room, the most used bathroom and the basement/cellar. The basement/cellar is a combination of (partly) heated basements and non-heated storage cellars. In most of the studied rooms it was possible to open the windows for airing purposes.

The analysis showed that the mean weekly moisture supply in bathrooms was significantly higher than all other room types for all outdoor temperatures (below and above +5ºC). The moisture supply in living rooms was significantly higher than in the bedrooms and basements for outdoor temperatures below +5ºC. For temperatures above + 5ºC the moisture supply was significantly higher in living rooms compared to the basements. There were no significant difference between bedrooms and basements.

The mean weekly moisture supply was significantly lower for high occupancy (> 50m^2/person) compared to lower occupancy (< 50 m^2/person). There were no significant differences in mean weekly moisture supply between the various types of building, between year of construction or between the various types of basic ventilation.

According to our measurements it would seem that the design curves given in EN ISO 13788 (EN ISO 13788, 2001) need to be modified if they are to be used in hygrothermal analysis, both with regard to shape and deflection points, and with regard to the level for varied occupancy and room types. The highest levels of moisture supply have been measured in the bathrooms, but it is probably unnecessarily conservative to design the whole house according to these high levels. It would probably be more relevant to use the measurements for the living rooms as basis for the design of the whole building, and carry out a special analysis for the bathrooms (and other similar rooms such as laundry rooms) if necessary.

2.8 Diurnal variations of indoor air humidity in Norwegian houses (Paper VI)

Knowledge of the indoor air humidity in houses is required for many purposes. One of the most important input parameters when doing a hygrothermal analysis of the building envelope using simulation models, is knowledge about typical levels of indoor air humidity. For most purposes, knowledge of the average indoor air humidity over a certain time period (weeks, months, years) is sufficient, and that is also what has been documented and reported in most large-scale measurements of indoor air-humidity levels in houses. In some cases however knowledge of typical daily variations of the indoor air humidity is needed, for instance when assessing the risk for internal surface condensation or when assessing the moisture-buffer effect of the hygroscopic materials in a room. We also registered that instantaneous measurements of indoor air humidity are often made without realising that one single measurement value may be of little interest when considering the large variations throughout the day and week. In this study typical daily variation of indoor RH, temperature and moisture supply of living rooms, bedrooms and bathrooms have been investigated.

Indoor air humidity and temperatures were measured in 87 houses in Trondheim, Norway during the heating season. The measurements were carried out at 15 min. intervals over a period of seven days. The moisture supply (Δv) was calculated on an hourly basis.

It was found that the variation of RH and moisture supply generally followed the expected daily variation of moisture production due to the use of the house and the rooms. However, RH in the living rooms did not vary much during the day. The mean daily amplitudes of RH, temperature, indoor water-vapour content and moisture supply were relatively similar for the living rooms and the bedrooms, while the variations were higher for the bathrooms. The amplitudes of this study compare well with other studies. The dependency of the ventilation system and the outdoor temperatures on the amplitudes were found to be small. It was found that the moisture supply, when calculated on an hourly basis, is highly sensitive to changes in the outdoor air water-vapour content during the day and week. As a general conclusion, therefore, measurements of indoor air humidity should be made on a long-term basis, i.e. minimum one week of measurements.

2.9 Moisture and mould damage in Norwegian houses (Paper VII)

Dampness and other excessive moisture accumulation in buildings are closely connected to observations of mould, or other microbial growth. The behaviour of moisture and air movements can be characterised by physical parameters, but the biological processes take place according to a complicated network of regulating factors. Several phenomena make up the microbial ecology of an indoor environment.

Several studies have examined the aspects of moisture that are associated with biological contamination; these include exhaust in kitchens and bathrooms; below-grade moisture seepage; bulk water (plumbing leaks, roof drainage, and envelope penetration); condensation on inadequately insulated outside walls; and inappropriately sized cooling coils (i.e. incorrect latent heat ratio). In many of the epidemiological studies showing a link between moisture and adverse respiratory health effects or lung disease, exposure is often defined using both qualitative and quantitative methods. Exposure assessment methods used to characterise moisture and mould include the following: (1) physical measurements (e.g., humidity, temperature); (2) sampling and analysis to detect moisture-related microbes and/or chemicals in air and dust; (3) visual inspections for moisture and mould (observations); or (4) reports from individual inhabitants and workers in questionnaire or interview form. Reports of damp spots, water leakage or water damage, and mould or mildew from individual-report questionnaires, are used as substitute measures for the number of fungi in several published epidemiological studies.

The aim of this study has been as follows: (1) describing indicators of visible moisture problem in buildings observed by inspectors and comparing these to individually reported moisture problem; (2) comparing the air humidity in

bedroom, living room, bathroom and basement with or without one or more indicator on a visible moisture problem and with or without registered mould growth; (3) comparing the influence of some building characteristics on the number of houses with one or more indicators of a visible moisture problem or registered mould growth compared to those without any registered indications of mould growth.

The survey includes both individually reported information about housing and inspections from 205 homes in Trondheim, Norway. Indoor air humidity levels and viable mould spores in the indoor air have been measured in a selection of the houses.

In this study children's bedrooms and living rooms have a relatively low share of indicators of a moisture problem. In 42% of the houses with no reported sign of a moisture problem whatsoever, the inspectors found one or more indicators of a moisture problem. There is a tendency in our study of a higher percent share of houses with one ore more indicator of a moisture problem among the houses where the inhabitants themselves have reported a moisture problem once, compared to those who have never reported a problem.

Rooms with one or more indicators of a visible moisture problem have a higher moisture supply compared to those with no indicators (this does not include basement/cellars). Regarding rooms with or without registered growth, one would expect the same result, but in this study the differences are even smaller and appear only in children's bedrooms and bathrooms.

Indoor moisture is associated with some building characteristics. In this study there is a link between a higher percent share of houses with one or more moisture indicators and types of ventilation, types of foundation and building period. In this study there were more cases of registered mould growth in houses with no ventilation /natural ventilation compared to houses with mechanical ventilation, and in houses with basement cellars, compared to those with slab on ground. There was also a link between older houses and newer ones with regard to more registered mould.

2.10 Culturable mould in indoor air and its association with moisture related problems and asthma and allergy among Swedish children (Paper VIII)

Several studies show a link between moisture problems and asthmatic and allergic symptoms among persons living in the affected houses. There is however only limited knowledge about which agents in indoor air, and what levels of exposure, causes the health effects.

A case control study with 198 children with asthmatic and allergic symptoms (cases) and 202 healthy individuals (controls) in Värmland in Sweden has investigated the relationship between mould measurements and different indexes of mouldy odour and visible signs of dampness in the homes of the children (both

observed and reported). Associations between mould measurements in the building and the children's health have also been investigated.

Sampling was carried out during October 2001 - April 2002. Trained inspectors performed visual inspections and indoor air-quality assessments, including air and mould sampling, in the homes. The results from all the samples in each house have been placed in two categories describing whether or not the house has an unnatural occurrence of mould spores in the indoor air (semi-quantitative method).

Analysis of potential associations between concentrations of spores (CFU) in the air and different health parameters or different indexes of mouldy odour and visible signs of dampness in the homes were performed using nonparametric tests (Mann-Whitney *U*-test). Log-transformed, normally distributed concentrations were tested with parametric tests (*t*-test). The analyses were considered statistically significant when $p < 0.05$.

Analyses of potential associations between houses with or without an unnatural occurrence of mould spores in the indoor air (semi-quantitative method), and different health parameters or different indexes of mouldy odour and visible signs of dampness in the homes were performed using Pearson chi-square test.

There were no significant differences in spore concentrations between the observed categories of mouldy odour and signs of visible dampness in the homes, or reported signs of moisture or mouldy odour. When using the semi-quantitative method in distinguishing whether houses were mould-infected or not, there were no significant differences in percentage share between the observed indexes of mouldy odour or visible signs of dampness (either observed or reported).

When comparing the spore concentration in houses with children's health, there were no significant differences where cases had higher values than the controls. Using the semi-quantitative method in distinguishing whether houses were mould-infected or not, there was still no significant differences in percentage share between the cases and controls.

This investigation could not find any links between spore concentrations in the indoor air and signs of dampness and mouldy odour reported by parents or observed by professional inspectors. Neither was there any link between spore concentration and asthma/allergy among children. With these results as a basis, there is no reason for one-time air sampling of mould CFU in indoor air of homes in order to identify risk factors for asthma/allergy in children living in Scandinavian countries.

3 Concluding remarks

In this PhD study, moisture-acceptance criteria concerning mould growth have been developed for several building materials. In general it seems that spruce and chipboard have a greater resistance to mould growth compared to plywood and gypsum. As the RH increased the germination of the spores was faster, and the development and the strength of the mould growth increased. The experiments also showed that an increase in 1% RH had a greater influence on the mould growth than an increase in temperature of 8ºC when the RH was above 85%. Exposure of building materials to high temperatures (up to 60ºC) decreases, or inhibits, the mould growth. But when the temperature exposure is discontinued, growth continues as if nothing had happened.

Four different board-based wind barriers were also tested during the experiments. Two were plasterboard-based and two were wood-fibre based (hardboard). The results of these experiments showed that wood-fibre (hardboard) based wind-barrier boards had a comparatively greater resistance to mould growth than plasterboard-based wind-barrier boards. This was reflected both in the length of time up until proof of visible growth (detectable with the naked eye), and the extent of growth after incubation periods of 11 weeks. Compared to the other material tested (chipboard, gypsum, plywood and spruce), the wind-breaking materials had a greater resistance to mould growth. This is reassuring, given that these materials are more susceptible to moisture such as precipitation during the construction of the building.

Low-slope compact roof is a type of construction with a high level of risk regarding built in moisture and mould growth. The field investigation showed that the drying out potential for the water-damaged roofs were higher than expected, and could not be explained simply by diffusion. In the field experiment, measurements and hygrothermal simulations showed a significantly faster rate of drying for roof elements with substantially more ventilation (with small ventilation holes drilled at the parapet of the roof). Both studies investigated the mould growth occurring in the compact wood-frame roofs, for a relatively high level of built-in moisture. The measured moisture content was at such a high level, one would expect extensive mould growth in the roof. The observations showed, however, relatively little mould growth. This could be explained by three possible factors, either alone or in combination. One possible explanation could be the high temperature levels (up to 60ºC) occurring during sunny periods which stops or decreases the mould growth. The growth experiment in this PhD study confirms such an effect. A second explanation is that the moisture content in the roofs may have become too low to facilitate mould growth, due to the fast rate of drying out. A third possible factor could be that the materials used in the roof constructions are not conducive to mould growth, as e.g. insulation materials. In conclusion flat or low-slope compact roofs would seem to represent a more robust construction regarding the risk of mould growth than first expected.

High indoor relative humidity is a risk factor for moisture damage and mould growth. The results given in this study show that moisture supply is not a constant value throughout the year, but is dependent on the outdoor temperature. This effect is probably due to more ventilation (more open windows) and less moisture production (less indoor activity) during the warm period of the year. According to our measurements it would seem that the design curves given in EN ISO 13788 need to be modified if they are to be used in hygrothermal analysis, both with regard to shape and deflection points, and with regard to the level of varied occupancy and room types. The highest levels of moisture supply have been measured in the bathrooms, but it is probably unnecessarily conservative to design the whole house according to these high levels. It might be better to use the measurements for the living rooms as basis for the design of the whole building, and carry out a special analysis for the bathrooms (and other similar rooms such as laundry rooms) if necessary.

It was also found that the variation of RH and moisture supply generally followed the expected daily variation of moisture production due to the use of the house and the rooms. However, RH in the living rooms did not vary much during the day. The mean daily amplitudes of RH, temperature, indoor water-vapour content and moisture supply were relatively similar for the living rooms and the bedrooms, while the variations were higher for the bathrooms. The dependency of the ventilation system and the outdoor temperatures on the amplitudes were found to be small. It was found that the moisture supply, when calculated on an hourly basis, is highly sensitive to changes in the outdoor air water-vapour content during the day and week. As a general conclusion, therefore, measurements of indoor air humidity should be made on a long-term basis, i.e. minimum one week of measurements.

Knowledge of associations between building characteristics and physical measurements indoors, and indicators of moisture damage and mould growth are important in a risk-reducing strategy for mould growth. In this study rooms with one or more indicators of a visible moist problem had a higher moisture supply compared to those with no indicators (excluding basements/cellars). No such link was found between water supply and rooms with registered mould growth. Neither were there any links between indicators of dampness and mould growth indoors (as indoor culturable mould spores). This shows that reliance on measurements of mould spores in the indoor air, whether there is a moisture problem in the building or not, is too unpredictable. Reported or observed data concerning water staining and measurements of indoor air humidity are also necessary to verify a moisture problem indoors. Moisture measurements should be made on a long-term basis, as suggested earlier in this PhD study.

In a risk-reducing strategy concerning indoor moisture damage and mould growth, it is of special interest to gain more knowledge of building characteristics associated with these kinds of problems. In this study there was a link between a higher percent share of houses with one or more moisture indicators and types of ventilation, types of foundation and building period. There were more cases of registered mould growth in houses with no ventilation / natural ventilation compared to houses with mechanical ventilation, and in houses with basement cellars compared to those with slab on ground. There was also a link between

greater registered mould growth in older houses compared to newer ones. Houses with a fireplace for solid fuels (wood) and wood stored inside also had an increased risk of mould growth. These findings state, not surprisingly, that old houses with poor ventilation and cellars are the houses having the greatest potential for sustaining moisture damage and mould growth. In a risk-reducing strategy it might be useful to improve the ventilation and carry out improvements to the foundations in order to avoid potential moisture damage.

Knowledge about which agent is causing the reported health problems in buildings with moisture related problems is limited. In this study there was no link between mould-spore concentrations (CFU) in the children's bedrooms and asthma/allergy among the children. Based on these results, there is no reason to carry out one-time air sampling of mould CFU in indoor air of homes in order to identify risk factors for asthma/allergy in children living in Scandinavian countries. These results might also indicate that there could be agents other than mould spores that are the cause of the health effects in damp buildings.

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The master's students have been supervised by J. Holme(all), A. Steen-Hansen (first five) and T. Kvande (last five)

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I. **Holme**, J. (2009) Mould growth on board-based wind-barrier products *Energy Efficiency and New Approaches – Proceedings of the Fourth International Building Physics Conference* (Bayazit N.T. *et al*. eds), Beysan Matbaacilik ve Reklamcilik, Istanbul, 75-82.

II. **Holme**, J. and Kvande, T. (2010) Mould growth on building materials and the effect of periodical exposure to "higher" temperatures. *International Bio-deterioration and Bio-degradation*, (submitted).

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Paper I

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Mould growth on board-based wind-barrier products

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ABSTRACT: In recent years there has been an increasing awareness of the negative effect of damp building materials on indoor climate and health. Investigations have revealed a close relationship between moisture and mould in buildings and troubles such as respiratory ailments, headaches and abnormal tiredness. Knowledge about the properties of various materials regarding resistance to mould attacks is most important in order to predict and prevent attacks in building structures, and the main purpose of this investigation has been to chart the criteria for mould growth on various board-based wind-barrier products. Four different board-based wind barriers were tested during the experiments. Two were plasterboard-based and two were wood-fibre based (hardboard).The material samples were sterilised, conditioned, infected and incubated in climate boxes representing six differing environments with different temperatures and relative humidity (RH).The results of these experiments show that wood-fibre (hardboard) based wind-barrier boards have a comparatively greater resistance to mould growth than plasterboard-based wind-barrier boards. This is reflected both in the length of time up until proof of visible growth (detectable with the naked eye), and the extent of growth after incubation periods of 6 and 11 weeks

1 INTRODUCTION

In recent years there has been an increasing awareness of the negative effect of damp building materials on indoor climate and health. Investigations have revealed a close relationship between moisture and mould in buildings and troubles such as respiratory ailments, headaches and abnormal tiredness.

Scrutiny of surveyed building damage examined by SINTEF Byggforsk during the period 1993 - 2002 has shown that more than 75 % is due to moisture, whereof 60 % can be related to design and construction of the outer climate shield (Lisø,T. Kvande et al. 2006). In the coming years it is highly likely that building materials, structures and exterior envelope surfaces will have to withstand ever-increasing climatic loads. Periods with large amounts of precipitation and frequent storms along the Norwegian coast are expected to intensify (Lisø 2006).

The construction period, before the external cladding has been installed, is the time during which board-based wind-barriers are exposed to the heaviest climatic loads. In exposed locations, materials will also be subject to moisture at a later time due to rain being driven through the cladding and onto the wind barrier. A wind-barrier layer must therefore be both water-repellent and be sufficiently watertight to prevent the wall within from becoming damp. (NBI 573.121)

Knowledge about the properties of various materials regarding resistance to mould attacks is most important in order to predict and prevent attacks in building structures, and the main purpose of this investigation has been to chart the criteria for mould growth on various board-based wind-barrier products.

2 TEST MATERIALS

Four different board-based wind barriers were tested during the experiments. Two (GU1 and GU2) were plasterboard-based and two (TF1 and TF2) were wood-fibre based (hardboard). These are further described in Table 1. Testing was carried out during the period 27th March 2007 to 13th June 2007.

Table 1. Description of the test material

Test-material	Thickness (mm)	Density (kg/m^3)	Description
GU1	9,5	844	Glass-fibre reinforced and moisture impregnated core, with a cardboard on both sides
GU2	9,5	818	Impregnated plaster core allocated with cardboard. The cardboard is impregnated to be water-repellent, and treated with a natural conservation reagent. This is supposed to give the plasterboard better moist-technical-propertys and an increased protection against mould growth
TF1	12	266	Asphalt impregnated wood-fiber based windbarrier. One side is impregnated with asphalt to make it airtight
TF2	15	315	The plate consists of wood fibres that is impregnated with asphalt and urea. The front side is impregnated with asphalt to make it airtight. TF2 is a improved version of TF1

3 TEST PROGRAMME

3.1 General

The material samples were sterilised, conditioned, infected and incubated in climate boxes representing six differing environments with different temperatures and relative humidity (RH). (see Table 2). The incubation periods were six weeks (samples at 32.5ºC) and eleven weeks (samples at 15ºC). The mould growth was checked during weeks 3, 4, 5 and 6 for samples at 32.5ºC, and during weeks 3, 4, 5, 6 and 11 for samples at 15ºC. Front and reverse sides of the products were tested by means of individual material samples. Three replicas were utilised for each test.

Table 2. Overview of the different environment and saline solution in the climate boxes

No	Salt	RH [%]	T (ºC)
1	Potassium Clorid (KCl)	85.9	15.0
2	Potassium Nitrate (KNO_3)	95.4	15.0
3	Sterile water	100.0	15.0
4	Potassium Clorid (KCl)	83.7	32.5
5	Potassium Nitrate (KNO_3)	91.5	32.5
6	Sterile water	100.0	32.5

Total number of samples utilised in the experiment was 180 pcs. 5 (products) x 2 (front and reverse sides) x 3 (replicas) x 6 (environments) = 180 pcs.

3.2 Method

3.2.1 *Static climate chambers*

Our static climate chambers comprise enclosed plastic boxes (600 x 400 x 120 mm), totalling 12 pcs, placed in rooms with a stable air temperature. Each box, which is airtight, has a 4-mm thick plate-glass lid. Other openings are sealed on the inside by means of gaffer tape which, together with a rubber sealing strip between plastic box and plate-glass lid, ensures an air-tight environment.

At the bottom of the box is an aluminium grating on which the samples are placed. The grating is installed at a height of 50 mm above the bottom of the box. In addition, each box is equipped with an access hole allowing an apparatus for measuring relative humidity to be introduced. Sealing of the hole is by means of a rubber bung.

The required temperature for the climate boxes is achieved by placing them in SINTEF Byggforsk's climate room at 15^0C and 32.5^0C respectively.

Air humidity in the climate chamber is achieved by using saturated saline solutions in accordance with Table 2 (Greenspan 1977). The bottom of each box is filled with saline solution to a depth of approx. 3 cm. In order to achieve the correct RH, the trays containing the saline solution are allowed to stand for two days.

3.2.2 *Preliminaries*

The board-based wind-barrier products were cut by band saw into test pieces measuring 70 x 70 mm. The samples were dried at 50 ºC for a total of three days (in order to achieve stable weight) and thereafter weighed. After this the samples were wrapped in plastic and sent away for sterilisation (gamma irradiated with radiation doses of 31.1 kGy)

3.2.3 *Conditioning*

The material samples were placed in the climate chamber at 20°C and 70 % RH for one week. Checking of conditioned weight was carried out by the weighing of a specific selection of 45 test pieces on days 6 and 7 of the conditioning period, which showed percentage weight changes of less than 0.1 %.

3.2.4 *Infecting*

The test pieces were infected by means of a spore suspension comprising four mould species (see Table 4) sourced from the VTT Technical Research Centre of Finland. The mould samples arrived in small ampoules and after reception were transferred to agar dishes for further growth of the culture.

Table 3. Mould species used in the test

Species	VTT number
Aspergillus versicolor	D-96660
Chaetomium globosum	D-96644
Cladosporium cladosporioides	D-96646
Penicillium chrysogenum	D-96661

A spore suspension with a concentration of $2x10^6$ sp/ml was utilised. Each test piece had $1x10^6$ sp (0,5 ml) sprayed onto the side to be examined

3.2.5 *Control measurements*

Control measurements of RH in the climate boxes were undertaken using a hand-held humidity gauge. The gauge was passed through the access hole in the side of the box when, after fifteen minutes, readings of relative humidity were taken.

Control measurements of RH were carried out twice a week. Continual logging of the temperatures was also undertaken for both climate rooms in which the climate boxes were placed.

The test pieces were weighed weekly after completion of the infecting process. All weighing of the test pieces was carried out in the climate rooms in which the respective boxes were placed, and the test pieces were taken out of the climate boxes one at a time. The climate box lids were lifted up for only a short period; each time the test pieces were to be removed and replaced after weighing.

All figures were entered directly into the spreadsheet and compared with earlier registered weights in order to reveal any keying/typing errors.

3.2.6 *Analyses*

Visual analyses of mould growth were undertaken weekly following infection/ contamination by photographing and control weighing. The degree of coverage was estimated by laying a digital grid (10x10 squares) over the test piece images for thereafter to determine the number of squares showing growth.

In addition, from week three onwards, the material samples were put under a microscope in order to chart microscopic growth. Five points, at each corner as well as at the centre of the piece of material respectively, were examined by microscope (40X with downlight).

Mould growth, ranked in accordance with Table 5, follows approx. the ranking employed by Qiao Wang (Wang 1992).

4. Ranking table of the mouldgrowth

Ranking	Mouldgrowth
0	No growth
(0-1]	Trace of hyfea found in 1 of 5 points (microskop, 40X)
(1- 2)	Trace of hyfea found in 2 of 5 or more points (microskop, 40X)
[2-3)	Visual growth, degre of coverage 0-33 % of the sample
[3-4)	Visual growth, degre of coverage 33-66 % of the sample
[4-5]	Visual growth, degre of coverage 66-100 % of the sample

3.2.7 *General*

All equipment associated with conditioning, preparation of spore suspension and infection/contamination was sterilised beforehand using alcohol followed by rinsing with sterilised water.

Rubber gloves were employed when handling test pieces at all stages of the experiment.

4 RESULTS

4.1 Material testing at 15°C

The growth results for material testing placed at 15°C are portrayed in Fig. 1. The growth ranking in the graphs are based on the highest value of three replicas.

At 15°C and 85.9% relative humidity (RH) no growth was registered on the front side of any of the materials. Microscopic growth (ranking 1.0) was observed on the reverse side of TF1 after six weeks. However, this was not observed after eleven weeks.

At 95.4% RH microscopic growth was discovered on the reverse side of all materials, with the exception of TF1, after six weeks. TF2 had growth (ranking 1.0) already after four weeks. After eleven weeks there was visible growth (ranking 2.0) on the front side of GU2 and TF2. TF1 had microscopic growth (ranking 1.9). The reverse sides all materials except TF1 showed visible growth (ranking 2.1-2.6). TF1 had microscopic growth (Ranking 1.9).

At 100% RH visible growth was registered on the front side of GU1 (ranking 2.3) and GU2 (ranking 3.0) already after three weeks. They were completely covered with growth during the course of six weeks. TF2 and TF1 had microscopic growth (ranking 1.9) on the front side after six weeks. TF2 had visible growth after 11 weeks (ranking 2.3). On the reverse side of the materials there was visible growth on GU1 and GU2 also after three weeks (ranking 2.2), while TF2 and TF1 had microscopic growth (Ranking 1.9) after four weeks. The reverse sides of GU1 and GU2 were completely covered by growth (ranking 5.0) after six weeks. TF2 had some visible growth (ranking 2.1) after 11 weeks, while TF1 still had microscopic growth after eleven weeks.

4.2 Material testing at 32.5 °C

The growth results for material samples placed at 32.5°C are portrayed in Fig.2. The growth ranking in the graphs are based on the highest value of three replicas.

At 32.5°C and 83.7% relative humidity (RH) neither microscopic nor visible growth was shown on either the front side or the reverse side of any of the tested material types during the course of six weeks.

At 91.5% RH there was no visible or microscopic growth on the front side of the materials. Microscopic growth (ranking 1.0) was registered on GU1 and GU2 during week five; correspondingly for TF2 in week six. No growth was registered on TF1.

At 100 % RH there was visible growth after three weeks on the front side of the materials GU1 (ranking 2.2) and GU2 (ranking 3.0). Visible growth on the two hardboard-based building materials occurred first in week four (ranking 2.3 - 2.5). Visible growth was registered on the reverse side of the test pieces after three weeks on GU1 (2.2), GU2 (2.2), TF2 (2.6) and TF1 (2,2). The extent of growth increases gradually for all materials up until week 6.

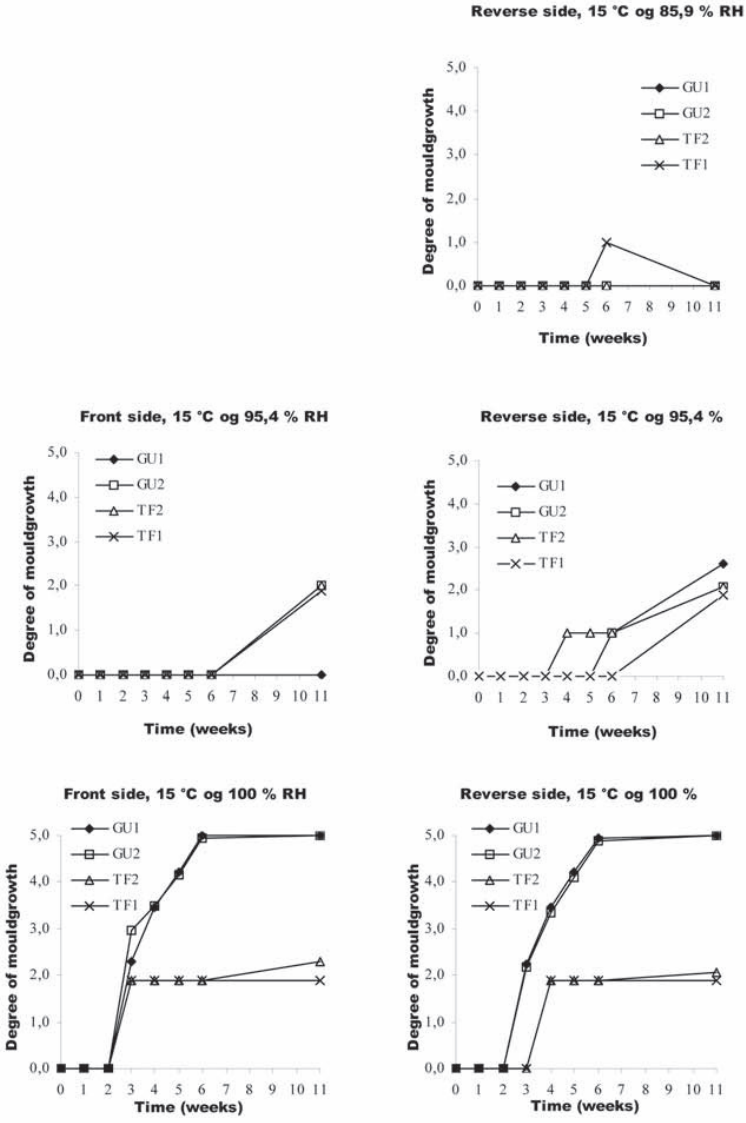

Figure 1 Mould growth on front and reverse side of the samples at 15 °C and 85,9, 95,4 and 100 % relative humidity. Degree of growth; 0=No growth, (0-2)=Trace of hyfea (microskop), [2-5]=Visual growth. Degree of coverage 0-100%.

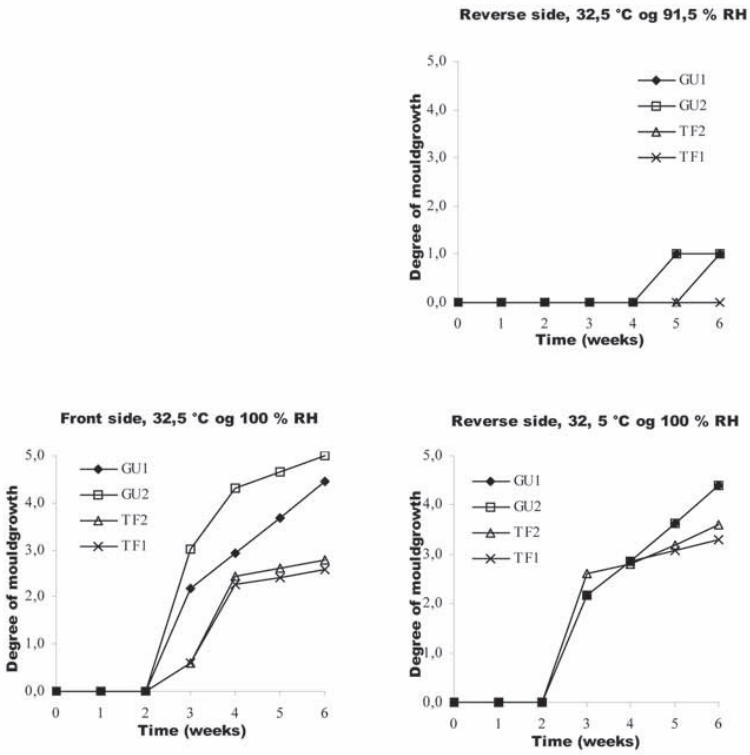

Figure 2. Mould growth on front and reverse side of the samples at 32,5 °C and 91,5 and 100 % relative humidity. Degree of growth; 0=No growth, (0-2)=Trace of hyfea (microskop), [2-5]=Visual growth. Degree of coverage 0-100%.

5 DISCUSSION

5.1 General

At constant temperature the results show a tendency towards greater and earlier growth with increased relative humidity. This applies to samples placed at both 15°C and 32.5°C. This can be explained by increased water activity which in turn gives a higher growth speed for the germinating spore (Ayerst 1969; Trinci 1971).

If one compares the results for tests at a given time, at constant RH, with varying temperatures, one will also see a tendency towards a greater extent of growth at the higher temperature. This is in compliance with results from earlier experiments (Grant, Hunter *et al.* 1989; Wang 1992; Nielsen, Holm *et al.* 2004). The effect of increased temperature in the temperature interval in question (15°C – 32.5°C) is nevertheless smaller compared to the effect of varying RH with regard to mould growth.

5.2 Plasterboard

The lower humidity limit for growth on GU1 and GU2 was found to lie in the interval 85.9 – 95.4% RH at 15°C and 83.7 – 91.5% RH at 32.5°C. Growth was first detected after 5 weeks. This result is in accordance with findings described in published paper. K F Nielsen *et al* detected growth on plasterboards at 20°C and 90% RH. Growth at lower humidity levels was first proved within twelve weeks (Nielsen, Holm *et al.* 2004).

5.3 Front vs. reverse side

For GU1 the growth was detected at lower RH on the reverse side compared with the front side. In view of the fact that both the front and reverse sides have similar cardboard, this is not what one would expect. Nevertheless, as the growth is low (ranking 1.0) after 6 weeks at 15°C and 95.4% RH, and

(ranking 1.0) after 5 weeks at 32.5°C and 91.5% RH, this gives few grounds for concluding that there are differences between front and reverse sides. At 100% RH the extent of growth is the same for front and reverse sides, as one would expect.

For GU2 growth was also detected at lower RH on the reverse side compared with the front side. This, however, is what one would expect considering that the front side is impregnated and has added preservatives which, according to the manufacturers, in combination with improved moisture-technical properties should provide increased security against mould attacks. As in the case of GU1, the growth rate is very low (ranking 1.0) after 6 weeks at 15°C and 95.4% RH, and (ranking 1.0) after 5 weeks at 32.5°C and 91.5% RH. At 100% RH, the growth on the front side is approx. equal to 15°C, and slightly stronger than at 32.5°C compared with the reverse side and thus does not comply with the findings above. Should the "improved moisture-technical properties" entail increased moisture diffusivity for the cardboard on the front side, it is conceivable that moisture in vapour form has been able to permeate more rapidly resulting in a higher water activity in the cardboard at an earlier stage. Differences in growth ranking can possibly be explained by the starker contrast formed by the grey/green hypha growth and the red cardboard on the front side relative to the hypha growth on the grey surface of the reverse side.

5.4 GU1 vs. GU2

Comparing the growth on GU1 and GU2 one can see approx. equal growth on the reverse side for samples placed in 100% relative humidity (RH). The reverse side of GU1, as opposed to GU2, is impregnated, but this does not appear to have any appreciable effect on the growth difference. On the front side, however, one registers somewhat greater growth on GU2 compared with standard GU1. The difference is most apparent at 32.5°C and, as mentioned earlier, does not comply with the manufacturer's declaration. The difference can possibly be explained in the same way as the above-mentioned variation between the front and reverse side of GU2.

5.5 Wood-fibre board (Hardboard)

Hypha growth (ranking 1.0) was detected on one of the replicas of TF1 at 15°C and 85.9% RH after 6 weeks. At 95.4% RH, however, no growth could be detected, neither at 91.5% RH and 32°C, nor on the front or reverse sides. This would indicate that the hypha incidence detected at 85.9% RH and 15°C is due to a slightly higher initial moisture admission that has caused germination. Once the moisture level was reduced, hypha growth thereafter went into hibernation. The initial moisture can be due to damp infection with too short subsequent drying time prior to placement in the climate box. Examination by microscope after 11 weeks shows no growth on TF1 at 15°C and 85.9 % RH. This substantiates the theory about an earlier germination being made possible, but further development not taking place.

The lower humidity limit for growth on TF1 will thereby lie within the interval 95.4 –100% RH at 15°C with microscopic hypha growth within three weeks. At 32.5°C the limit value will be 91.5 – 100 % RH and then with visible growth within 3 weeks (ranking 2.2). The lower humidity limit for microscopic growth (ranking 1.0) on TF2 was found to be 85.9 – 95.4% RH at 15°C after four weeks, and 83.7 – 91.5% RH at 32.5°C (within 6 weeks).

Compared with experiments undertaken earlier, the limit values for growth on TF1 lie slightly higher for our measurements. The results for TF2, however, comply somewhat better. Qiao Wang (Wang 1992) could detect growth on bitumen-impregnated wood-fibre board (hardboard) at 85% RH and 15°C within 6 weeks, and within 4 weeks at 90% RH. The difference could be due to varying properties of the types of material used in the experiments resulting from varying components or manufacturing methods. In addition, there could be variations resulting from the use in experiments of different mould varieties having differing humidity and temperature requirements.

5.6 Front vs. reverse side

At 100% RH and 15°C microscopic growth was observed on the front side of TF1 and TF2 one week earlier than on the reverse side. Otherwise the front and reverse sides were equal at week eleven as well. At 100% RH and 32.5°C, however, visible growth was detected one week earlier on the reverse side of both TF1 and TF2 (week 3) compared with the front side. This is what one would initially expect, in view of the fact that both products have a bituminous coating on the front side while the reverse side reveals visible untreated wood fibres.

5.7 TF1 vs. TF2

Growth was detected at 95.4% RH and 15°C on the reverse side of TF2, which first occurs at 15°C and 100 % RH for TF1. To start with, the reverse side of TF2 ought to show equal or better resistance to mould growth, in view of the fact that all the fibres are impregnated with bitumen and carbolic acid/urea (www.hunton.no BIT) compared with the results for front and reverse sides of TF1respectively. Admittedly, the growth demonstrated is only detectable under a microscope and does not develop in size/volume. This could indicate an initial growth resulting from moisture, added during the infecting process, that has later stagnated.

5.8 Plasterboard-based wind barriers vs wood-fibre (hardboard) wind barriers

At 15°C and 100% RH there was visible growth on the front and reverse sides of the GU products after 3 weeks. After 6 weeks, the test pieces were well covered with mould growth (ranking 5.0). However, the condition of the wood-fibre based (hardboard) wind barrier products at 15°C and 100% RH showed only microscopic growth after 3 weeks (front side) and 4 weeks (reverse side). After 6 weeks there was still only microscopic growth (ranking 1.9). After 11 weeks there was visible growth on both front and reverse sides of TF2 (ranking 2.3 and 2.1), while TF1 still had only microscopic growth.

At 32.5°C and 100 % RH the difference between GU and wood-fibre based boards (hardboard) was less. Visual growth was seen one week later (week 4) on the front side of the wood-fibre based compared with the GU products. After 6 weeks the extent of the growth was lower for the front side of the wood-fibre based product (ranking 2.8 for TF2 and 2.6 for TF1) compared with the front sides of the GU-based products (ranking 4.4 and 5.0). The reverse sides of the products were fairly similar both in time when the growth appeared and in extent.

At lower RH it is difficult to determine any noticeable difference between the products. After 11 weeks there was visible growth on the front side of one GU product and TF2 (both ranking 2.0) at 15°C and 95.4% RH. Correspondingly, the reverse sides at the same temperature and RH have shown visible growth on all products with the exception of TF1.

5.9 Uncertainty factors

For reasons of space, front and reverse sides of material samples for identical environments were not placed in one and the same box, which could have had an effect on relative growth. However, weekly control measurements of humidity and temperature were carried out in all the boxes showing that humidity conditions could vary by up to 3.0% at the lowest RH levels. These variations are a result of slight deviations in the temperature of the room in which the climate boxes were placed. Over time, however, this has proved stable.

Analysis of microscopic hypha growth was carried out by microscope examination of five points on each material sample. This number of points could be too few, but they were a compromise between accuracy and length of time the test pieces were kept outside the containers bringing about changes in moisture content.

It proved difficult to separate a commencing growth of hypha (recognisable by a transparent thread) from the test material's composition, which *inter alia* comprises binding agents (transparent glue threads) and coloured particles. This, however, only affected growth ranking (0-1]. Growth ranking 1.9 is associated with a network of hypha which gives a small margin for misinterpretation. There is also the possibility of the material structure concealing microscopic growth, but again this is only applicable for growth ranking (0-1].

Evaluation of percentile coverage (visible growth w/ naked eye) was carried out by analysis of digital images after placement of a digital grid (10x10 squares). Contrast between fungus growth and material thus becomes important and leads to uncertainty of detection and ranking of the white fungus/hypha growth against a light background.

Spore concentrations were checked by means of a spore count. As it was difficult to check the number of spores that were actually "spore proficient," this constitutes an uncertainty factor as regards the "infection pressure" to which the test materials have been exposed.

5.10 Conclusion

The results of these experiments show that wood-fibre (hardboard) based wind-barrier boards have a comparatively greater resistance to mould growth than plasterboard-based wind-barrier boards. This is reflected both in the length of time up until proof of visible growth (detectable with the naked eye), and the extent of growth after incubation periods of 6 and 11 weeks. The difference applies to growth at approx. 100% relative humidity. After 11 weeks at lower RH and 15°C there is a relatively similar degree of proof and degree of growth between the plasterboard and wood-fibre (hardboard) products.

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Paper II

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Mould growth on building materials and the effect of periodical exposure to "higher" temperatures

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Abstract

This study have examined the levels of constant relative humidity (RH) and constant temperatures at which mould growth will grow on spruce, plywood, chipboard and gypsum plasterboard respectively. We have also examined the effect that periodically higher temperatures have on growth. In general it seems that spruce and chipboard have a greater resistance to mould growth compared to plywood and gypsum. As the RH increased the germination of the spores was faster, and the development and the strength of the mould growth increased. The experiments also showed that an increase in 1% RH had a greater influence on the mould growth than an increase in temperature of 8 ºC when the RH was above 85%. Exposure of building materials to high temperatures (up to 60 ºC) decreases, or inhibits, the mould growth. But when the temperature exposure is discontinued, growth continues as if nothing had happened.

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Keywords; Mould growth, building materials

Introduction

During the last decade there has been an increased focus on the negative consequences of damp building materials on indoor environment and health. Epidemiological studies indicate a clear link between damp interiors and negative health effects (Bornehag *et al*., 2001). It is not the moisture itself that is harmful, but other causes such as chemical degassing, microbial growth and similar mechanisms. Mould growth can also be an early indication of an indoor moisture problem.

In Norway, it is usual to build houses without any form of protection against snow or rain during the construction period. This means that large parts of the building are exposed to an ongoing risk of built-in moisture damage, unless a correct and necessary drying-out of the building is implemented once it has been enclosed, and before any indoor work is started.

In colder climates, there is always a risk of condensation whenever moist air comes into contact with cold surfaces. This can occur during the wintertime if warm, moist air leaks into the cooler outer parts of the building structure, such as walls and roofs, or when cold bridges in the construction provide cooler indoor surfaces.

With more stringent energy requirements leading to tighter and better-insulated houses, this condensation risk could increase in the future. In particular, the moisture content of air in houses without mechanical ventilation is increasing, while roofs and walls are becoming “colder" than before due to thicker insulation.

Moisture damage resulting from leaks or condensation often leads to mould growth on indoor surfaces of hidden interior structures. Because of the risk of possible negative health effects of mould, national authorities do not allow visible mould growth or mouldy odour of any kind in buildings.

Spruce, plywood, chipboard and gypsum plasterboard are frequently-used construction materials in timber houses. These are all materials that have the potential for mould growth. In order to be able to assess whether there is a risk of mould growth, we need to know the building-material’s properties with respect to humidity and temperature, as well as the time needed for the mould growth to establish itself on the material's surface. It is also of interest to know more about the effects of varied and high temperatures on mould growth. Field studies conducted in moisture-damaged Norwegian roofs, would indicate that growth is hindered / stops as a result of high temperatures in summer (Geving and Holme, 2010) (Holme *et al.,* 2008). In the study by Geving and Holme (2010), the temperature reached as high as >60ºC in plywood covered by a dark-coloured roofing membrane, and >50ºC in plywood covered by a light-coloured roofing membrane.

Today there are calculation programmes that can estimate the risk of mould growth in buildings (eg. WUFI). These programmes are based on theoretical models using measurements of moulds in field and laboratory experiments. In our experience, however, these calculation programmes often predict too much mould growth, both regarding the

time until growth is established and the volume. Because of this optimism, we still need experiments that can verify, or provide new input, concerning the different levels of humidity and temperature that mould needs in order to grow on various building materials

In this study, we have examined the levels of constant relative humidity (RH) and constant temperatures at which mould growth will grow on spruce, plywood, chipboard and gypsum plasterboard respectively. We have also examined the effect that periodically higher temperatures have on growth.

Materials and methods

This investigation was conducted as two separate experiments. In the first experiment plywood, gypsum plasterboard, spruce and chipboard were all tested for mould growth under different climatic conditions (constant temperature and relative humidity (RH)) for 32 weeks. In the second experiment, the same materials were exposed to "higher temperatures" for two hours, three days a week. The materials are further described in Table 1. Testing was carried out during the period October 2007 to May 2008.

All the materials were cut by band saw into test pieces measuring 70 x 70 mm. The samples were dried at 50 ºC for a total of three days (in order to achieve stable weight) and thereafter weighed. After this the samples were wrapped in 0.15mm PE-foil and sent away for sterilisation (gamma irradiated with radiation doses of 31.1 kGy). Prior to the infecting of the material, samples were placed in the respective climate in which they were to remain during the 22-day incubation period. According to NS-EN 323, the conditioned weight is when the percentage weight change is less than 0.1% within a 24-hour period. The samples which were incubated at ~99% RH were not conditioned for 22 days prior to infecting. Instead these samples were placed in sterilised water for one hour.

The test pieces were infected by means of a spore suspension comprising three mould species (see Table 2) sourced from the VTT Technical Research Centre of Finland. The mould samples arrived in small ampoules and after reception were transferred to agar dishes for further growth of the culture.

A spore suspension with a concentration of 2×10^6 sp/ml was utilised. Each test piece had 1×10^6 sp (0.5 ml) sprayed onto the upper side during testing.

The material samples were incubated in climate boxes representing eight environments with different temperatures and relative humidity (RH) (see Table 3). The samples exposed to higher temperature (experiment 2) were all placed in climate boxes at 21ºC and ~ 99% RH. The incubation periods were 32 weeks for the samples in static climate and 15 weeks for the samples exposed to "higher temperatures". The mould growth was checked once every week. Three replicas were utilised for each test.

In the second experiment the materials were exposed to temperatures of 40, 50 or 60ºC respectively for two hours, three days a week (Monday, Wednesday and Friday). The temperature exposure started 24 hours after the inoculation of the samples. The temperature treatment lasted for 12 weeks. In addition, reference samples were placed in the same environment, but these samples did not undergo temperature exposure.

Visual analyses of mould growth were undertaken weekly following infection/ contamination by photographing and control weighing. The degree of coverage was estimated by laying a digital grid (10x10 squares) over the test-piece images for thereafter to determine the number of squares showing growth. In addition the material samples were put under a microscope in order to chart microscopic growth. Five points, at each corner, as well as at the centre of the piece of material respectively, were examined by microscope (40X with down light).

Mould growth, ranked in accordance with Table 4.

Results

Experiment 1 – Constant climatic conditions

The mould growth on plywood, gypsum plasterboard, spruce and chipboard at various temperatures and relative humidity (experiment 1) are presented in Figures 1 to 4 respectively. The effect of exposure to periodically higher temperatures, 40, 50 and 60 ºC respectively (experiment 2) are shown in Figures 5 to 8. The growth ranking in the graphs is based on the highest value of three replicas. The samples placed at ~75 % RH and 15 ºC or 23 ºC (experiment 1), did not acquire any growth (neither microscopically nor visually) during the 32-week long test period, and have therefore not been presented in the results.

Plywood

At 99% RH visible growth was registered after 3 weeks (see Figure 1). The test pieces placed in 23ºC had a higher growth rate between 9 and 13 weeks compared to the samples placed in 99% RH and 15ºC. All samples at 99% RH had strong growth all over the samples after 16 to 18 weeks.

The test pieces placed at 95.4% RH and 15ºC acquired visible growth after 12 weeks. The degree of mould growth reached a maximum level after 19 weeks.

At 94% RH and 23 ºC visible growth was registered after 14 weeks. The degree of mould growth did not exceed level 6 during the test period.

At 85.6% RH and 15 ºC visible growth was registered after 21 weeks. After 32 weeks the degree of mould growth was at level 5.8.

The test pieces placed in 84.7% RH and 23 ºC did not acquire any visible growth during the test period.

Gypsum plasterboard
The test pieces placed at 99% RH and 23 ºC acquired visible growth after 2 weeks (see Figure 2). Maximum growth according to the growth scale was achieved within 4 weeks. The other samples placed in 99% RH but at 15 ºC acquired visible growth after 4 weeks and maximum growth within 10 weeks.

The test pieces at 95.4% RH and 15 ºC acquired visible growth after 11 weeks and maximum growth after 22 weeks.

At 94.0% RH and 23 ºC visible growth was registered after 17 weeks, and reached almost maximum growth according to the degree of mould growth after 32 weeks.

The test pieces placed at 85.6% RH and 84.7% RH did not acquire any growth at all during the 32 week long test period.

Spruce
The test pieces placed at 99% RH and 15 ºC or 23 ºC acquired visible growth after 3 weeks (see Figure 3). The growth speed seemed to be almost the same for the test pieces placed at both temperatures. Maximum growth was achieved after 15 weeks.

The test pieces placed at 95.4% RH and 15 ºC acquired visible growth after 16 weeks. At the end of the 32 weeks long test period the degree of mould growth was at level 5.

The test pieces at 94% RH and 23 ºC acquired visible growth after 12 weeks. The growth was faster in the beginning compared to the test pieces at 95.4% RH, but in the end the degree of mould growth was about level 5 for these samples as well.

At 85.6% RH and 15 ºC visible growth was registered after 15 weeks. After 32 weeks the degree of mould growth was at level 3.
The test pieces at 84.7% RH acquired only microscopic growth throughout the 32-week long test period.

Chipboard
The test pieces placed at 99% RH and 15 ºC or 23 ºC acquired visible growth after 2 weeks (see Figure 4). Both series had the same growth rate during the 6 first weeks, but after this the growth rate was higher for the test pieces at 23 ºC compared to the pieces placed at 15 ºC. The test pieces placed at 23 ºC acquired the highest level of growth after 19 weeks. The test pieces at 99% RH and 15 ºC increased their growth again after 15 weeks, and achieved maximum growth according to the growth scale after 22 weeks.

The test pieces at 95.4% RH and 15 ºC and 94.0% RH and 23 ºC had a very similar growth rate with only microscopic growth throughout the 32-week long test period. The test pieces at 85.6% RH and 15 ºC and 84.7% RH and 23 ºC also achieved only microscopic growth during the test period.

Experiment 2 – Temperature exposure

Plywood
Test pieces placed at 40 ºC and 50 ºC started to grow one-week later than the reference samples (see Figure 5). The reference samples acquired visible growth after 3 weeks, while samples treated at 40 ºC and 50 ºC acquired visible mould growth after 4 weeks. After 4 weeks the degree of mould growth was at level 6 for both the test series treated at 40 ºC and 50 ºC and the reference samples. The mould growth stayed at this level throughout the 15-week long test period. The test pieces treated at 60 ºC had a different growth rate compared to the to other test series. Microscopic growth was first registered after 6 weeks, and visible growth was registered after the temperature treatment was stopped after 12 weeks. Under normal conditions the growth increased and was at the same level as the other test series one-week later.

Gypsum plasterboard
The reference samples acquired visible growth after 3 weeks and reached the highest degree of mould growth according to the scale after 15 weeks (see Figure 6). The test pieces treated at 40 ºC started to grow faster than the reference samples, and acquired visible growth at level 6 after only 2 weeks. These samples stayed at this level through out the test period. The test pieces treated at 50 ºC started to grow after 4 weeks and acquired visible growth after 5 weeks. These samples also stayed at level 6 throughout the test period. The test pieces at 60 ºC did not acquire any growth as long as the temperature treatment went on. When the temperature treatment stopped, the mould growth quickly increased. At this point, the growth pattern looked very much the same as for the reference sample.

Spruce
The samples at 40 ºC acquired the fastest growth with visible growth after 3 weeks (see Figure 7). The reference samples and the samples at 50 ºC acquired visible growth after 4 weeks. The samples at 60 ºC acquired visible growth after 6 weeks. All samples ended with a growth level about 4 - 4.5 after 15 weeks.

Chipboard
The reference samples and the samples treated at 40 ºC acquired visible growth after 3 weeks (see Figure 3). The samples treated with 50 ºC acquired visible growth after 5 weeks. After the temperature treatment, the growth on all samples seemed to increase again. The samples at 60 ºC only acquired microscopic growth during the 12 weeks with temperature treatment. After the temperature treatment, the mould growth increased to the same level as the other test series.

Discussion

Climatic conditions for mould growth

The degree of mould growth on all the building materials tested in this project, showed an increasing growth according to the level of relative humidity (RH) to which the test

pieces were exposed. It would also appear that the temperature difference between 15 and 23 ºC is less important than a difference in relative humidity (RH) between 95.4 and 94% and 85.6 and 84.7% respectively.

At ~75% RH no growth was registered on any of the materials. This is in accordance to the level of water activity needed for growth to be established for most species of moulds. According to Grant *et. al.*, most moulds need a water activity of at least 0.85-0.90 (Grant *et al.*, 1989).

At ~85% RH microscopic growth was registered after 5 to 6 weeks on spruce and Chipboard. Viitanen and Ritschkoff (1991) observed microscopic growth after 5 and 6 weeks on test samples of spruce incubated at 86-88% RH and temperatures of 15 and 20 ºC (Viitanen and Ritschkoff, 1991) . In another study, Wang found that chipboard acquired visual mould growth after 8 and 5 weeks at RH 85% and temperatures of 12 and 20 ºC (Wang, 1992). In the present study, spruce acquired visual growth after 17 weeks following exposure at 85% RH and 15 ºC. Viitanen and Ritschkoff registered visual mould growth on spruce after 12 weeks, but then at a temperature of 20 ºC (Viitanen and Ritschkoff, 1991). The difference in mould growth on spruce between our study and in the study of Viitanen and Ritschkoff could be explained by a difference in the quality between the spruce samples used in the two experiments. It is a known fact that the sapwood of any wood is less resistant to fungal infection than the heartwood. In addition, the durability of the heartwood increases radically from pith to the highest level near the sapwood-heartwood interface, and there is also an increase in durability from the bottom to the top of a tree (Zabel and Morell, 1992).

We observed visual growth on chipboard exposed to 85% RH and 15 ºC after 28 weeks. Wang made similar observations already after 10 weeks (Wang, 1992). In our study at RH ~85% and temperature 15 ºC, plywood had a slower and smaller growth compared to chipboard and spruce up until 20 weeks. After 20 weeks the growth on plywood increased dramatically, and was higher than the other material tested throughout the test period. Experiments on plywood conducted by Nielsen *et al*. showed only minimal growth on plywood after 17 weeks (Nielsen *et al*., 2004). Wang registered microscopic growth after 6 weeks on plywood exposed to 85% RH and 15 ºC. No visual growth was registered during the 10-week long experiment (Wang, 1992). Both these results of Nielsen and Wang are comparable to our results. Neither did we have any visible growth on plywood after 17 weeks.

In this survey, no mould growth was registered on any test pieces of gypsum plasterboard exposed to ~75% and ~85% RH. At ~95% RH the growth development for gypsum plasterboard was lower up until 10-15 weeks compared to the other materials tested. From this moment onwards, the mould growth increased considerably compared to the other materials. At ~99% RH gypsum is the material tested that achieved the fastest and strongest mould growth. It is mainly the cardboard covering the gypsum core that acts as a viable source of nutrition for the moulds. According to the experiments it would seem that the moisture content of the cardboard needs to reach equilibrium with a RH on ~95% before the mould is capable of using it for nutrition. The results in this study are in

accordance with the study of Nielsen *et al.* They found small amounts of mould growth at 86% RH and 20 ºC, and substantial growth after 17 weeks at 95% RH and 10 ºC (Nielsen *et al.,* 2004). In another study, mould growth was registered on gypsum plasterboard at 90% RH and 23 ºC, while no growth was registered at 90% RH and 15 ºC (Ritschkoff *et al.,* 2000).

In our study, spruce and plywood are the materials where microscopic and visual mould growth was first registered at RH ~85%. Viitanen observed microscopic growth after 6 and 5 weeks for test pieces of spruce incubated at 86-88% RH and temperatures at 15 or 20 ºC. The samples at 20 ºC first acquired visible growth after 12 weeks. At 96 - 98% RH samples exposed to 15 or 20 ºC acquired visible growth after 4 weeks (Viitanen and Ritschkoff, 1991).

At ~99 % RH spruce clearly has less visible mould growth compared to the other materials. From a general point of view, it would seem that spruce has the highest resistance to mould growth of all the materials tested in this study. According to Shi, spruce can have wood extractives that decrease the mould growth (Shi *et al.,* 2006). Plywood and chipboard are also based on wood materials, but these are materials based on processed wood where possible wood extractives have been destroyed during the manufacturing process. Plywood and chipboard also contain other organic material such as glue, which also might function as nutrition for the mould fungi.

Temperature treatment effect

When the materials tested in this study were exposed to “high” temperatures (temperatures above 40 ºC), for two hours, two days a week, the growth was clearly reduced for the samples exposed to 60 ºC, both with regard to the length of time up until proof of microscopic and visual growth, and the extent of the growth. This could probably be explained by a combination of delayed germination of the spores, and unfavourable growth conditions for the mycelia due to the temperature exposure. The maximum temperature for mycelia growth by most fungi is often at 40-50 ºC, because the protein (enzyme) denaturing caused by heat then takes place. Fungi, however, may exhibit a change in gene expression, which could lead to the synthesis of “heat-shock proteins”. These proteins would appear to prevent and/or repair general damage, denaturation and the aggregation of other cellular proteins, as they are not only induced by heat, but also by heavy metals and oxidants (Jennings and Lysek, 1999). Spores are frequently more thermo-tolerant than the corresponding mycelia. The basidiospores of S. lacrymans were killed by 32 hours at 60 ºC or 1 hour at 100 ºC. However, 4 hours at 65 ºC reduced the germination rate from 30 to 8% (Hegarty and Seehann, 1987). In between temperature exposures, the moulds in this experiment had time during which the temperature and the relative humidity were favourable for mould growth. During these periods the spores could germinate, and the mycelia could produce “heat-shock proteins” for protection, and then continue with the growth, but at a slower rate compared to the reference samples.

When the temperature treatment stopped, the mould growth increased substantially on all the materials tested. The growth was then comparable to the growth on the reference samples at in the beginning of the test. This also confirms that the spores do not die during the temperature treatment at 60 ºC, but rather that the higher temperature delays the germination of the spores, and has an inhibiting effect on the mycelia growth. Results from studies on moulds isolated form the soil showed that *Penicillium Chrysogenum* does not grow when exposed to temperature at 55 ºC. However, as soon as the temperature is changed to 35 ºC, the spores germinate and the mycelia start to grow (Salar and Aneja, 2006).

Conclusion

The degree of mould growth on all the building materials tested in this project, showed an increase in growth depending on the level of relative humidity to which the test pieces had been exposed. It would also seem that the temperature difference between 15 and 23 ºC is less important than a difference in relative humidity between 95.4 and 94.0% and 85.6 and 84.7%. At ~75% RH no growth was registered on any of the materials.

Plywood is the material in this test with the greatest potential for mould growth. Visual growth was first registered at 85.6% RH and 15 ºC after 21 weeks of exposure. At ~99% RH visible visual growth was registered after 3 weeks, with maximum growth after 9 weeks.

Gypsum plasterboard had the second-best potential for mould growth, but at a level in RH above ~95%. At ~99% RH visual growth was registered after 2 weeks, and maximum growth was reached after 4 weeks when the temperature was 23 ºC.

Spruce had less mould growth compared to plywood and gypsum plasterboard. At 95.4% RH and 15 ºC visual growth was registered after 17 weeks, and the growth did not exceed level 5, showing a thin visible layer with 66% coverage. When the RH was ~99% spruce proved to be the material with the least growth of all the materials tested.

Chipboard had only microscopic growth at RH less than ~99 (both at 15 ºC and 23 ºC). Above ~99% RH chipboard had visible growth after 2 weeks, with maximum growth after 19 weeks.

In these experiments, there was no difference in mould growth between samples exposed to 40 ºC and 50 ºC for two hours, three times a week, compared to the reference samples not exposed to “higher” temperatures.” Mould started to grow later on the samples exposed to 60 ºC, and the growth was less compared to the other samples. However, when the temperature exposure stopped after 12 weeks, mould started to grow on these samples in a similar way to the reference samples.

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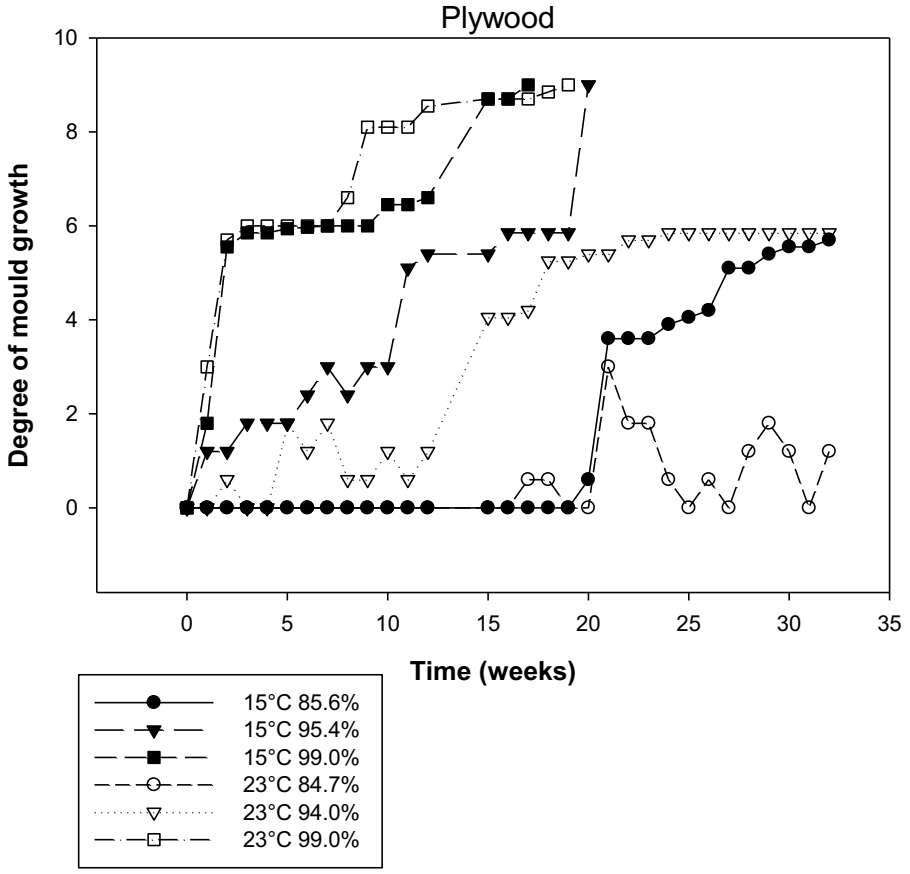

Figure 1. The degree of mould growth on plywood, at different temperatures and relative humidity.

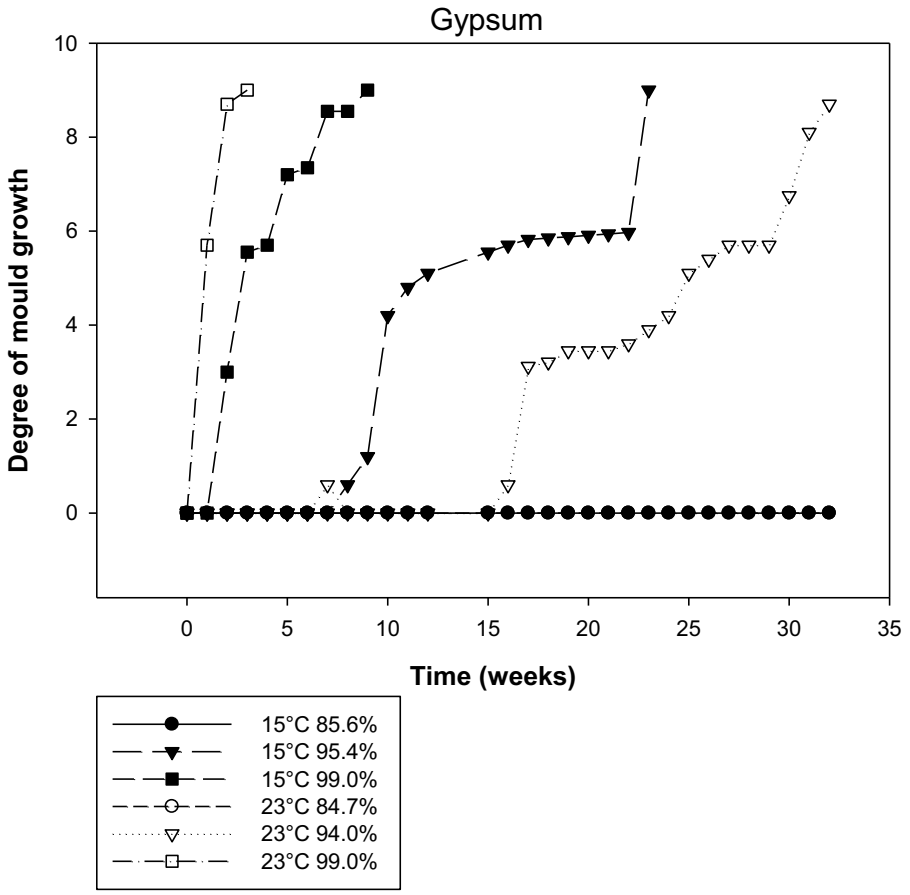

Figure 2. The degree of mould growth on gypsum, at different temperatures and relative humidity.

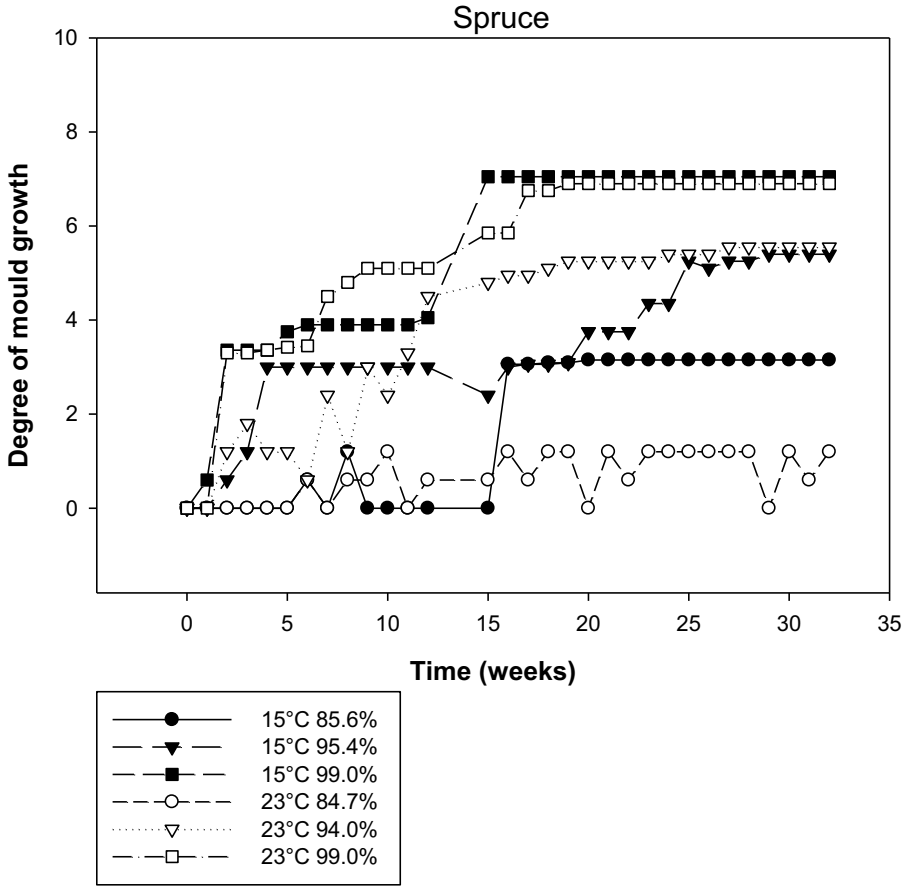

Figure 3. The degree of mould growth on spruce, at different temperatures and relative humidity.

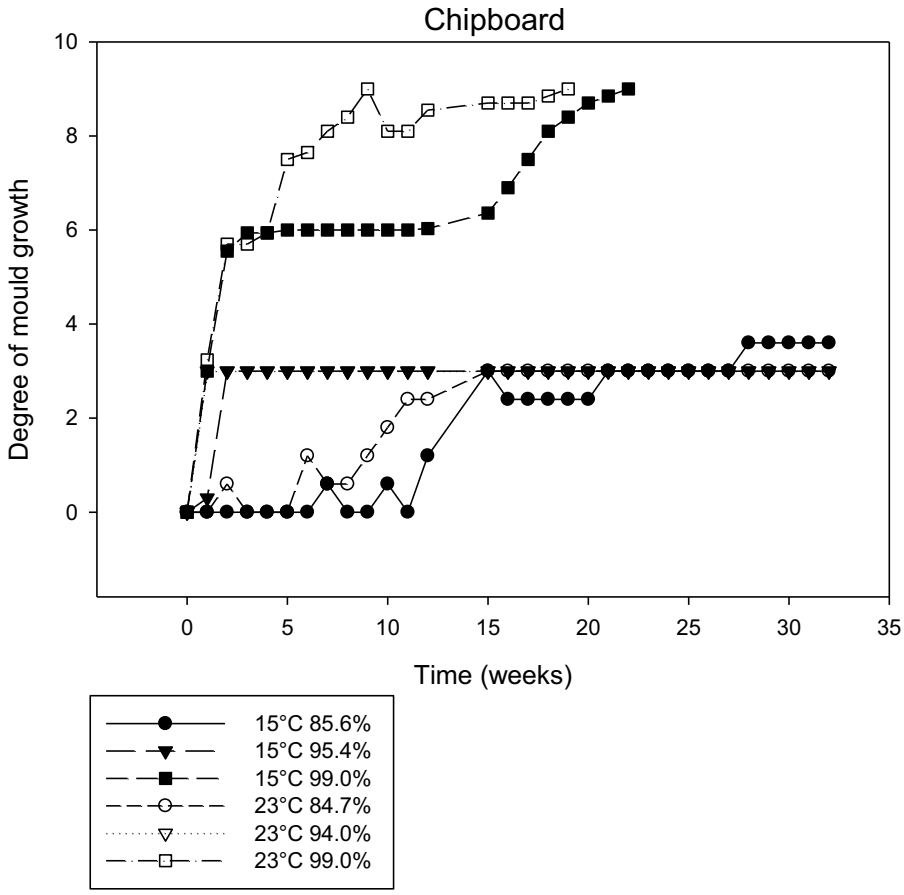

Figure 4. The degree of mould growth on chipboard, at different temperatures and relative humidity.

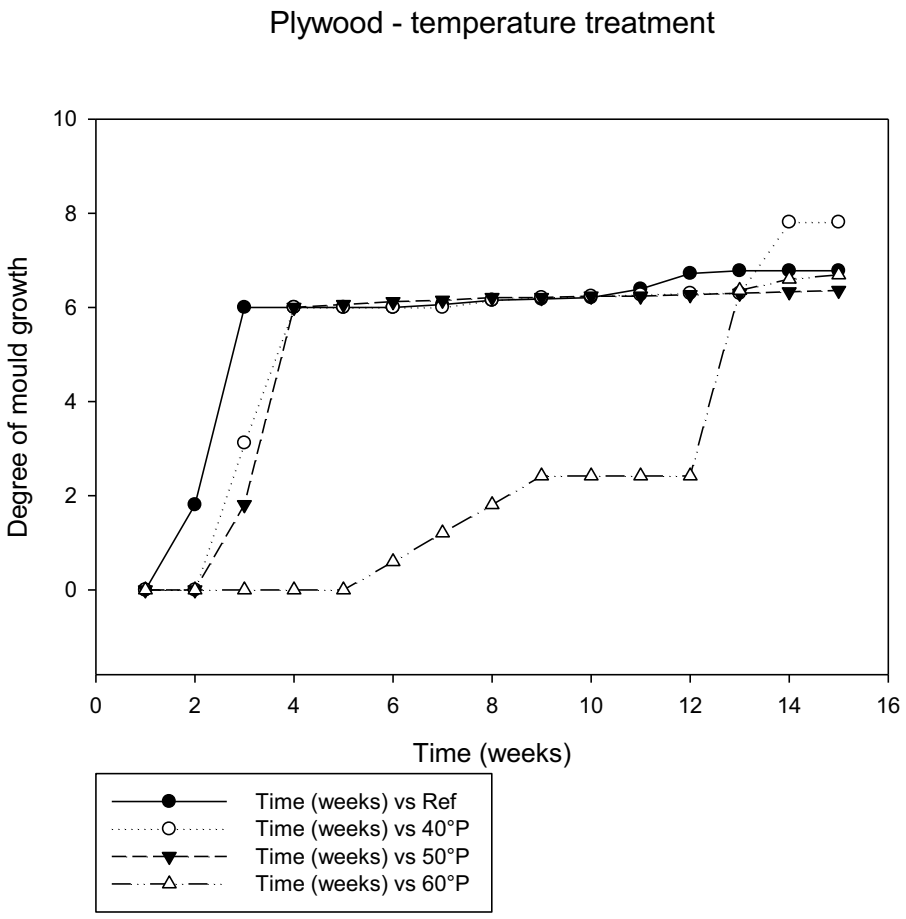

Figure 5. The degree of mould growth on plywood, exposed to temperatures of 40, 50 and 60ºC respectively for two hours three times a week.

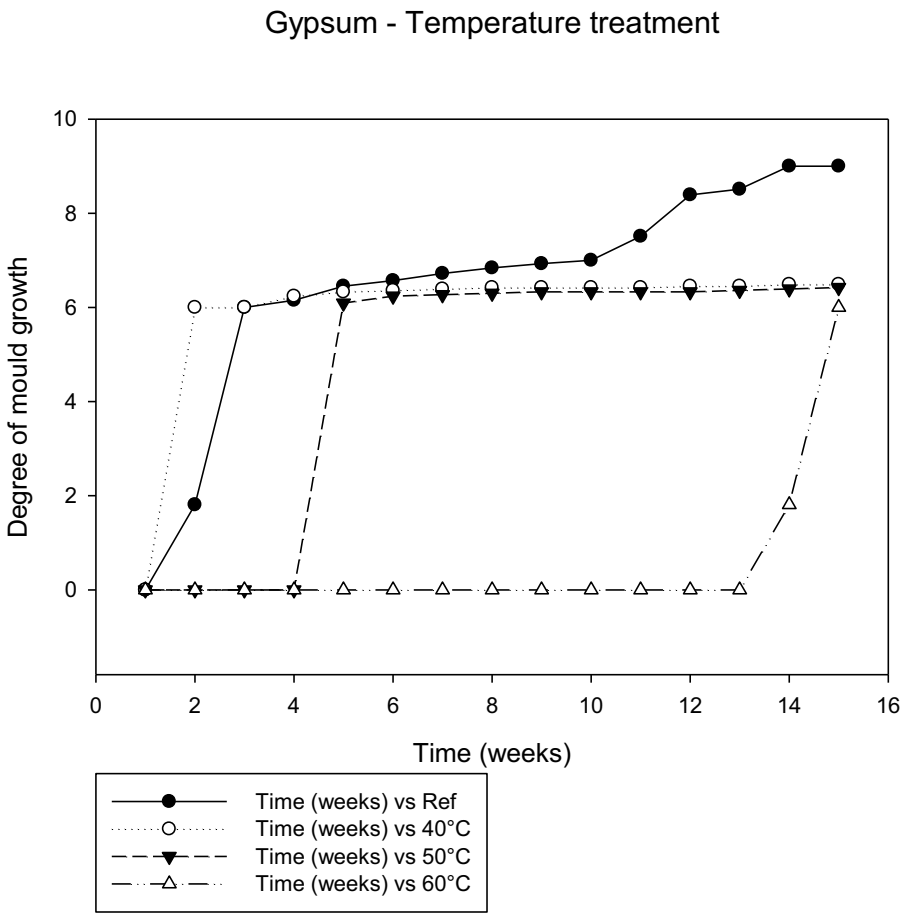

Figure 6. The degree of mould growth on Gypsum board, exposed to temperatures of 40, 50 and 60ºC respectively for two hours three times a week.

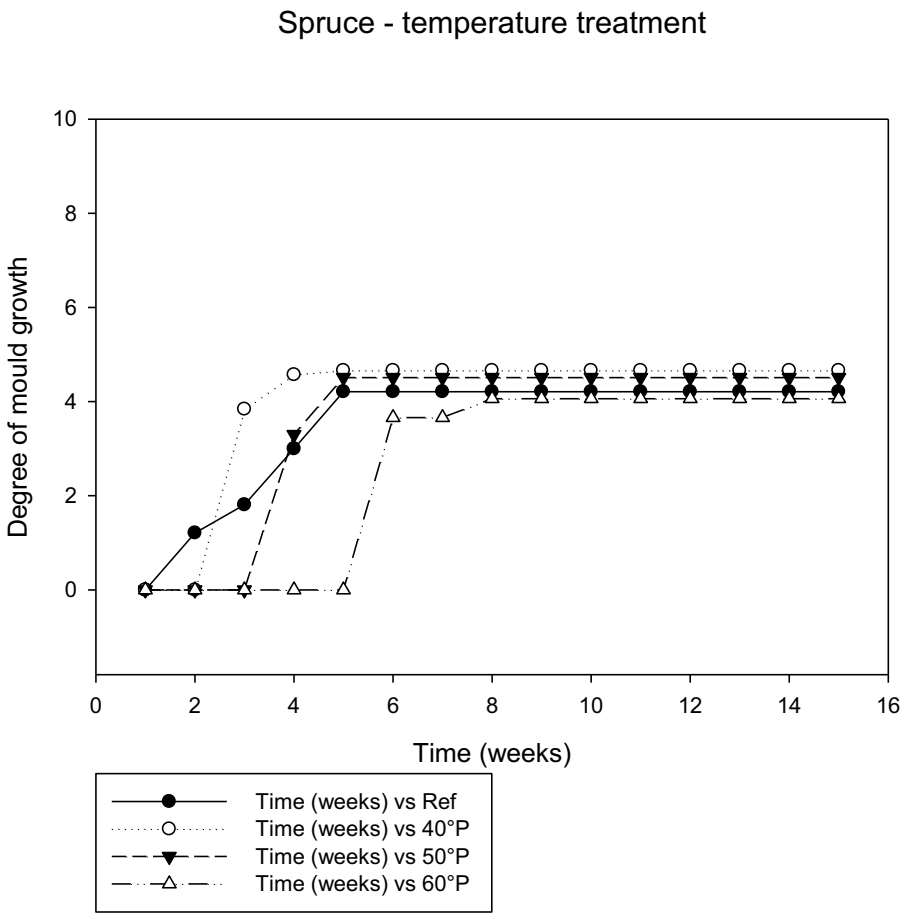

Figure 7. The degree of mould growth on spruce, exposed to temperatures of 40, 50 and 60ºC respectively for two hours three times a week.

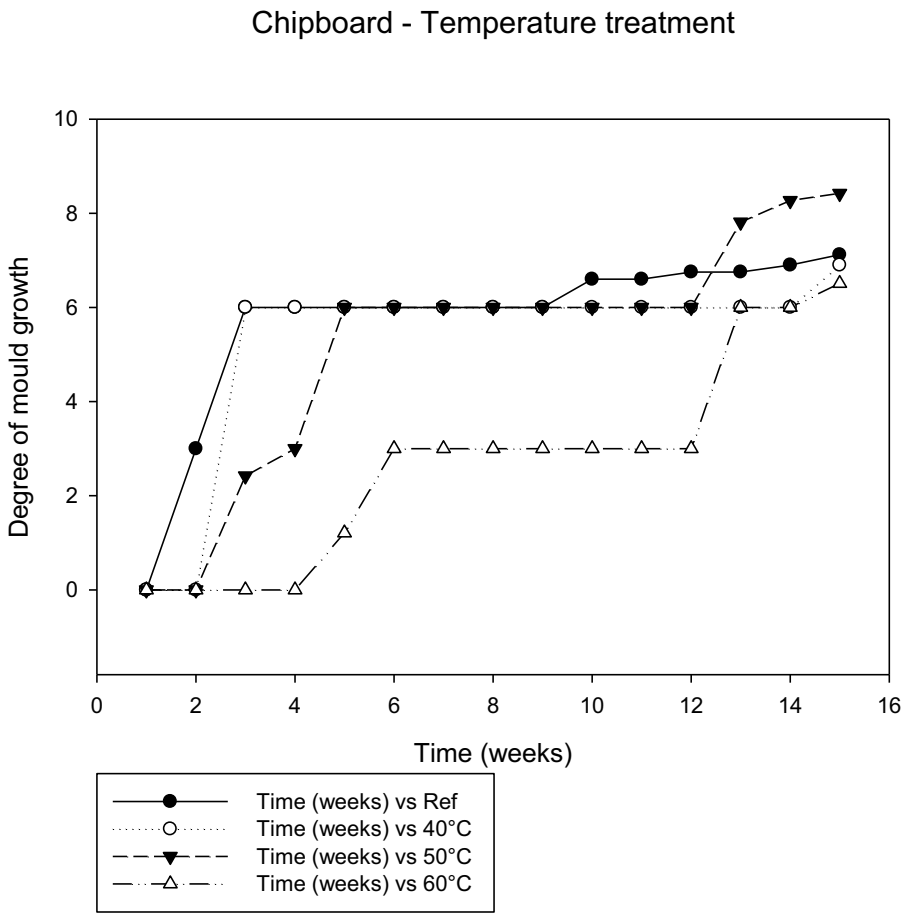

Figure 8. The degree of mould growth on chipboard, exposed to temperatures of 40, 50 and 60ºC respectively for two hours three times a week.

Table 1. Description of the test materials

Test material	Thickness (mm)	Density (kg/m3)	Description
Plywood	21	411	Plywood for use in dry conditions according to NS-EN 636-1, CE-classification NS-EN 13986-BC1. Thin layers of spruce which are joined together with glue. The directions of the fibres are turned 90º for each layer, but the front and back layers have the same orientation.
Chipboard	16	656	Chipboard for general-purpose use under dry conditions Type P1 according to NS-EN 312. Wooden chips which are glued together with (melamine) urea-formaldehyde glue.
Gypsum plaster board	12.5	728	Gypsum plasterboard Type A according to NS-EN 520. Gypsum core allocated with impregnated cardboard on both sides. The board is strong and stable.
Spruce	15	470	Planed. Strength class T1/C18 according to NS-EN 338

Table 2. Mould species used in the test

Species	VTT number
Aspergillus versicolor	D-96660
Cladosporium cladosporioides	D-96646
Penicillium chrysogenum	D-96661

Table 3. Overwiev of the different environments in the climate boxes, and which salt and temperature was used to achieve the correct relative humidity (RH)

Environment No.	RH [%]	Temperature (ºC)	Salt
1.	75.61 (±0.18)	15	Sodium Chloride (NaCl)
2.	85.92 (±0.33)	15	Potassium Chloride (KCl)
3.	95.41 (±0.96)	15	Potassium nitrate (KNO_3)
4.	~ 99	15	Distilled water
5.	75.36 (±0.13)	23	Sodium Chloride (NaCl)
6.	84.65 (±0.27)	23	Potassium Chloride (KCl)
7.	94.00 (±0.60)	23	Potassium nitrate (KNO_3)
8.	~ 99	23	Distilled water

Table 4. Ranking table of mould growth

	Ranking	Mould growth
Microscope	0	No growth
	0-1	0-33 % coverage in microscope
	1-2	33-66 % coverage microscope
	2-3	66-100 % coverage microscope
Visual (thin layer)	3-4	0-33 % coverage, thin visible layer
	4-5	33-66 % coverage, thin visible layer
	5-6	66-100 % coverage, thin visible layer
Visual (strong growth)	6-7	0-33 % coverage, strong growth
	7-8	33-66 % coverage, strong growth
	8-9	66-100 % coverage, strong growth

Paper III

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Moisture and Mould Growth in Compact Roofs – Results from a Three-Stage Field Survey

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KEYWORDS: building performance, building defects, climatic impact, field investigation, driving rain, moisture, micro-biological growth, roofs, weather protection, self-drying (dehydration) potential climate

SUMMARY:
Compact roof systems that are done right, using materials that are not mould-prone between a correctly installed vapour barrier and the roof waterproofing membrane, have typically been considered to be not very moisture sensitive. Moisture in compact roofs has therefore perhaps not received sufficient attention. With large precipitation amounts in southern Norway in the fall of 2000, the theme of built-in moisture in compact roofs again became relevant. Both in connection with roof work during periods with heavy precipitation and for example, from leakage, relatively large amounts of moisture can get trapped in the roof. This paper summerize some of the results from a field study was performed in order to investigate how flat, compact roof behave over time when moisture has been trapped in the construction. The investigation includes 12 roofs. 10 of the 12 roofs were chosen among roofs we knew had considerable problems with built-in moisture during the building period (fall 2000). Two of the roofs did not have any previously known moisture problems, and were therefore to act as reference roofs. Nine of the roofs were inspected in 2002, 2004 and 2007.

Even though the majority of compact roofs covered by this field investigation had moisture problems during manufacturing, the extent of moisture problems are decreasing. Compared to what was assumed beforehand, measurements in several of the roofs showed that dehydration was so extensive that mechanisms other than pure diffusion through the roofing or inward diffusion had possibly been a dominant factor in several instances. Other mechanisms contributing towards drying out may be convection currents in the roof and outward diffusion via the parapet, as well as lesser incidental air currents through all or portions of the roofs surface.

Microbiological growth observed innside the compact roofs are limited, confirming a small potential for growth in such construstions. This is due to the general robustness of the thermal insulation regarding growth and unfavourable maximum temperature amplititude (> 60°C). We assess a limited or negligible impact of indoor air quality caused by the observed microorganicms inside the investigated compact roofs.

1. Introduction

With the high levels of precipitation in southern Norway during the autumn of 2000, built-in moisture in compact roofs again became an important issue. Exacting building schedules and heavy precipitation during construction increase the risk of moisture entrapment in the roof structure. Similarly leakages are known to occur during the actual building process, as this is a period often characterised by much movement, traffic and other building activity, even after completion of the roof. In addition, there are many other reasons why roof leakages develop during the building's service life. Sometimes considerable quantities of water can penetrate into a roof.

A "compact roof" is a roof where the various material layers have been laid close together without ventilation. Compact roofs can be executed both as flat roofs (gradient < 6°) and sloping roofs (gradient > 6°) (Building

Research Design Sheet 525.207). This is the predominant type of roof construction used for large buildings in Norway. When correctly executed, with non-perishable materials between a correctly dimensioned/ installed moisture barrier (Noreng 1996) and well-executed waterproof roofing, compact roofs are not considered to be highly susceptible to moisture ingress. As a consequence, insufficient attention has been paid to moisture in compact roofs.

The most frequent questions have generally been along the lines: What happens in the long and short term in cases where moisture has been allowed to penetrate the construction? What kind of problems can we expect? Will moisture result in dripping from the roof, corrosion of fastenings, reduced insulating capabilities, rotting of roof woodwork and/or mould formation in the future? Will moisture in the roof construction create problems of such a nature that all moist materials must be replaced, or will there be sufficient natural dehydration through the roofing, parapets, etc. whereby these problems would be avoided?

2. Principal objective and scope

The purpose of the field investigation is to establish the extent of moisture in compact roofs, ascertain how roofs with moisture will develop over time, determine whether they will dry out of their own accord or if prolonged moisture creates problems such as condensation droplets, corrosion, reduced insulation capabilities, mould formation or fungal growth. The investigation was intended to give increased knowledge about a roof's dehydrating (self-drying) capability, and the problems we can expect from moisture in compact roofs.

This paper presents some of the results from a field investigation concentrating on moisture condition in the roofs, a roof's dehydrating (self-drying) capability and microbiological growth.

3. The field investigation

3.1 Extent of the field investigation

The field investigation comprises surveys of twelve compact-roof constructions carried out in three separate stages. Eleven of the twelve roofs are located in Eastern Norway and were examined in June 2002. The twelfth roof was located in Trondheim and was examined in October 2002. 2004 comprises eight of the eleven roofs in Eastern Norway (examined in June 2004) and the roof in Trondheim (examined in October 2004) (Noreng et al. 2005). The nine roofs were examined again in 2007 in the same month as in 2004. The 2004 and 2007 investigations were intended to be a follow-up and continuation of the 2002 investigation by re-examining a selection of the same roofs after a two-year (2004) and five-year (2007) period.

For reasons of economy the number of roof constructions that were examined was restricted to twelve in 2002 and nine of the same twelve roofs in 2004 and 2007. Nevertheless the investigation provides some clear advance indications that can be considered representative for the types of roof construction examined.

3.2 The roofs – localisation and composition

The roofs were chosen so that a majority of the constructions should have encountered actual moisture problems during the build period. On request, a number of key figures in the building trade put forward suggestions regarding buildings where they had experienced moisture problems during construction. As it rained a lot in the autumn of 2000, causing many problems in Eastern Norway, nine roofs were intentionally picked from among this selection. On Roof Nos. 3, 7, 8 and 9 the moisture problems during the build period were reported as being "serious," and on Roof Nos. 4, 5, 6, 10 and 11 the moisture problems during the build period were reported as being "very serious." Even though attempts were made to prevent or limit the source of the precipitated moisture by various means, such as covering with tarpaulins, this had only a limited effect. For Roof Nos. 4 and 6, ventilation louvres were installed afterwards in an attempt to dry out the building moisture. No other special means of covering, nor subsequent drying-out measures were implemented.

Roof Nos. 1 and 2 did not have any known moisture problems and were therefore chosen to act as reference roofs. When uncovering the reference roofs it was discovered that the moisture barrier over the DT-elements was missing, something that gave an opportunity for some moisture ingress from the inner side for most of the year (and drying-out inside the building during other parts of the year).

Finally a portion of the roof above an office wing at SINTEF Building and Infrastructure's premises in Trondheim was examined (Roof No. 12). This proved to be of great interest because five years previously this particular roof had been executed as an experimental roof and had been pre-fitted with instruments enabling measurements to be taken of moisture/ humidity and temperature after a given amount of water (1 litre per m²) had been applied to the roof construction (Time et al. 2002). Table 1 indicates the roofs covered by the investigation.

TABLE 1: Examined roofs, with indications of presumed extent of building moisture and composition of the roof structure.

No.	Useage Area [m²]	Roofing year	Presumed extent of building moisture	Composition of roof structure	Examined year
1	Warehouse 2400 m²	2000/ 2001	Normal	Single-layer bitumen roofing, 50 mm mineral wool insulation, DT-concrete elements w/ open joints (no moisture barrier)	2002 2004 2007
2	Warehouse 800 m²	1989	Normal	Dual-layer bitumen roofing, 50 + 30 mm mineral wool, DT-concrete elements w/ open joints (no moisture barrier)	2002 2004 2007
3	Office block 750 m²	Autumn 2000	Serious	Dual-layer bitumen roofing, 50 mm mineral wool, + 200 mm EPS, PE-foil moisture barrier, concrete	2002
4	Office wing 1200 m²	2000/ 2001	Serious	Bitumen roofing, 200-300 mm mineral wool, PE-foil moisture barrier, steel supporting plates	2002 2004 2007
5	Offices 500 m²	2000/ 2001	Very serious	PVC roofing foil, 100 mm mineral wool, PE-foil moisture barrier, 50 mm mineral wool, steel supporting plates	2002 2004 2007
6	Packing house 3000 m²	2000/ 2001	Very serious	Bitumen roofing, 100 mm mineral wool, PE-foil moisture barrier, 50 mm mineral wool, perforated steel supporting plates	2002 2004 2007
7	Office wing 150 m²	Autumn 2000	Serious	Single-layer bitumen roofing, 50 mm EPS insulation, wooden under-roof (no moisture barrier)	2002
8	Material store 900 m²	Autumn 2000	Serious	Dual-layer bitumen roofing, 200 mm mineral wool, bituminous moisture barrier w/loose overlaps, steel supporting plates	2002
9	Residential and day-care centre 450 m²	2000/ 2001	Serious	PVC roofing foil, matted glass-fibre migration barrier, 200-250 mm EPS, PE-foil moisture barrier, concrete	2002 2004 2007
10	Sports hall 800 m²	Autumn 2000	Very serious	PVC roofing foil, 200-250 mm mineral wool, PE-foil moisture barrier, concrete	2002 2004 2007
11	Shopping mall 5000 m²	2000/ 2001	Very serious	PVC roofing foil, 200-250 mm mineral wool, old roofing foil, 150 mm old mineral wool PE-foil moisture barrier, steel supporting plates	2002 2004 2007
12	Office wing 600 m²	1997	Serious	FPO roofing foil, 30 mm mineral wool, + 0-100 mm EPS, old PVC roofing foil, 50 mm old insulation, Dina elements filled with insulation	2002 2004 2007

3.3 Field investigation – observations and measurements

A survey report was made for each of the roofs giving details of the participants, building, roof geometry and design/construction, as well as date of the roofing work. The actual examinations were made by taking measurements and observations at three to five points along an imaginary line drawn across the roof. The constructions were uncovered in order to make more detailed observations, take measurements of moisture content such as RH/temperature measurements, as well as take samples of roof insulation materials for more accurate evaluation back in our own laboratory. The measurement and observation points in 2004 and 2007 were positioned adjacent to those chosen in 2002 and simply moved approx. 0.5 m so that new samples could be taken from an undisturbed area. The survey reports contain pictures and sketches showing the measuring point locations as well as detailed observations and measurements.

Sample taking and analyses with a view to possible microbiological growth formed an important part of the investigation. Mycoteam AS and SINTEF Energy Research assisted us with these examinations. The salient points from the analyses are included in this paper.

3.4 Concerning moulds/fungi and investigation of micro-biological activity

In this paper we have differentiated between moulds, blue-stain fungus, wood-decaying fungus, yeasts and bacteria. Dispersal of the fungi species mentioned is by means of microscopic spores which are spread by air currents and which are found in the air everywhere. Both viable and dead spores are to be found. It is difficult to give simple general rules for the criteria that determine growth. Access to nutrients, moisture, oxygen, temperature and time are important factors affecting growth. For mould RH $\geq$ 85 % and t $\geq$ 0 °C is a normal, but simplified criterion for growth on surfaces (Grant et. al., 1989).

In connection with the investigation into fungal growth and other possible biological activity, material samples were taken of roofing, insulation and moisture barriers. In addition, samples of outside air and of air from within the roof construction were collected for cultivation in the laboratory.

4. Some results from the investigation

4.1 Moisture content of insulation samples

An overview of the moisture content in samples of insulation materials from the roofs is given in Table 2. Only results from the nine roofs followed during the whole five-year periode are included. Roof No. 5 differs from the other due to a moisture content in the rock wool exceeding 1.0 weight percentage. Except Roof No. 11 all roofs undergo drying during the periode 2002-2004. In 2004 only Roof Nos. 5 and 11 contain rock wool exceeding 1weight percentage water. During the periode 2004-2007 further drying of the roofs are measured. The exeption is Roof No. 11, which now contains 16.8 weight percentage water. The other roofs contain less than 0.35 weight percentage water.

4.2 Micro-biological activity

Table 2 includes observation of microbiological growth in 2002, 2004 and 2007. Only results from the nine roofs followed during the whole five-year periode are included. Microbiological growths were observed in seven of the nine roofs already in 2002, see Table 2. The growths were mainly blue-stain fungus observed at the back of the roofing, at the surface of the thermal insulation or inside the insulation. In addition minor or moderate growth of mould (cladosporium, aspergillus and penicillium) were observed. Bacteria were observed in one roof. Roof No. 11 and 12 differ from the other because of conspicuous microbiological growth.

In 2004 microbiological growths were observed in all of the nine roofs (see Table 2). Blue-stain fungus is still the most common growth, however, the amount of mould is increasing. Observations indicate growth in Roof Nos. 2, 4, 6, 9, 10, 11 and 12 during the periode 2002-2004.

The microbiological activity decreased during the periode 2004-2007. Growths were observed in six of the nine roofs in 2007, see Table 3. Blue-stain fungus is still the most common growth and mould is still growing in some of the roofs. No growths were observed in Roof No. 5, 6 and 10.

TABLE 2: Moisture content in insulation samples taken from Roofs Nos. 1 to 12 in 2002, 2004 and 2007. N.B: Moisture content of 1 volume-% in 100 mm thick insulation yields 1 litre of water per m².

No.	Sample point	Thermal insulation	Summer 2002		Summer 2004		Summer 2007	
			[weight-%]	[volume-%]	[weight-%]	[volume-%]	[weight-%]	[volume-%]
1	P1-Ø	Rock wool	0.41	0.07	0.29	0.05	0.27	0.04
	P2-Ø	Rock wool	0.41	0.07	0.28	0.04	0.21	0.03
	P3-Ø	Rock wool	0.43	0.07	0.29	0.05	0.21	0.04
	P4-Ø	Rock wool	-	-	0.25	0.04	-	-
2	P1-Ø	Rock wool	0.31	0.03	0.22	0.03	0.13	0.02
	P1-N	Rock wool	0.34	0.07	0.12	0.01	-	-
	P5-Ø	Rock wool	-	-	0.15	0.03	0.22	0.04
	P5-N	Rock wool	-	-	0.55	0.06	0.20	0.02
4	P1-Ø	Rock wool	-	-	0.38	0.08	0.15	0.02
	P1-N	Rock wool	-	-	0.22	0.03	0.25	0.03
	P2-Ø	Rock wool	-	-	0.31	0.06	0.22	0.03
	P2-N	Rock wool	-	-	0.40	0.05	0.05	0.01
	P3-Ø	Rock wool	3.31	0.40	0.24	0.03	0.15	0.02
	P3-N	Rock wool	-	-	0.36	0.03	0.20	0.03
	P6-Ø	Rock wool	-	-	-	-	0.21	0.03
	P6-N	Rock wool	-	-	-	-	0.13	0.01
5	P1-Ø	Rock wool	150.00	17.80	93.70	13.13	0.11	0.02
	P1-oD	Rock wool	225.00	17.60	-	-	0.13	0.01
	P1-du	Rock wool	0.60	0.07	0.31	0.04	1.12	0.13
	P2-Ø	Rock wool	-	-	0.47	0.08	0.31	0.05
	P2-oD	Rock wool	-	-	-	-	0.28	0.03
	P2-uD	Rock wool	-	-	0.28	0.03	0.17	0.02
6	P1-oD	Rock wool	11.00	1.00	0.42	0.06	0.24	0.02
	P1-du	Rock wool	-	-	0.22	0.03	0.19	0.03
	P2-oD	Rock wool	-	-	-	-	0.23	0.02
	P2-uD	Rock wool	-	-	-	-	0.19	0.02
9	P1-Ø	EPS	0.87	0.02	0.72	0.01	26.32	0.48
	P1-N	EPS	-	-	0.44	0.01	0.08	0.00
	P2-Ø	EPS	34.00	0.55	0.70	0.17	0.26	0.00
	P2-N	EPS	-	-	0.09	0.06	0.46	0.01
	P3-Ø	Rock wool	-	-	0.37	0.01	0.24	0.00
	P3-N	Rock wool	-	-	0.97	0.01	-	-
	P3-N'	EPS	-	-	0.60	0.00	0.37	0.01
10	P1-Ø	Rock wool	0.33	0.05	0.33	0.06	0.11	0.02
	P1-N	Rock wool	-	-	0.25	0.02	0.09	0.01
	P2-Ø	EPS	-	-	0.79	0.02	0.50	0.01
	P2-N	EPS	-	-	0.48	0.01	0.59	0.01
	P3-Ø	Rock wool	0.36	0.06	0.36	0.04	0.13	0.02
	P3-N	Rock wool	-	-	0.40	0.04	0.14	0.02
11	P1-Ø	Rock wool	-	-	0.24	0.04	0.11	0.02
	P1-ugt	Rock wool	0.41	0.06	-	-	6.35	0.63
	P2-Ø	Rock wool	-	-	0.37	0.06	95.92	14.11
	P2-ugt	Rock wool	14.32	1.20	13.10	1.29	8.71	1.24
		Rock wool	-	-	-	-	6.11	0.70
	P3-Ø	Rock wool	-	-	1.70	0.23	0.23	0.03
	P3-ugt	Rock wool	1.40	0.20	38.80	5.52	-	-
	P3-N	Rock wool	-	-	13.40	1.42	0.24	0.02
12	P1-ø	Rock wool	0.34	0.03	0.31	0.06	0.24	0.05
	P1-m	Rock wool	0.41	0.07	-	-	-	-
	P1-n	Rock wool	0.37	0.08	0.33	0.04	0.42	0.05
	P6-ø	Rock wool	0.62	0.14	0.33	0.06	0.33	0.06
	P6-m	EPS	1.18	0.02	-	-	-	-
	P6-n	EPS	1.65	0.03	1.88	0.03	1.10	0.02
	P7-ø	Rock wool	1.35	0.21	0.55	0.10	0.29	0.06
	P7-n	EPS	1.66	0.03	2.18	0.04	0.91	0.02
	P9-ø	Rock wool	7.93	1.43	0.50	0.09	0.27	0.06
	P9-ugt	EPS	-	-	-	-	1.33	0.03

TABLE 3: Microbiological activity observed in 2002, 2004 and 2007.

No.	Registered growth in 2002	Registered growth in 2004	Registered growth in 2007	Comments
1	Yes	Yes	Yes	Sparse growth
2	No	Yes	Yes	Sparse growth
4	No	Yes	Yes	Sparse growth
5	Yes	Yes	No	Decreasing growth
6	Yes	Yes	No	Decreasing growth
9	Yes	Yes	Yes	Decreasing growth
10	Yes	Yes	No	Decreasing growth
11	Yes	Yes	Yes	Sparse growth
12	Yes	Yes	Yes	Sparse growth

5. Discussion

5.1 Moisture content and drying potential

Reports received from the roof entrepreneurs at the beginning (concerning the building-in of considerable amounts of moisture from precipitation into the roofs) seem to be confirmed by 2002 of the investigation. Nevertheless, in several places we could see that even though moisture had quite clearly penetrated into the roofs, there was less evidence of moisture in the roofs 1½ years after the roofing period than the reports from the roofing period would suggest. In 2004 and 2007, after a further two and five years, this impression was reinforced.

There are several mechanisms contributing towards drying out of possible moisture in compact roofs over a period of time: outward diffusion through the roofing, inward diffusion, convection currents in the roof and outward diffusion via the parapet, as well as lesser incidental air currents through all or portions of the roof surface.

Drying out (dehydration) via outward diffusion through the roofing is minimal and varies according to the type of roofing and also e.g. with the outside temperature. In the field investigation eleven of twelve roofs were located in the southeastern part of the country. Compared to what was assumed beforehand, measurements in several of the roofs showed that dehydration was so extensive that mechanisms other than pure diffusion had possibly been a dominant factor in several instances.

In order to assist with the drying out of building moisture, ventilation louvres were installed on two of the roofs (Roof Nos. 4 and 6) after the building was completed but prior to the examinations in 2002. The sizes, quantity and locations were different on the two roofs. When we returned to implement 2004, the ventilation louvres had been removed from both roofs. We were told that this was because the roofs in the meantime were considered to be dry and that ventilation louvres were therefore no longer necessary. As an example we would mention Roof No. 6: A large number (64) of ventilation louvres were retrofitted in the bituminous roof covering. The moisture content of the mineral wool in 2002 was measured as being 1.0 % (volume). This is a fairly high moisture content. The position of the sampling point was approx. 2 m away from four of the ventilation louvres. As we do not know how much moisture was present in the roof from the start, it is difficult to judge the effect of the ventilation louvres up to the examination in 2002. The drying out that was registered between 2002 and 2004 (measured value in 2004 was 0.06 % by volume) is however so large that dehydration mechanism other than pure diffusion must have had a significant effect. It therefore looks as if the ventilation louvres have made a positive contribution.

5.2 Microbiological growth potential

Microbiological growth may appear on almost every material exposed by moisture. The humidity exposure may be caused by water supply/leakage or by high air humidity. Microbiological growth may appear both on organic materials (wood, textile, cardboard etc.) (Nielsen, Holm et. al. 2004) and on inorganic materials (concrete, clay brick, natural stone etc.) settled by organic compounds (Viitanen 2004) E. g. component in compact roofs such as roofing, thermal insulation, vapour barrier etc, are polluted by organic compounds from the manufacturing and from the everyday use of the building. Hence, the contents of organic compounds in compact roofs may be sufficient nutrition for growth of mould, yeast and bacteria. Such growths are normally harmless for the substratum itself, but it may decompose emollients and adhesives in vapour barriers and roofings, increaseing the stiffness and brittleness of the material and then the risk for fracture and leakages.

Trace of mould and/or bacteria was observed in seven of the nine roofs in 2002, none of them with strong growth. Neither was a gradient of growth according to the tickness of the roofs observed. In 2004 trace of mould and/or bacteria was observed in all the nine roofs, none of them with strong growth. It is now observed a trend of less blue-stain fungus in the roofing and/or in the thermal insulation close upon the roofing. However, the amount of growth was small, making it difficult to carry out a secure determination of species. Teoretically limited growth was supposed beneath roofing due to the temperature amplitude reaching maximum summer temperature exceeding 60°C. Such high temperature expect to restrain/kill mould growth (IOM 2004). Limited growth observed in 2002 and 2004 correspond with this theory.

Bacteria were in 2004 observed on the vapour barrier and partly on the thermal insulation against the vapour barrier in several of the roofs. Some places mould and blue-stain fungus are also found at the same places. The analysis of growth did not distinguish upper and under side of the vapour barrier. However, the observation indicates more bacteria on the upper side (i.e. inside the compact roofs). Approximately no microbiological growth was found inside the thermal insulation with exeption of sparse growth inside the insulation in Roof Nos. 9 and 11.

In 2007 microbiological activity was found in Roof Nos. 1, 2, 4, 9, 11 and 12. No activity was found in Roof Nos. 5, 6 and 10 even though microbiological growth has been observed earlier. Lack of growth in these roofs may be due to decomposition of the former growth and no new growth, or due to circumstances attached to sparse growth in the roof. In addition to the roofs without microbiological activity, the growth in Roof No. 9 was less than in 2004.

The microbiological growth in Roof No. 11 and maybe also in No. 4 increasesed in the periode 2004-2007. However, the increasing is small and it may be due to variations of growth in the construction.

The moisture content in the roofs, except of Roof No. 1, 2 and 10, was from the beginning very high, varying between 225.00 and 0.31 weightpercent in the rock wool. The first inspection of the roofs (2002) was carried out during the first one and half year after manufacturing. Expecting some drying during that periode, it is likely to expect the initial moisture content to be even higher than determined in 2002.

A moisture content of 0.8 weightpercent in rock wool correspond to 95% RH. Test of mould growth in thermal insulation indicate growth at 95% RH (Konsumverket 2002, Foarde et. al. 1996). Condensation in the outer part of compact roofs appears during the winter season dependent of the moisture content. The possibility for condensation supports the trend towards more mould at the underside of the roofing and/or the insulation against the roofing. However, the amount of microbiological growth in the compact roofs was limited indicateing unfavourable growing conditions in this type of construction.

5.3 Indoor air impact of micro-biological growth in compact roofs

Even growing inside a closed construction element e.g. compact roof, microorganism may at least theoretically influence the indoor climate. That occure because spores and particles (mycotoxins) as well as volatile matters they produce (MVOC), may be transferred to the indoor air by airflow through the construction element. MVOC may also partly diffuse the vapour barrier influencing the indoor air.

Compact roofs don’t normaly have any intended ventilation. Correct manufactured the vapour barrier will avoid downward airflow through the roof into indoor living room. Indoor overpresse beneath the roof construction prevent inward airflow from the compact roof. Hence, spores or mycotoxins from microbiological growth inside a compact roof likely intrude the indoor air quality beneath the roof. The risk potential may be larger due to the growths production of MVOC and diffusion through the vapour barrier. However, the potential risk is decreasing

dependent of the growths distance above the vapour barrier. The microbiological growths were mainly obserbed in the outer part of the compact roofs. Due to indoor overpressure, airflow likely goes upward against the roof. Ventilation of the living room is also an important measure to reduce the potential impact of MVOC-migration.

It is a vital risk for microbiological impact of indoor air quality if water is leaking from the roof down to the ceiling, wooden cornice or the upper part of walls. This point of view is not included in this paper, but empirically the indoor air quality is more vulnerable to microbiological growth at those places because of growth inside the vapour barrier.

6. Conclutions

Even though the majority of compact roofs covered by this field investigation had moisture problems during manufacturing, the extent of moisture problems are decreasing. Compared to what was assumed beforehand, measurements in several of the roofs showed that dehydration was so extensive that mechanisms other than pure diffusion through the roofing or inward diffusion had possibly been a dominant factor in several instances. Other mechanisms contributing towards drying out may be convection currents in the roof and outward diffusion via the parapet, as well as lesser incidental air currents through all or portions of the roofs surface.

Microbiological growth observed innside the compact roofs are limited, confirming a small potential for growth in such construstions. This is due to the general robustness of the thermal insulation regarding growth and unfavourable maximum temperature amplititude (> 60°C). We assess a limited or negligible impact of indoor air quality caused by the observed microorganicms inside the investigated compact roofs.

7. Acknowledgements

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Paper IV

Geving, S. and **Holme**, J. (2010) The drying potential and risk of mould growth in compact wood-frame roofs with built-in-moisture , *International Journal of Building Physics* 33(3): 249-269.

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Paper V

Geving, S., **Holme**, J., and Jenssen, J. (2008) Indoor air humidity in Norwegian houses*, Proceedings of the 8th Symposium on Building Physics in the Nordic Countries* (Rode C. eds), Report R-189, Dept. of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, 801-808

Indoor air humidity in Norwegian houses

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KEYWORDS: *moisture supply, indoor air humidity, hygrothermal calculations, indoor climate, indoor relative humidity*

SUMMARY:
In this study indoor air humidity levels have been measured in 117 houses in Trondheim, Norway. The houses were randomly selected for each of the following types; detached one family houses, semidetached two family houses, undetached (chained) houses and apartment buildings. The temperature and relative humidity were measured at 15 minutes interval over a period of one week during the heating season. The measurements were made in bedrooms, living rooms, bathrooms, cellars/basements and outdoors. The moisture supply, which is the difference between indoor and outdoor air water vapour content, were determined. The dependence on outdoor temperature were analyzed. The effect of other influencing factors such as occypancy (area per person), type of house, type of room, age of house and ventilation type were also investigated.

1. Introduction

Large scale measurements of indoor air humidity levels in buildings are required for many purposes. One of the most important input parameters when doing a hygrothermal analysis of the building envelope using simulation models is knowledge about typical levels of indoor air humidity. Knowing the typical variations of indoor air humidity in a specific type of buildings, it is also possible to compare with measurements in one specific building, for instance to assess the risk for moisture problems.

A common way of expressing the indoor air humidity load is by the *moisture supply*. The moisture supply (Δv), is defined as the difference between indoor (v_i) and outdoor (v_e) air water vapour content (in g/m^3). The moisture supply is used when the relative humidity is not controlled but allowed to undergo wide variations due to several factors such as weather conditions, building characteristics, moisture generation and ventilation. It is generally considered that the moisture supply tend to be relatively constant in a house during the colder part of the heating season (outdoor temperature < 0 - +5 ^{o}C), while it decreases when the outdoor temperature increases. In the standard EN ISO 13788 (EN ISO 13788, 2001) this is expressed as the moisture supply being contant for outdoor temperatures below 0 ^{o}C, while the moisture supply decreases linearily to 0 g/m^3 at outdoor temperatures of 20 ^{o}C, se example in Figure 1. Above 20 ^{o}C the moisture supply is 0 ^{o}C. EN ISO 13788 defines five standard humidity classes to be used as design values in hygrothermal calculations. For houses two classes applies; Δv = 4 g/m^3 for dwellings with low occupancy and Δv = 6 g/m^3 for dwellings with high occupancy (constant value when outdoor temperature is below 0 ^{o}C). According to Kalamees, Juha and Kurnitski (2006) a more correct representation of the design curves would be a contant moisture supply below approximately +5 ^{o}C and a linear decrease down to a constant value at approximately +15 ^{o}C and higher temperatures.

The indoor moisture supply in houses have been investigated in many earlier field studies. Tolstoy (1993) measured the moisture supply during winter in about 1500 houses in Sweden. The moisture supply for single-

family houses was between 2 – 5 g/m^3, with an average of 3,6 g/m^3. For multi-family dwellings the moisture supply was between 1,5 – 4 g/m^3, with an average of 2,9 g/m^3. Several other field studies have been performed, a summary is given in (Kalamees, 2006). According to Kalamees (2006) most of the studies yields average moisture supply during winter between about 2 – 3 g/m^3 for living rooms. The variation between different houses are on the other hand quite large, meaning that design values for hygrothermal calculations should be selected somewhat higher than the average values. The International Energy Agency Annex 24 (Sanders, 1996) has recommended the use of the 10% critical level for climate loads when doing a hygrothermal simulation of the external envelope. This means a moisture supply higher than the critical level should not appear in more than 10% of the cases. Kalamees, Juha and Kurnitski (2006) did full year measurements in houses with low/medium occupancy (average 42 m^2/person) and calculated that the 10 % critical level was close to 4 g/m^3 during the cold period ($T_{out} \leq +5$ °C) and close to 1,5 g/m^3 during the warm period ($T_{out} \geq +15$ °C). The average values were 1,8 g/m^3 and 0,5 g/m^3 for the cold and warm period respectively.

The measurements presented in this paper has been part of the study "Prevention of atopy among children in Trondheim" (Jenssen et.al., 2001). This analysis work of the measurements have been part of the ongoing SINTEF strategic institute project "Climate 2000 - Weather Protection in the Construction Process".

Indoor air humidity levels have been measured for a week during the heating season in 117 houses in Trondheim, Norway. The houses were randomly selected for each of the four following building types; 44 detached one family houses, 32 semidetached two- or four family houses,18 undetached (chained) houses and 21 apartment buildings. Most of the houses in Norway (except for apartment buildings) are lightweight timber-frame houses, and so was the case also in this study. In each house measurements were made in a children bedroom, the main living room, the most used bathroom and the basement/cellar. The basement/cellar are a mix of (partly) heated basements and non-heated storage cellars. Most of the studied rooms had the possibility of opening the windows for airing purposes. The houses had all types of basic ventilation; no ventilation (i.e. not planned with airing inlets/outlets), natural ventilation, exhaust ventilation and balanced ventilation.

2. Method

In 32 of the 117 houses the indoor air humidity levels were measured during the heating season November 2000 – March 2001 as a part of a preproject for the "Prevention of atopy" – study. These measurements are previosly presented in (Jenssen, Geving and Johnsen, 2002), but are also included in this work. The rest of the houses (85 houses) were measured during the period May - July 2003, September 2003 – June 2004, September – December 2004.

The first 32 houses were selected through this procedure: A total of 300 buildings in Trondheim were randomly selected for each of the four building types mentioned above. For each building, one family was selected to receive a questionnaire. The response rate was 35 %. 8 or 9 buildings of each type were randomly selected for home inspections and measurements.

The last 85 houses were selected through this procedure: Parents of the children that were included in the "Prevention of atopy"-study were asked for permission to perform inspection of their houses until enough participants had accepted. There were 200 participants in this home inspection study, but RH and temperature were measured in only 85 of these 200 houses. This means the houses were "randomly" selected among a population (with small children in the house) that had accepted to participate in the "Prevention of atopy"-study.

The temperature and relative humidity (RH) were measured at 15 minutes interval over a period of seven days. Small logging units were used (Tiny tag, TGU 1500, Intab). The loggers were positioned away from windows, heating units, direct sunlight or outer door. The loggers were placed between 1,5 – 2,0 m above floor level. The accuracy of the loggers were ± 5 % RH and ± 0,5 °C. Hourly data for outdoor RH were retreived from an automatic weather station located in Trondheim operated by the Norwegian Meteorological Institute, with an accuracy of ± 2 % RH and ± 0,5 °C. The moisture supply (Δv) was calculated on an hourly basis. Mean weekly values for the moisture supply were calculated from these hourly values.

3. Results

The results are given in tables 1-4, and figures 1 and 2. All analysis are made on the basis of weekly means of the moisture supply and outdoor temperature. The 90% percentile (i.e. 10% critical level) has been calculated

together with the mean values (when enough valid N). Design curves from EN ISO 13788 for houses (low and high occupancy) are given for comparison in the figures.

A significantly higher ($p < 0,03$, Paired samples t-test) mean weekly moisture supply for outdoor temperatures below + 5°C compared to moisture supply for outdoor temperatures above + 5°C was found. This applies for all room types, except for bedrooms ($p = 0,08$).

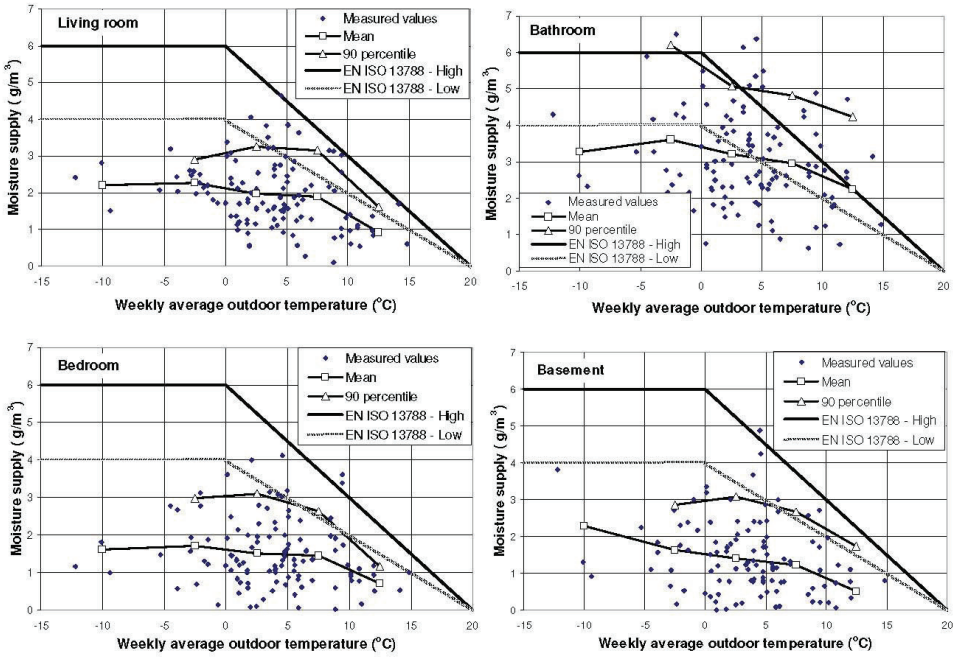
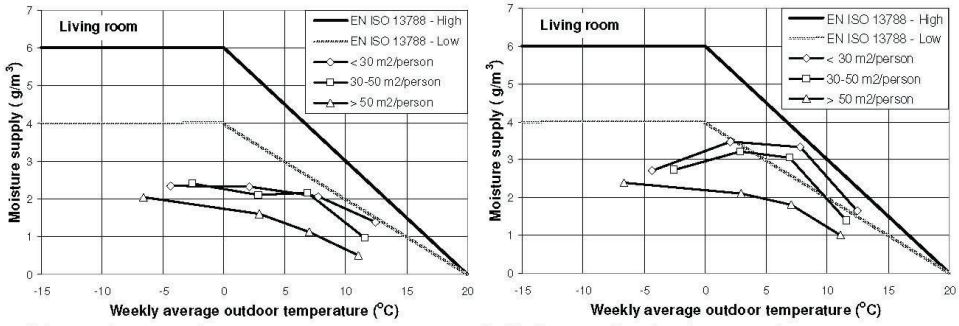


FIG. 1: Moisture supply for varius outdoor temperature in living rooms, bathrooms, bedrooms and basements.



a. Mean moisture supply b. 90 % percentile of moisture supply

FIG. 2: Moisture supply for varius outdoor temperature and level of occupancy for living rooms.

The analysis showed that the mean weekly moisture supply in bathrooms were significantly higher ($p < 0,05$, Anova-test) than all other rom types for all outdoor temperatures (below and above +5°C). The moisture supply in living rooms were significantly higher than in the bedrooms and basements for outdoor temperatures below +5°C. For temperatures above + 5°C the moisture supply were significantly higher in living rooms compared to the basements. There were no significant difference between bedrooms and basements. Due to the strong dependance of room type, the rest of the analysis is made for each room type separately.

An effect of level of occupancy was found for living roms. The mean weekly moisture supply was significantly lower ($p < 0,05$, Anova-test) for high occupancy (> 50m^2/person) compared to lower occupancy (< 50 m^2/person). It was however no significant difference between a low level of occupancy (< 30 m^2/person) and a medium level of occupancy (30 – 50 m^2/person). This effect is illustrated in figure 2. There was no significant effect of occupancy for the other room types, except that for bathrooms the moisture supply was significantly lower ($p < 0,05$, Anova-test) for high occupancy (> 50m^2/person) compared to medium occupancy (30 - 50 m^2/person). There was found no significant difference ($p >> 0,05$, Anova-test) in mean weekly moisture supply between the various building types. There were also no significant difference ($p >> 0,05$, Anova-test) in moisture supply when comparing the year of construction (three periods; before 1961, 1961 – 83, after 1983). Furthermore there was found no significant difference between the various types of basic ventilation systems of the houses (no ventilation, natural ventilation, exhaust ventilation and balanced ventilation). The effect of a single exhaust fan in the bathroom was not investigated.

TABLE. 1: Moisture supply for various outdoor temperature intervals.

			Moisture supply (g/m^3)		
Room type	T outdoor	Valid N	Mean	Std dev	90%
Bathroom	< -5°C	N=5	3,26	0,81	.
	-5°C - 0°C	N=14	3,60	1,44	6,20
	0°C - +5°C	N=50	3,21	1,28	5,08
	+5°C - +10°C	N=30	2,95	1,21	4,82
	+10°C - +15°C	N=12	2,24	1,06	4,24
Basement	< -5°C	N=5	2,28	1,21	.
	-5°C - 0°C	N=14	1,64	0,85	2,85
	0°C - +5°C	N=55	1,41	1,14	3,08
	+5°C - +10°C	N=29	1,23	0,84	2,67
	+10°C - +15°C	N=12	0,51	0,73	1,74
Bedroom	< -5°C	N=5	1,62	0,66	.
	-5°C - 0°C	N=13	1,72	0,93	2,98
	0°C - +5°C	N=57	1,51	1,04	3,10
	+5°C - +10°C	N=30	1,44	0,94	2,64
	+10°C - +15°C	N=12	0,72	0,40	1,16
Living room	< -5°C	N=5	2,20	0,48	.
	-5°C - 0°C	N=14	2,28	0,39	2,90
	0°C - +5°C	N=57	1,98	0,95	3,26
	+5°C - +10°C	N=30	1,89	0,97	3,15
	+10°C - +15°C	N=12	0,92	0,48	1,61

TABLE. 2: Moisture supply for various degree of occupancy (heated area per person) and outdoor temperature.

		Moisture supply (g/m^3)							
	Occupancy	T outdoor ≤ 5 °C				T outdoor ≥ 5 °C			
Room type	(m^2/person)	Valid N	Mean	Std dev	90 %	Valid N	Mean	Std dev	90 %
Bathroom	≤ 30	N=12	3,20	1,16	4,92	N=8	2,63	1,28	.
	30 - 50	N=37	3,54	1,41	5,95	N=21	3,12	1,03	4,66
	≥ 50	N=17	2,88	1,01	4,31	N=12	1,95	0,89	3,26
Basement	≤ 30	N=14	1,40	0,94	3,02	N=8	1,17	1,24	.
	30 - 50	N=39	1,58	1,24	3,35	N=20	1,08	0,77	2,52
	≥ 50	N=18	1,25	0,83	3,02	N=12	0,76	0,73	2,07
Bedroom	≤ 30	N=16	1,74	1,00	3,31	N=8	1,17	1,26	.
	30 - 50	N=38	1,57	1,01	2,81	N=21	1,48	,81	2,63
	≥ 50	N=18	1,43	1,02	3,18	N=12	0,80	0,58	1,69
Living room	≤ 30	N=16	2,27	0,89	3,60	N=8	1,89	1,08	.
	30 - 50	N=39	2,17	0,81	3,21	N=21	1,77	0,82	3,08
	≥ 50	N=18	1,60	0,84	2,64	N=12	0,97	0,69	2,11

TABLE. 3: Moisture supply for various periods of building year and outdoor temperature.

		Moisture supply (g/m^3)							
		T outdoor ≤ 5 °C				T outdoor ≥ 5 °C			
Room type	Building year	Valid N	Mean	Std dev	90 %	Valid N	Mean	Std dev	90 %
Bathroom	← 1960	N=26	3,38	1,35	5,51	N=16	2,75	1,16	4,42
	1961 - 83	N=29	3,01	1,23	4,56	N=12	2,93	1,15	4,96
	1983 →	N=11	3,39	1,01	4,97	N=12	2,48	1,44	5,17
Basement	← 1960	N=29	1,69	1,14	3,18	N=15	0,85	0,99	2,83
	1961 - 83	N=31	1,31	0,87	2,36	N=12	1,14	0,78	2,46
	1983 →	N=11	1,67	1,53	4,66	N=12	1,22	0,79	2,54
Bedroom	← 1960	N=28	1,75	1,13	3,65	N=16	1,54	0,87	2,88
	1961 - 83	N=33	1,51	0,93	2,96	N=12	1,04	0,79	2,31
	1983 →	N=11	1,14	0,67	2,05	N=12	1,14	0,96	3,13
Living room	← 1960	N=29	2,19	0,94	3,39	N=16	1,78	1,17	3,30
	1961 - 83	N=33	1,99	0,87	3,05	N=12	1,36	0,59	2,34
	1983 →	N=11	1,80	0,41	2,45	N=12	1,60	1,06	3,46

but it is probably unnecessary conservative to design the whole house according to these high levels. It is probably better to use the measurements for the living rooms as basis for the design of the whole building, and do a special analysis for the bathrooms (and other similar rooms such as laundry room) if necessary. In our measurements the bedroom values are significantly lower than the living room values. It should however be noted that the bedrooms are children bedrooms, and that the parent bedrooms might have higher values. Kalamees, Juha and Kurnitski (2006) report slightly higher values for bedroms than for living rooms (0,2 g/m^3 higher in average, T_{out} < + 5^{o}C) and this might be due to this beeing parents (two persons) bedrooms. It should however be noted that in Norway it is rather common to sleep with open windows in the bedroom also during winter, giving a better ventilation and a lower temperature. In (Jenssen, Geving and Johnsen, 2002) the weekly mean temperature in 31 childrens bedrooms in Trondheim were measured to +13,5 ± 4,3 ^{o}C.

While there were no significant effect of the ventilation system, there was found a significant effect of the level of occupancy for living rooms as shown in figure 2. From our findings and the findings of Kalamees, Juha and Kurnitski (2006) we propose the following moisture design curves based on the 10% critical level as given in figure 3. "Low" could be used for living rooms in houses with low occupancy (>50 m^2/person) and areas where the moisture production is low (e.g. cellars), "Medium" for living rooms with medium/high occupancy (<50 m^2/person) and bedrooms, and "High" for bathrooms and laundry rooms. Whether it applies for other countries than Norway must however be further investigated.

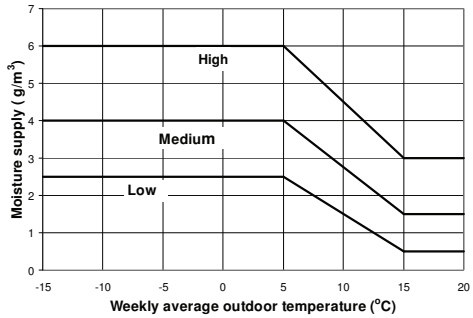


FIG. 3: Proposed moisture supply design curves for Norwegian houses (based on 10% critical level).

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Paper VI

Geving, S. and **Holme**, J. (2009) Diurnal variations of indoor air humidity in Norwegian houses, *Energy Efficiency and New Approaches – Proceedings of the Fourth International Building Physics Conference* (Bayazit N.T. *et al*. eds), Beysan Matbaacilik ve Reklamcilik, Istanbul, 807-814.

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Diurnal variations of indoor air humidity in Norwegian houses

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ABSTRACT: In this study indoor air humidity and temperature levels have been measured in 87 houses in Trondheim, Norway. The temperature and relative humidity were measured at 15 minutes interval over a period of one week. The measurements were made in bedrooms, living rooms, bathrooms and outdoors. The moisture supply, which is the difference between indoor and outdoor air water vapour content, was calculated. The dataset has previously been analysed in regard to average values of moisture supply and its dependency of outdoor climate. The subject of this study however, were to analyze the daily variations of indoor relative humidity, temperature and moisture supply for the various types of rooms. The typical diurnal amplitudes of relative humidity, temperature and moisture supply are presented together with the statistical variation. The effect of influencing factors such as type of basic ventilation of the house, type of building, time of the year and the level of average indoor air humidity were investigated.

1 INTRODUCTION

Knowledge of the indoor air humidity in houses is required for many purposes. One of the most important input parameters when doing a hygrothermal analysis of the building envelope using simulation models is knowledge about typical levels of indoor air humidity. For many purposes knowledge of the average indoor air humidity over a certain time period (week, month, year) is sufficient, and that is also what has been documented and reported in most large scale measurements of indoor air humidity levels in houses. In some cases however the knowledge of typical daily variations of the indoor air humidity is needed, for instance when assessing the risk for internal surface condensation or when assessing the moisture buffer effect of the hygroscopic materials in a room. We also register that instantaneous measurements of indoor air humidity are often made without realising that one single measurement value may be rather uninteresting considering the large variation throughout the day and week.

A common way of expressing the indoor air humidity load is by the *moisture supply*, defined as follows:

$$\Delta v = v_i - v_e \quad (1)$$

where Δv = moisture supply (g/m^3); v_i = indoor air water vapour content (g/m^3); v_e = outdoor air water vapour content (g/m^3). The moisture supply is often used instead of relative humidity (RH) when the RH is not controlled but allowed to undergo wide variations due to several factors such as weather conditions, building characteristics, moisture generation and ventilation.

The mean indoor moisture supply (over a week, month or year) in houses have been investigated in many earlier field studies, a summary is given in (Kalamees, 2006). It is generally considered that the mean moisture supply measured over a prolonged period tend to be relatively constant in a house during the colder part of the heating season (outdoor temperature < 0 - +5 °C), while it decreases when the outdoor temperature increases (EN ISO 13788, 2001), (Kalamees, Juha & Kurnitski, 2006). According to (Kalamees, 2006) most of the studies yields average moisture supply during winter between approximately 2 – 3 g/m^3 for living rooms.

While there are many studies that investigate the mean indoor air humidity in houses over a prolonged period of time, the number of studies that investigate the daily variations are fewer. Most studies that include daily variations involves measurements in only a few number of houses, in few types of houses and in few types of rooms, i.e. the data is not representative for a national housing stock as a whole. Mihalka & Matiasovsky (2006) reports daily variation of vapour production (in kg/h) measured in the central hall in four identical flats in an apartment building in Slovakia. Holm, Antretter & Lenz (2005) made measurements of RH in the living room in 11 houses of various types in Germany, showing exam-

ples of typical daily and weekly variations. Holm, Antretter & Lenz. (2005) reported that the daily fluctuations were around the same bandwidth during both summer and winter. The fluctuations ranged between ± 6 – 20 % RH. Winterly daily fluctuations of RH often depended on fluctuations in the temperature. The highest fluctuations were found for low room volumes and rooms with a low wood percentage in envelope (i.e. low moisture buffer capacity).

The English Warm Front project measured daily fluctuations of moisture supply for living rooms and bedrooms in 1600 low income households (Ridley et.al., 2007). A general finding in (Ridley et.al., 2007), Holm, Antretter & Lenz (2005) and Mihalka & Matiasovsky (2006) were that the indoor air humidity in the living roms increases during the morning when people get up from bed, that there were peaks at noon if people were at home and that there were a peak in the evening when people were using the room after dinner. For the bedroms the daily variation were smaller than in the living rooms, but following the same trend a small peak in the morning and a larger peak in the late evening (Ridley et.al., 2007). The decrease of indoor air humidity during the night were generally slower in the bedrooms than in the living rooms (Ridley et.al., 2007).

Kalamees (2006) documented the daily amplitudes of indoor climate in bedrooms and living rooms in 46 lightweight timber frame detached houses in Finland. Balanced ventilation showed a significantly lower daily amplitude of RH and moisture supply than exhaust ventilation. Rooms with hygroscopic indoor surface materials had significanly lower daily amplitudes of RH and moisture supply than rooms with non-hygroscopic indoor surfaces.

Korpi et.al. (2008) investigated the daily amplitudes of indoor RH, temperature and absolute humidity in the master bedroom in 69 heavyweight detached houses in Finland. There were relatively little variation between summer and winter amplitudes. Different types of heawyweight exterior walls had little influences on the indoor air humidity. For timber frame houses a higher amplitude of humidity and temperature than in heavyweight houses is reported.

The measurements presented in this paper has been part of the study "Prevention of atopy among children in Trondheim" (Jenssen et.al., 2001). The analysis work of the measurements have been part of the ongoing SINTEF strategic institute project "Climate Adapted Buildings". The dataset has previously been analysed in regard to mean indoor moisture supply and its dependency of outdoor climate (Jenssen , Geving & Johnsen, 2002) and (Geving, Holme & Jenssen, 2008).

2 METHOD

Indoor air humidity and temperature levels have been measured for a week during the heating season in 87 houses in Trondheim, Norway. The houses were selected for each of the four following building types; detached one family houses (41 %), semidetached two- or four family houses (28 %), undetached (chained) houses (13 %) and apartment buildings (18 %). Most of the houses in Norway (except for apartment buildings) are lightweight timberframe houses, and so was the case also in this study.

In each house measurements were made in a bedroom, the main living room and the most used bathroom. The bedroom was selected to be the bedroom where the child included in the "Prevention of atopy"-study slept, and that would typically be the master/parent bedroom since the children typically was under one year old. However, some children have probably been sleeping alone without their parents in a children bedroom.

The year of construction had the following distribution; before 1961 (34 %), 1961 – 1983 (37 %) and after 1983 (29 %). The mean heated floor area of the houses was 127 m^2 (std. dev. = 89 m^2). Non-heated area like cold cellars etc are not included in this floor area.

Most of the studied rooms had the possibility of opening the windows for airing purposes. The houses had all types of basic ventilation; no ventilation (8 %), natural ventilation (55 %), mechanical exhaust ventilation (30%) and balanced ventilation (7 %). "No ventilation" means that there was not installed any airing inlets/outlets in walls or window frames.

The houses were selected through this procedure: Parents of the children that were included in the "Prevention of atopy"-study were asked for permission to perform inspection of their houses until enough participants had accepted. There were 200 participants in this home inspection study, but relative humidity (RH) and temperature were measured in only 87 of these 200 houses. This means the houses were "randomly" selected among a population (with small children in the house) that had accepted to participate in the "Prevention of atopy"-study.

The temperature and RH were measured at 15 minutes interval over a period of seven days. Small logging units were used (Tiny tag, TGU 1500, Intab). The loggers were positioned away from windows, heating units, direct sunlight or outer door. The loggers were placed between 1,5 – 2,0 m above floor level. The accuracy of the loggers were ± 3 % RH and ± 0,5 ^{o}C. Hourly data for outdoor RH were retreived from an automatic weather station located in Trondheim operated by the Norwegian Meteorological Institute, with an accuracy of ± 2 % RH and ± 0,5 ^{o}C. The moisture supply (Δv) was calculated

on an hourly basis. The measurements were made during the period May - July 2003, September 2003 – June 2004, September – December 2004. In 45 of the houses the weekly average outdoor temperature were below 5 °C during the measurements, and for the last 42 houses the outdor temperature were between 5 and 15 °C.

3 RESULTS

3.1 *Variation of indoor climate during the day*

Mean values of indoor climate parameters are given in Table 1. Since it is shown that these paremeters varies over the year, i.e. they are dependant of the outdoor temperature, the values are divided in two groups for weekly mean outdoor temperatures below and above 5 °C. A detailed analysis of mean moisture supply, including the dependancy of outdoor temperature, is given in (Geving, Holme & Jenssen, 2008).

Mean daily amplitudes of indoor climate parameters are given in Table 2. For each house and each room the mean daily amplitude was calulated based on seven amplitudes (amplitude is the difference between maximum and minimum hourly value during the day) during the week. Based on these values the mean and standard deviation is calculated for the group of 87 houses.

It was investigated whether the mean daily amplitudes depended on the time of the year. When comparing the groups of houses with weekly mean outdoor temperatures below and above 5 °C only small differences were found. The effect of the type of ventilation on the mean daily amplitudes vere also investigated. The differences were rather small (no significant differences were found). When comparing subdivisions for houses with moisture supply below and above the mean value, we found a significant higher Δv_{amp} when the moisture supply was higher than the mean value compared to when the moisture supply was lower than the mean value. As an example the effect of these subdivisions is shown in Table 3 for the living rooms only.

Table 2. Mean daily amplitudes of indoor RH, temperature and moisture supply (valid N= 87).

Room type	Parameter (amplitude)	Mean	Std dev
Living room	RH_{amp} (%)	7	3
	T_{amp} (°C)	3.5	1.8
	$v_{i,amp}$ (g/m^3)	1.8	0.5
	Δv_{amp} (g/m^3)	2.1	0.5
Bedroom	RH_{amp} (%)	9	4
	T_{amp} (°C)	3.2	1.4
	$v_{i,amp}$ (g/m^3)	1.8	0.7
	Δv_{amp} (g/m^3)	2.2	0.6
Bathroom	RH_{amp} (%)	16	6
	T_{amp} (°C)	2.6	1.6
	$v_{i,amp}$ (g/m^3)	4.0	1.4
	Δv_{amp} (g/m^3)	4.2	1.3

Table 3. Values of mean daily amplitudes for the living rooms of indoor RH, temperature and moisture supply for various subdivisions.

Subdivision	RH_{amp} (%)	T_{amp} (°C)	Δv_{amp} (g/m^3)
No ventilation	7	4.1	1.8
Natural ventilation	7	3.6	2.2
Exhaust ventilation	7	3.3	2.1
Balanced ventilation	6	3.4	1.9
Outdoor temperature ≤ 5 °C	7	3.9	2.1
Outdoor temperature > 5 °C	7	3.1	2.2
Moisture supply < mean value	6	4.0	1.9
Moisture supply ≥ mean value	8	3.9	2.2

Table 1. Mean values of indoor RH, temperature and moisture supply (Valid N = 45 and 42 for weekly mean outdoor temperature below and above 5 °C respectively).

		T outdoor ≤ 5 °C				T outdoor > 5 °C & < 15 °C			
Room type	Parameter	Mean	Std dev	10 %	90 %	Mean	Std dev	10 %	90 %
Living room	RH (%)	35	6	28	43	39	7	32	45
	T (°C)	21.5	1.7	19.0	23.3	22.2	1.6	21.0	23.4
	Δv (g/m^3)	2.2	0.9	1.2	3.2	1.6	1,0	0.6	3.0
Bedroom	RH (%)	43	9	33	54	43	10	33	53
	T (°C)	16.5	3.3	12.3	19.1	19.0	2.4	15.6	21.3
	Δv (g/m^3)	1.8	1.1	0.7	3.1	1.2	0.9	0.2	2.5
Bathroom	RH (%)	38	8	29	49	39	8	31	49
	T (°C)	23.3	2.9	20.1	26.7	24.3	2.1	22.0	26.0
	Δv (g/m^3)	3.6	1.3	1.9	5.3	2.8	1.2	1.2	4.4

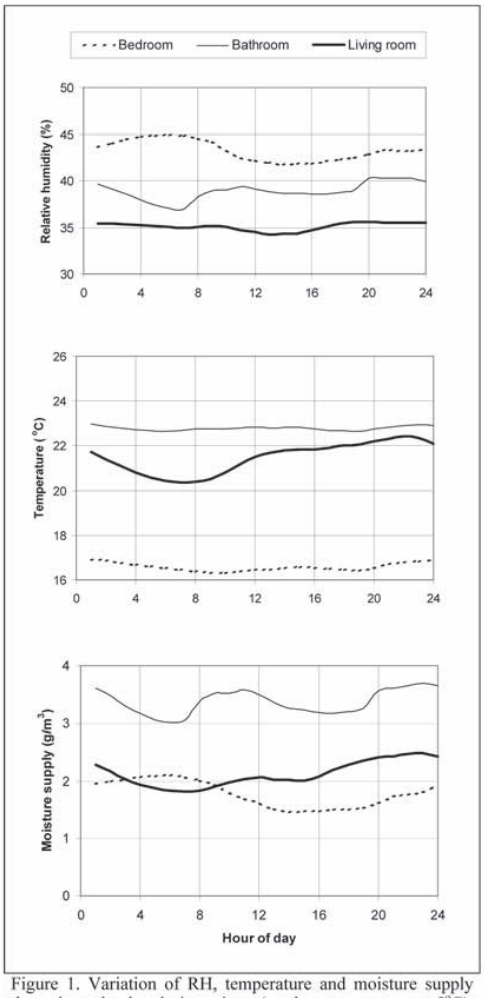

Figure 1. Variation of RH, temperature and moisture supply throughout the day during winter (outdoor temperature < 5°C). Mean values for 43 of the 85 houses based on 7 days of measurement for each house.

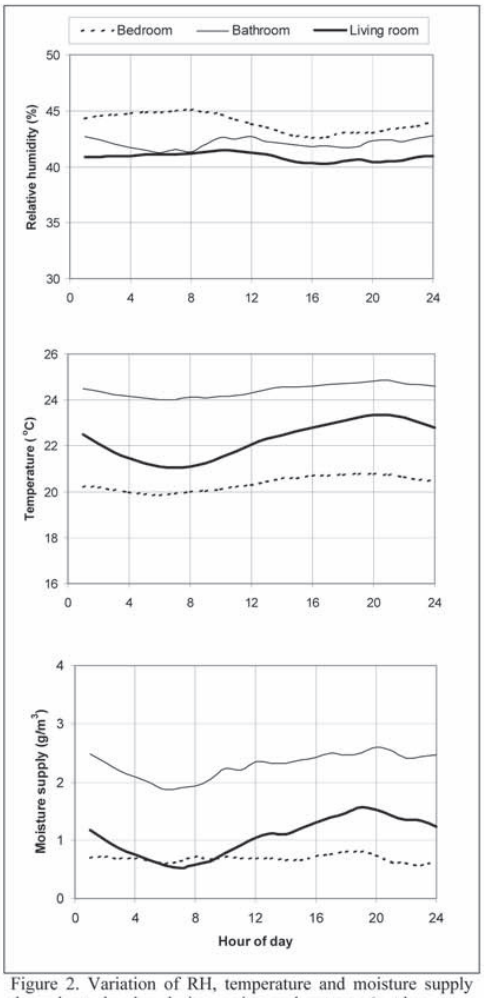

Figure 2. Variation of RH, temperature and moisture supply throughout the day during spring and autumn (outdoor temperature between 5 – 15 °C). Mean values for 42 of the 85 houses based on 7 days of measurement for each house.

The typical variation of indoor air temperature, RH and moisture supply throughout the day is presented in Figures 1 and 2. For every house and for every hour of the day (1a.m. – 24 p.m.) a mean value is calculated for a particular time of hour based on the seven values throughout the week. Based on these mean hourly values from all 87 houses the mean value for the group of 87 houses (e.g. two groups of 45 and 42 houses) is calculated for every hour of the day.

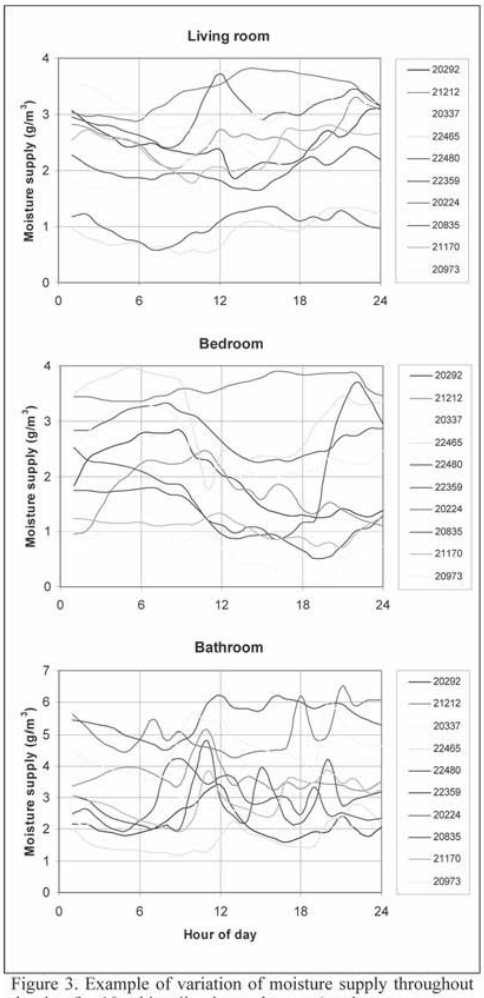

Figure 3. Example of variation of moisture supply throughout the day for 10 arbitrarily chosen houses (outdoor temperature between ÷3 and +1 °C). Mean values based on 7 days of measurement for each house.

Since the variation throughout the day shown in Figures 1 and 2 are average values based on hourly values from seven days and 87 houses, we realise that typical peaks will be damped due to moisture production occuring at different times during the day in different houses/families. As an example of a more typical variation throughout the day the moisture supply during the day is shown for 10 arbitrarily chosen houses in Figure 3. Hourly means of RH, temperature and moisture supply are shown in Figure 4 for a specific house during one specific day.

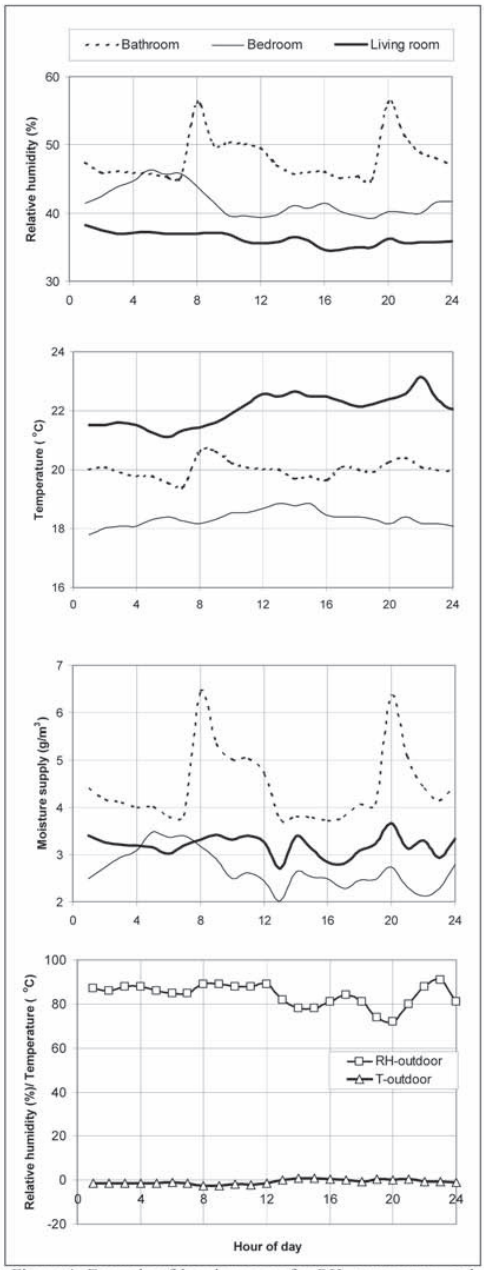

Figure 4. Example of hourly means for RH, temperature and moisture supply throughout the day measured for one specific house (no. 20973) during one specific day (daily mean outdoor temperature was – 0,9 °C).

3.2 *Variation of moisture supply during a week*

When calculated on an hourly basis we find that the moisture supply may vary considerably during the week if the outdoor air water vapour content (v_e) changes rapidly. Two examples of the variation of moisture supply during a week are given in Figure 5 and 6. It is selected periods where the outdoor air water vapour content are changing relatively much during the week.

Figure 5 and 6 shows a decrease in the daily mean moisture supply over the week, as v_e increases over several days. Probably due to hygroscopic surfaces, furniture etc the indoor air water vapour content (v_i) is not increasing at the same rate as v_e, and in this way influencing the hourly and daily values of the moisture supply. When v_e suddenly decreases, we see the opposite effect, i.e. the moisture supply suddenly increases.

Figure 6 also shows the large discrepancy of real hourly RH and calculated RH if not including the hygroscopic inertia (moisture buffer effect) of interior surfaces. The calculated values of RH were calculated from hourly values of outdoor air water content (v_e) and using the weekly mean moisture supply (= 1,55 g/m^3), i.e. RH = (v_i/$v_{i,sat}$)*100, v_i = v_e + 1,55.

From this we realise that calculating hourly indoor RH by using mean moisture supply may lead to much higher fluctuations of RH than what is occurring in reality.

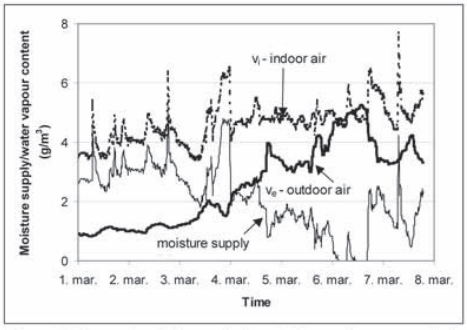

Figure 5. Example of the variation of the moisture supply in the living room throughout a week (in house no. 151), during a period where the outdoor air water vapour content is changing relatively much.

4 DISCUSSION

4.1 *Variation of indoor climate during the day*

The daily variation of indoor air relative humidity and the moisture supply in houses are generally dependant of many factors such as; variation of moisture production during the day, fluctuations of indoor air temperature (e.g. by daily heating strategy, solar radiation), short term variations of ventilation (e.g. opening windows, increasing/decreasing level of mechanical ventilation), the volume of the room, and the amount of hygroscopic surfaces (building envelope, furniture etc.).

Since almost all the above mentioned factors interact in a complicated way, it is difficult to predict the daily air humidity variations. Also when studying statistical data on large scale measurements as done in this investigation, it is difficult to compare and analyze the data due to these interacting factors.

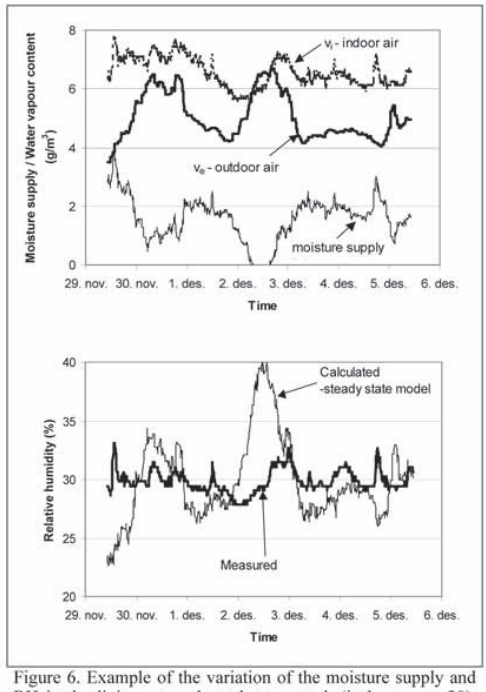

Figure 6. Example of the variation of the moisture supply and RH in the living room throughout a week (in house no. 30), during a period where the outdoor air water vapour content is changing relatively much.

Short term variations of moisture production and ventilation during the day is depending on the occupants, and the way they use the house. As shown in Figure 3 we see that the daily variations of moisture supply varies to a great extent between different houses and families. However certain trends can be observed from Figure 1 – 3:

In the bedrooms the moisture supply and RH is generally lowest during the afternoon (14 – 18 p.m.), starts increasing as people gets home from work, and reaches its peak in the morning (6 - 8 a.m.) when people get out of bed. It should however be noted

that the moisture supply tend to be rather constant during the day when the outdoor temperature is above 5 °C (Figure 2). It should be noted that in Norway it is rather common to sleep with open windows also during most of the winter time (except when it is very cold).

In the living rooms we see that RH is not varying much during the day, compared to the other room types. Temperature is however varying, with a peak late in the evening (20 – 22 p.m.) and the lowest value in the morning (6 – 8 a.m.). The moisture supply follow the trend of the temperature. The peak is late in the evening (20 – 23 p.m.) when people have been home for a while, spending time in the living rooms. When people go to bed the moisture supply starts to decrease, reaching its lowest value in the morning (6 – 8 a.m.). If people is home during the day it is a tendency that we have a small peak at noon, if none is at home the moisture supply starts increasing when people get home from work. It should be noted that for most of the measured houses, it was probably one parent and a small child (age under one year) being at home during the day.

For the bathrooms we observe that when outdoor temperatures are below 5 °C there are generally two peaks for the mositure supply and RH, one during the morning (8 - 11 a.m.) and one during the evening (20 – 24 p.m.). This is probably due to the occupants mainly taking showers in the morning or in the evening. From Figure 3 we do however see that the moisture supply in the bathrooms is strongly dependant on when the occupants are taking a shower. For instance we observe that in some houses the first showers are taken early in the morning (6 – 7 a.m.), probably before going to work. Occupants being at home during the day may however take a shower later in the morning (9 – 11 a.m.). Though the air humidity of the bathroom is generally the most difficult to predict.

We observe that the mean daily amplitudes given in Table 2 are much higher than the amplitudes that can be observed in Figure 1 and 2. This is to be expexted since the values shown in Figures 1 and 2 are average values based on hourly values from seven days and 87 houses. Typical peaks will be damped due to moisture production occuring at different times during the day in different houses/families.

The daily amplitudes of RH, temperature and moisture supply are compared to other references in Table 4. When comparing the daily amplitudes for bedroms and living rooms we find that the amplitudes of RH and moisture supply compare very well with the measurements of Kalamees (2006). The measurements of Korpi et.al. (2008) do however show lower amplitudes, both for RH and moisture supply. One explanation could be that the measurements of Korpi et al. (2008) were made in houses with heavyweight constructions, while Kalamees (2006) made measurements in houses with lightweight constructions – the last being more typical for the houses in this study. The amplitude of the temperature is however much lower both for (Kalamees, 2006) and (Korpi et.al., 2008) compared to this study. This could be due to the houses investigated in (Kalamees, 2006) and (Korpi et.al., 2008) being new houses with modern ventilation and heating systems, while in this study the age of the houses are from very old to new, with all types of heating and ventilation systems.

The dependancy of the ventilation system on the amplitudes were found to be small. This compare well with the findings of Kalamees (2006).

Table 4. Comparison of mean daily amplitudes of indoor RH, temperature and moisture supply with other references

Reference	Room type	RH_{amp} (%)	T_{amp} (°C)	Δv_{amp} (g/m^3)
This study	Living room	7	3.5	2.1
This study	Bedroom	9	3.2	2.2
Kalemees, 2006	Bedroom *	9	1.8	2.0
Korpi et.al, 2008	Bedroom	6	1.0	1.3

* May also include measurements from the living room.

4.2 *Variation of moisture supply during a week*

As shown in Figure 5 and 6 the moisture supply is highly sensitive for changes in the outdoor air water vapour content (v_e). This is due to the indoor air water vapour content (v_i) not following these changes at the same rate. The hygroscopic inertia of interior surfaces and furniture dampens how quick v_i can react on changes of v_e. Since the moisture supply is the difference between v_i and v_e, this dampening can lead to variations of moisture supply from day to day even if the moisture production and the ventilation is the same. As shown in Figure 6 the hourly value of the moisture supply can even be negative.

A general conclusion from the above is that measurements of indoor air humidity should be made on a long term basis, i.e. minimum one week of measurements. This is a necessity if moisture supply is to be used as a main parameter.

5 CONCLUSIONS

Typical daily variations of indoor RH, temperature and moisture supply of living rooms, bedrooms and bathrooms have been surveyed. It was found that the variation of RH and moisture supply generally followed the expected daily variation of moisture production due to the use of the house and the rooms. RH in the living rooms did however not vary much during the day.

The mean daily amplitudes of RH, temperature, indoor water vapour content and moisture supply were relatively similar for the living rooms and the bedrooms, while the variations were higher for the bathrooms. The amplitudes of this study comply well with other studies.

The dependancy of the ventilation system and the seasonal variation of outdoor temperatures on the amplitudes were found to be small.

It was found that the moisture supply, when calculated on an hourly basis, is highly sensitive for changes in the outdoor air water vapour content during the day and week. A general conclusion is therefore that measurements of indoor air humidity should be made on a long term basis, i.e. minimum one week of measurements as in this study.

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Paper VII

Holme, J., Geving, S., and Jenssen, J. (2008) Moisture and Mould Damage in Norwegian Houses*, Proceedings of the 8th Symposium on Building Physics in the Nordic Countries* (Rode C. eds), Report R-189, Dept. of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, 1213-1220

Moisture and Mould Damage in Norwegian Houses

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KEYWORDS*: Moisture indicators, moisture supply, mould growth, building characteristics*

SUMMARY*:*

Several studies have demonstrated associations between living in "damp" buildings and health effects such as respiratory symptoms, asthma and allergy. There is only limited knowledge about which agents in indoor air and what levels of exposure that causes the health effects. One possible agent is mould. Because of this there is a strong need for understanding the associations between building characteristics and mould growth.

The survey "Prevetion of atopy among children in Trondheim" includes both self-reported information about housing, and inspections and measurements from 205 homes. The study includes registered building characteristics such as construction, installations systems and moisture problems. Measurements include temperature, relative humidity and mould spores in the indoor air. The measurements were made in bedrooms, living rooms, bathrooms, basements/cellars and outdoor air.

50 percent of the houses had one or more indicator of a visible mould problem. In 42 % of the houses with no reported moisture problem, the inspector found an indicator of a problem. Looking at the moisture supply there were som higher values in rooms with a visible moisture indicator and in rooms with registered mould growth compared to rooms with no indications or mould. Type of ventilation, foundation and building period, have an influence on the precent share of houses with one or more indicator of a visible moisture problem or regisrered mould growth.

1. Introduction

Dampness and other excessive moisture accumulation in buildings are closely connected to observations of mould, mildew, or other microbial growth. The behaviour of moisture and air movements can be characterized by physical parameters, but the biological processes take place according to a complicated network of regulating factors. Several phenomena make up the microbial ecology of an indoor environment (IOM 2004).

Several studies have examined the aspects of moisture that are associated with biological contamination; these include exhausts in kitchens and bathrooms; below grade moisture seepage; bulk water (plumbing leaks, roof drainage, and envelope penetration); condensation on inadequately insulated outside walls; and inappropriately sized cooling coils (i.e. incorrect latent heat ratio) (Spengler et al. 1994, Trechsel 1994, Dales et al. 1997). In many of the epidemiologic studies showing an association between moisture and adverse respiratory health effects or lung disease, exposure is often defined with both qualitative and quantitative methods (Bornehag et al. 2001, Bornehag et al. 2004). Exposure assessment methods used to characterize moisture and mould include the following: (1) physical measurements (e.g., humidity, temperature); (2) sampling and analysis to detect moisture related microbes and/or chemicals in air and dust; (3) visual inspections for moisture and mould (observations); or (4) self reports from inhabitants and workers in questionnaires or interviews (reports).

Reports of damp spots, water leakage or water damage, and mould or mildew from self-report questionnaires, are used as surrogate measures for the number of fungi in several published epidemiologic studies (Kilpelainen et al. 2001, Pirhonen et al. 1996, Dales et al. 1991, Platt et al. 1989, Strachan 1988). Several studies have relied on home inspections by professionals (observations) for verifying self reported moisture and mould in the home (Haverinen et al. 2001, Platt et al. 1989, Dharmage et al. 1999a, Verhoeff et al. 1994). Dharmage et al. 1999b and Garrett et al. 1998 measured the presence of fungal propagules in air and demonstrated that observed house characteristics, such as visible mould or dampness patches, have validity as measures of mould concentrations and dampness in homes. Dharmage et al. 1999b showed that higher total airborne fungal concentrations were associated with reported visible mould.

Fungal exposure and its association with moisture damage in a building are complex and multifaceted. Many types of fungal species are reported to grow in the indoor home environment (IOM 2004). One way to provide a better understanding of the influence of residential characteristics (and behaviour) on fungal levels is to clarify the definitions of "fungal levels." Most studies use total airborne fungi concentrations or report a dominant type of fungi species, such as *Cladosporium* or *Aspergillus*, in their exposure assessment analyses. Li and Kendrick 1995 found significantly higher airborne fungal spore counts of specific species (*Aspergillus/Penicillium*, *Cladosporium*, unidentified basidiospores, etc.) in damp residences (defined as homes with visible mould, water damage, or water in the basement). Fungi can grow only on a surface or in a substrate. Many conditions of the surrounding environment (e.g., relative humidity and temperature) affect fungal growth by increasing or decreasing the drying potential of the substrate. In general, water requirements for fungi are species specific. Exposure assessments may prove more useful if a broad group of fungal species is selected according to their nutrient requirements and substrate characteristics, including water availability.

As studies increasingly support the presence of health risks associated with moisture related agents (microbes and/or chemicals), there is a strong need for understanding fungal concentrations and physical measurements as they relate to the microenvironment (associations between building characteristics and mould growth).

Such knowledge is important to make future prevention of mould growth in new and already existing houses possible. Since 20-30% of the existing buildings are affected by moisture problems (IOM 2004) we need knowledge for measures in such buildings, i.e. what should we do in a problem building, how much of the affected material should be taken away, etc. It may also be a tribute to improve the characterization of commonly used moisture/mould indicators, such as observation of mould, odours, ventilation and reports of moisture and water sources in the house.

The aim of this study has been the following;

- Describe indicators of visible moisture problem in buildings observed by inspectors and compare these to self reported moisture problem.
- Compare the air humidity in bedroom, living room, bathroom and basement with or without one or more indicator on a visible moisture problem and with or without registered mould growth.
- Compare the influence of some building characteristics on the number of houses with one or more indicator on a visible moisture problem or registered mould growth compared to those without any registered indications or mould growth.

2. Method

The work presented in this paper is part of the study "Prevention of atopy among children in Trondheim" (Jenssen et.al., 2001). Parents of the children that were included in the "Prevention of atopy"-study were asked for permission to perform inspection of their houses until enough participants had accepted. The survey includes both self-reported information about housing and inspections from 205 homes in Trondheim, Norway. Indoor air humidity levels and viable mould spores in the indoor air have been measured in a selection of the houses. The houses were randomly selected for each of the four following building types; detached one family houses, semidetached two family houses, undetached (chained) houses and apartment buildings. In each house measurements were made in the children bedroom, the living room, the most used bathroom and basement/cellar.

Six professional inspectors performed visual inspections and assessments of air humidity levels and viable mould spores in the indoor air. The inspectors were blinded to case-control status of the children living in the

homes. During these investigations, a checklist was followed regarding factors such as the type of building, building construction, type of ventilation, and mould and moisture problems. The inspectors observed possible moisture problem and sources, and finally graded each room and the house according to the following "moisture condition"; "no sign of moisture", "few" (1 or 2, small and spread symptoms on moisture), "more" (> 2 symptoms, clear signs of moisture) and "unambiguous sign of moisture" (breakdown and function failure).

Questions in the baseline questionnaire (reported) regarding signs of moisture problems in the house could be answered by "yes" or "no". If the answer was "yes" there was a follow up question regarding whether or not the problem had been fixed. Also this question could be answered by "yes" or "no".

Relative humidity (RH) and temperature of the indoor air were measured in 86 houses. The temperature and RH were measured at 15 minutes interval over a period of seven days. Small logging units were used (Tiny tag, TGU 1500, Intab). The loggers were positioned away from windows, heating units, direct sunlight or outer door. The loggers were placed between 1,5 – 2,0 m above floor level. The accuracy of the loggers were ± 5 % RH and ± 0,5 ^{o}C. The loggers were controlled in a climate chamber at 50% RH and 23 ^{o}C before being used. Hourly data for outdoor RH were retrieved from an automatic weather station located in Trondheim operated by the Norwegian Meteorological Institute. The moisture supply (Δv) was calculated on an hourly basis. The moisture supply is defined as the difference between indoor and outdoor air water vapour content (in g/m^3). Mean weekly values for the moisture supply were calculated from these hourly values.

In selected buildings, samples of viable micro organisms (fungi and bacteria) were taken in the child's bedroom, living room, bathroom and basement. The samples were taken approximately one meter above the floor, under normal conditions regarding use, heating and ventilation in the house. Reference samples were taken outdoors. The sampler used was a Biotest Standard RCS Sentrifugal Air Sampler (Biotest AG, Dreieich, Germany), which is a handheld, battery operated instrument that collects bioaerosols on a nutrient agar to allow direct culturing techniques to be used to enumerate airborne micro organisms. A fan draws air through the sieve plate causing airborne particles to impact on the agar plate and air is exhausted through the side of the sampler. All sampling equipment was calibrated before use. The samples were taken on both Tryptic Soy Agar (TSA) and Rose Bengal Agar (RBA). Sampling volume was set at 40 litres/minute in 8 minutes for each media.

Microscopical analyses at 400x and 1000x magnification in light microscope were conducted after cultivation at 22 ºC for 5-7 days. Identification of fungi was in general done to the level of specie. Amount and type of mould specie detected in the respective room, was compared to the sample taken outdoor. If the sample from the indoor air differed either in concentration, mould specie or both, compared to the sample taken from the outside, the room had registered mould growth.

3. Results

Table 1 shows the percent share of different indicators of a moisture problem in the houses, the child's bedrooms, living rooms, bathrooms and basements. 50 % of the buildings had one or more visible indicator of a moisture problem. The most common indicator was spots of moisture, swelling or capillary attraction of water in wood which appeared in 18 % of the houses. 15 percent had a leak from the ground, and 15 % showed condensation on surface other than windows. In the child's bedroom 11 % of the rooms inspected had one or more visible indicator on a moisture problem. The most dominant indicator was condensation on window (3%) and on surface (6%). Living rooms had fewer indicators compared to the other rooms. Only 5 % of the rooms had one or more indicators of a moisture problem. 21 % of the bathrooms had one or more indicator of a visible moisture problem. The dominating indicators were spots of moisture, swelling and capillary attraction of water (5 %) and condensation on window (5%) and surface (9%). 65 % of the basements had one or more indicator of a visible moisture problem. The most common indicator was not surprisingly, leakages from the ground (52 %).

The inspectors found that in the houses with no reported moisture problem ever, 42 % had one or more indicator on a visible moisture problem (Table 2). In the houses where a reported moisture problem had been repaired, the inspectors found an indication in 53 % of them. In the houses where a moisture problem never had been repaired, the percent share with one or more indicator on a visible moisture problem was 62 %. The percent share varies between the different types of rooms. The basements had a high percent share observed moisture indicator in each of the reported categories, all over 63 %.

Table 3 shows the mean moisture supply in child's bedroom, living room, bathroom and basement, with or without indicators of a visible moisture problem and with or without registered mould growth. Bathrooms had

the highest moisture supply with a mean on 3.16 g/m^3. Living rooms had a mean on 1.9 g/m^3. Child's bedrooms and basements had a mean around 1.5 g/m^3. There was a higher moisture supply in child's bedrooms, living rooms and bathrooms with one or more indicator on a visible moist problem compared to those with no observed indicator. In the basement however the moisture supply was higher in those with no indicator. Child's bedrooms and bathrooms had a higher moisture supply compared to those with no registered mould growth. In living rooms and basements the rooms with no registered growth had a higher moisture supply compared to those with a registered growth

Table 4 gives the percent share of houses and rooms with (yes) or without (no) mould growth in each category of the categorized (by inspectors) moisture condition in all houses, child's bedrooms, living rooms, bathrooms and basements. The percent share houses with registered mould growth in one or more rooms are higher in the two worse categories ("more" and "unambiguous") regarding the inspector's classification of the moisture condition of the whole house. The situation is the same for bathrooms.

Table 5 gives an impression on how different building characteristics influence on the percent share of houses with or without one or more indicator on a moisture problem, and with or without registered mould growth.

The percent share with "no ventilation" and "natural ventilation" is higher in the groups of houses with one or more moisture indicator and the houses with registered mould growth, compared to the houses with no indicator or no registered mould growth. The difference is significant ($p<0.05$).

The houses with one or more indicator on a moisture problem have a higher percent share of "basement" compared to those with no indicator. The houses with no indicator have a higher percent share of "other apartment". The difference in type of foundation is significant between houses with or without a moisture indicator. In houses with registered mould growth there were 13 % more houses with a basement/cellar compared to the houses with no registered growth. The houses with no registered growth had more slab on ground compared to the houses with mould growth.

43.9% of the houses with one or more indicator of a moisture problem were built before 1960. Less was built after 1984 (25.6%). In houses with no indicator fewer was built before 1960 (30.2%), and the distribution was quite like for the tree construction periods. Houses with registered mould growt were built before 1960 (47.2 %) and less after 1984 (19.4%). The houses with no registered mould growth were more even spread throughout the tree construction periods.

Looking at type of building there were no large differences between houses with or without indicators of a moisture problem and houses with or without a registered mould growth.

TABLE 1: The percent share of each visible indicator on a moisture problem in the houses, the child's bedrooms, living rooms, bathrooms and basements/cellars.

Moisture Indicator	Whole building (205)	Child's bedroom (205)	Living room (205)	Bathroom (205)	Basement/ cellar (46)
Spots of moisture, swelling, capillary attraction of water in wood	18	2	2	5	13
Blathers	7	0	0	0	11
Leakage from the ground	15	0	0	0	52
Condensation on windows	10	3	1	5	9
Condensation on surfaces other than windows	15	6	1	9	2
Leakage from sanitary installations	6	0	0	1	0
Other leakages	4	0	0	1	2
At least one indicator	50	11	5	21	65

TABLE 2: The percent share with one or more observed indicator of a visible moisture problem in houses and different type of rooms in each category of reported moisture problem

	Whole building (205)	Child's bedroom (205)	Living room (205)	Bathroom (205)	Basement (46)
Never reported a moisture problem (n =107)	42	8	5	18	67
Reported moisture problem are repaired (n = 32)	53	16	6	25	63
Reported moisture problem are not repaired (n =66)	62	14	6	24	65

TABLE 3: Moisture supply in child's bedroom, living room, bathroom and basement with or without indicators of a visible moisture problem, and with or without mould growth.

		Valid N	Mean	SD	Percentile 75
Child's bedroom		87	1.5	1	1.97
Living room		87	1.9	0.95	2.54
Bathroom		86	3.16	1.32	3.94
Basement		85	1.37	1.08	1.98
One or more indicator on a visible moisture problem					
Child's bedroom	*No*	79	1.47	1.0	1.97
	Yes	8	1.82	1.05	2.37
Living room	*No*	78	1.87	0.97	2.51
	Yes	9	2.20	0.75	3.0
Bathroom	*No*	69	3.12	1.3	3.94
	Yes	17	3.31	1.45	4.39
Basement	*No*	67	1.44	1.13	2.17
	Yes	18	1.13	0.87	1.83
Registered mould growth					
Child's bedroom	*No*	44	1.39	1.06	1.95
	Yes	6	1.55	0.91	2.40
Living room	*No*	40	1.87	1.05	2.53
	Yes	10	1.42	0.67	1.72
Bathroom	*No*	42	3.07	1.49	3.93
	Yes	7	3.17	0.74	3.63
Basement	*No*	10	1.2	0.74	1.8
	Yes	2	0.87	2.02	-

TABLE 4: The percent share of houses and rooms with (yes) or without (no) mould growth in each category of the "Moisture condition" in all houses, child's bedrooms, livingrooms, bathrooms and basements / cellars.

	All houses*		Child's bedroom		Livingroom		Bathroom*		Basement / cellar	
	Yes (43)	*No (96)*	*Yes (18)*	*No (121)*	*Yes (27)*	*No (112)*	*Yes (19)*	*No (120)*	*Yes (9)*	*No (21)*
No symptom	25.6	43.8	77.8	90.9	92.6	94.6	52.6	63.3	22.2	19.0
Few (1 or 2) small and spread symptoms	27.9	32.3	22.2	7.4	7.4	4.5	21.1	24.2		33.3
More (>2) and good visible signs	41.9	24.0		1.7	0.9		21.1	12.5	66.7	47.6
Unambiguous sign	4.7						5.3		11.1	

* Significant difference between the to groups ("yes" and "no") ($p < 0.05$)

TABLE 5: Different building characteristics influence on the percent share of houses with or without one or more indicator on a moisture problem, and with or without registered mould growth.

	One or more indicator on a visible moisture problem		Registered mould growth	
	No	*Yes*	*No*	*Yes*
Ownership				
Owner	64.3	60.6	59.1	64.3
Owner, housing cooperative	31.6	28.3	32.3	31.0
Tenant	4.1	11.1	8.6	4.8
No ventilation	2.9	11.8	5.3	11.6
Natural ventilation	39.2	52.9	44.2	58.1
Mechanical ventilation	49.0	29.4	41.1	27.9
Balanced ventilation	8.8	5.9	9.5	2.3
Basement/cellar	13.7	36.3	21.9	34.9
Crawl space	2.0	3.9	2.1	2.3
Slab on ground	40.2	42.2	41.7	30.2
Other apartment	43.1	16.7	33.3	30.2
Other	1.0	1.0	1.0	2.3
→ 1960	30.2	43.9	34.1	47.2
1961 to 1983	34.9	30.5	32.9	33.3
1984 →	34.9	25.6	32.9	19.4
Detached one family houses	26.5	36.3	34.4	26.2
Semidetached family houses	28.4	23.5	25.0	26.2
Undetached (chained) houses	9.8	17.6	12.5	19.0
Apartment buildings	32.4	20.6	27.1	23.8
Other house	2.9	2.0	1.0	4.8

4. Discussion

In this study 50 % of the houses had one or more indicator of a visible moisture problem. The prevalence is a bit high compared to other studies. The damp indoor space and health report (IOM 2004) have summarized published data on the prevalence of signs of moisture in buildings. The reported prevalence of signs of moisture ranged from 1 % to 85 %. In most datasets, at least 20 % of the buildings have one or more sign of a moisture problem.

In this study child's bedroom and living room have a relatively low share of indicators of a moisture problem. This is not surprisingly because these two rooms have few elements that can cause a water damage compared to i.e. bathroom and basements.

In 42 % of the houses with no reported sign of a moisture problem ever, the inspectors found one or more indicator of a moisture problem. Nevalainen et al. (1998) reported similar results, suggesting that the explanation was a result of a trained eye and of knowledge of what represents a critical problem. There is a tendency in our study in a higher percent share of houses with one ore more indicator of a moisture problem among the houses where the inhabitants themselves once have reported a moisture problem compared to those who never have reported a problem.

Rooms with one or more indicator on a visible moist problem have a higher moisture supply compared to those with no indicators (this does not include basement/cellars). These findings are not surprisingly, taken into account that the moisture indicators often brings water into the environment. Regarding rooms with or without registered growth we should expect the same result, but in this study the differences is even smaller and appears only in child's bedroom and bathroom. This is strange because water is the most important limiting factor fore mould growth (IOM 2004).

Indoor moisture is linked to some building characteristics. In this study there is an association between a higher percent share of houses with one or more moisture indicators and type of ventilation, type of foundation and building period. Reported dampness has been associated with age of the building, lack of central heating, humidifiers and pets (Sprengler et al., 1994; Tariq et al., 1996)). Older building tend to be colder and (Hunt and Gidman, 1982), and therefore to have higher RH. Microbiological has also been associated with building characteristics. Measures of microbial contamination have been found to be positively correlated with indoor temperature and humidity, age and size of buildings, use of wood stoves and fireplaces, absence of mechanical ventilation (IOM 2004). In this study there were more houses with registered mould growth in houses with no or natural ventilation compared to houses with mechanical ventilation, and in houses with basement cellar compared to those with slab on ground. There was also an association in more registered mould in older houses compared to newer ones.

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Paper VIII

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