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Biological growth on mineral façades

Sanne Johansson

Preface

This licentiate thesis has been made at division Building Materials, Lund University of Technology and is funded by FORMAS –the Swedish Research Council for Environment, Agriculture Sciences and Spatial Planning.

The basis of this project is a pilot study of mould growth on mineral building façades made by Kenneth Sandin (2002).
I would like to thank my supervisors Lars Wadsö and Kenneth Sandin for their help and knowledge at all time, thereby making this project possible. A special thank to Stefan Backe, for all the help with technical support and laboratory assistance. Also thanks to all my colleagues for all their support and simply making the everyday life better.

In addition Sto Scandinavia AB and Maxit AB are gratefully acknowledged for the help with materials and practical support.

Sanne Johansson

The included papers

Paper I Johansson, S., Li, Y. and Wadsö, L. (2005). "Biological organisms on building façades". *Proceedings of the 7th symposium on Building physics in the Nordic Countries*, The Icelandic Building Research Institute, Reykjavik, Iceland, pp: 719-724.

Paper II Johansson, S., Wadsö, L., and Sandin, K. (2005). "Microbial growth on building facades with thin rendering on thermal insulation". *Proceedings of the 7th symposium on Building physics in the Nordic Countries*, The Icelandic Building Research Institute, Reykjavik, Iceland, pp: 1126-1130.

Abstract

During the last years there has been reported considerable and rapid contamination on newly built rendered façades in Sweden due to biological growth. The problem is believed to occur mostly on façades of render applied on thermal insulation, but apart from this it is difficult to find which façades that will be infected. The aim of this project is to explain why certain façades gets heavy biological growth while other seemingly similar façades do not. We will do that by combining biological and building physical knowledge.

One of the major approaches in this project is to investigate building façades. We have investigated several buildings with discolored façades, mostly in Skåne, the southernmost part of Sweden, and tried to identify the organisms growing there. The most dominating organisms we found growing on the façades were lichens and algae. In addition we have investigated building façades with organized patterns of small round areas where no growth occur on otherwise quite fouled façades. These small round areas appears then on the façade as "white dots". Further investigations of the façades show that the "white dots" appear at each fastener placed under the rendering to fasten the thermal insulation to the structural wall behind. We believe that the fasteners are heat bridges, with higher outer surface temperature and therefore a lower surface relative humidity at which no microbial growth occurs. Results from computer simulations showed that the fasteners are heat bridges that in cases with thin layers of thermal insulation and rendering give a 1-2 K higher night-time temperatures than the rest of the façade. This makes a difference in relative humidity of 11%. This small difference in temperature gives high enough differences in moisture state to almost prevent microbial growth at the fasteners. As we know that organisms need a high relative humidity to grow, these results explains the uneven distribution of biological growth on the façades with "white dots".

Temperature and relative humidity measurements on façades of thin rendering on thermal insulation (light façades) and brick walls with rendering (heavy façades) shows that light façades are more directly influenced by the weather conditions than the heavy façades. The temperature varied much more on the light façades than the on the heavy façades; in a day of October 2005 the temperature on the red-colored light façade varied from 60.4°C during daytime to -0.4°C during the next night. During nights there is no difference between the lowest temperatures on the light façades on the south- and north-facing façades. The light façades gets colder in the night then the heavy façades due to the lower heat capacity in the construction, whereas the heavy façades with the higher heat capacity can store the heat from daytime during night. The red-colored façades, which had a higher temperature than the white-colored façades, have a significantly lower relative humidity with a difference of 20% relative humidity if it was not fully overcast. The relative humidity measurements during night on the south-facing façades shows that the white-colored heavy façade had a higher maximum relative humidity with an approximately difference of 10% relative humidity during night than the red-colored light façade in spite of the higher minimum temperature during night on the white-colored heavy façade.

The results from the temperature measurements above the fasteners in light façades show that the fasteners are heat bridges that increase the façade surface a few degrees during night, but also in the winter on the north-facing façade during daytime.

We will continue our measurements of temperature and relative humidity on heavy and light façades. In addition we will investigate biological growth on both the above façades and on newly built light façades. Also biological growth will be studied on samples with thin rendering on thermal insulation where we will investigate the influence of different abiotic factors. By this we hope to understand the mineral façade as a biological habitat and learn more about the organisms living there and which abiotic and biotic factors that control growth on façades.

Key words

List of symbols

A	Surface area	m^2
C	Heat capacity rate	W/K
c	Specific heat capacity	J/kg·K
D	Diffusivity	m^2/s
d	Thickness	m
E	Emissive power	W/m^2
E_b	Black body emission power	W/m^2
g	The rate of evaporation	Kg/m^2·s
ΔH_w	Heat of evaporation of water	KJ/kg
h	Heat transfer coefficient	W/m^2·K
I	Incoming radiation	W/m^2
J	Moisture flow	Kg/m^2·s
k_p	Permeability	Kg/m
m	Mass	kg
P_w	Pore water pressure	Pa
Q	Heat transfer	W
q	Heat flow	W/m^2
R	Thermal resistance	m^2·K/W
T	Temperature	K
T_E	Effective sky temperature	K
u	Moisture ratio	Kg/kg
u	Speed of wind	m/s
V	Volume	m^3
v	Water vapour content	Kg/m^3
w	Moisture content	Kg/m^3
Z	Moisture transport resistance	s/m
α	Absorptivity	
δ	Vapour permeability	m^2/s
ε	Emissivity	
η	Dynamic viscosity	Ns/m^2
θ	Angel between surface and incoming radiation	rad
λ	Thermal conductivity	W/m·K
λ	Wavelength	nm
ρ	Density	Kg/m^3
ρ	Reflectivity	
σ	Stefan-Boltzmann constant	W/m^2·K^4
τ	Transmissivity	
φ	Relative humidity	%
	subscripts:	
a	air	
con	convection	
cd	conduction	
dew	dew point	
diff	diffusion	
dry	dry	

e	outdoor	
f	fictive	
i	indoor	
l	liquid	
lw	long waved	
m	mean	
moist	moisture	
sat	saturation	
sw	short waved	
w	surface	
1	layer 1	
2	layer 2	
12	point between layer 1 and layer 2	

List of content

1 Introduction

During the last years there has been reported considerable and rapid contamination on newly built rendered façades in Sweden due to biological growth. All though every material in nature most likely will be contaminated with time, it is not usual to see mineral building façades considerably contaminated after only a few years. The problem is believed to occur mostly on façades of render applied on thermal insulation, but apart from this it is difficult to find clear relationships indication which façades might be infected. Several attempts have been made to explain the growth, often adjusted to suit different interests. Following suggestions has been made:

- The modern surfaces layers contains less effective biocides and/or more organic components
- The modern well insulated walls reach a higher moisture level, which favours biological growth
- Our environment is more polluted as well as the climate gets warmer and more humid

The aim of this project is to explain why certain façades gets heavy biological growth while other seemingly similar do not. We will do that with comparing biological knowledge with building physical and -technical knowledge. More strictly by investigate which organisms we find on facades and try to explain under which biotic and abiotic conditions is crucial for growth. We will do that with both *in-situ* and *in-vitro* studies. One of the major approaches in this project is to investigate building façades with our knowledge from building physics and biology. The following sections will therefore give an introduction to the building physics and biology necessary to give a fundamental background for understanding the subjects in this project.

2 Building physics

The chapter of building physics is written on the basis of different books which all used different symbols (Claesson et al., 1984; Hagen, 1999; Nevander and Elmarsson, 1994; Sandin, 1996). The symbols used in this chapter can be found in the list of symbols on the pages ix-x.

In northern part of Europe it is colder outdoors than indoors most of the year. It is therefore important to prevent heat loss from the inside to the outside of a building not only to save energy, but also to avoid condensation on surfaces and low surface temperatures. The thermal insulation of the external wall of a building is therefore a very important technical question. This is reduced through increased thermal insulation.

2.1 Heat transfer

Heat can be transported by conductivity, convection and radiation and additionally also in connection with moisture transport. In a non transparent and non porous material like metals thermal conductivity is the only way heat can be transferred. If the material is transparent as for example glass, radiation will also transfer some of the heat energy. Convection will influence the heat transport if materials like gasses and liquids are in motion. In porous materials all transport mechanisms of heat transport occurs.

2.1.1 Conduction

Conduction is the transfer of thermal energy in solids or fluids at rest. In a homogenous non-liquid material with a surface area (A) and a thickness of d and with a temperature difference on each side of the material (see figure 2.1), the quantity of heat (Q) is given by Fourier's law:

$$Q = -\lambda A \frac{T_2 - T_1}{\Delta d}$$
(eq. 2.1)
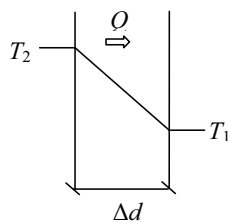
Figure 2.1 Heat transfer in a solid material in stationary conditions gives a linear temperature gradient from high to low temperature

The thermal conductivity (λ) is a materials property that indicates how well a material conducts thermal energy. The higher value of thermal conductivity the better is the materials conduction abilities. It should be noted that thermal conductivity varies with temperature and moisture, but in practical cases, where temperature differences is

3

small, the influence of temperature is often neglected. In practical cases calculations of heat transport are often made on a per-unit-area basis for areas of any size. Therefore the heat flux q is used instead of the heat transfer Q as the heat flux is the heat transfer that occurs over a unit area:

$$q_{cd} = -\lambda \frac{T_2 - T_1}{\Delta d} \qquad \text{(eq. 2.2)}$$

The quotient $\frac{\lambda}{d}$ equals the thermal resistance R for a layer. For an external wall with several layers placed between the indoor (T_i) to outdoor (T_e) temperature we write:

$$q_{cd} = \frac{(T_i - T_e)}{\Sigma R} \qquad \text{(eq. 2.3)}$$

ΣR is the total thermal resistance through the construction and includes the boundary resistances R_e and R_i for the outside and the inside respectively.

2.1.2 Convection

Heat transfer by convection is the mechanism by which thermal energy is transferred between a solid surface and a moving fluid like air. The movements can be caused by differences in air densities because of temperature variations (natural convection) or by the wind or ventilation systems (forced convection). The convective heat flow rate is given by:

$$q_{con} = h_{con}(T_w - T_a) \qquad \text{(eq. 2.4)}$$

Equation 2.4 is also called Newton's law of cooling.

The convective heat transfer coefficient (h_{con}) is not a thermal property like thermal conductivity and can therefore not be found as table values. The value depends highly of factors on circumstances of the natural- and forced convection at the surface. A façade is most of all exposed to different wind condition and the value can be determined as followed:

Windward weather side (speed of wind $u \leq 10$ m/s):
$$h_{con} = 5 + 4.5u - 0.14u^2 \qquad \text{(eq. 2.5)}$$

On the leeward (speed of wind $u \leq 8$ m/s):
$$h_{con} = 5 + 1.5u \qquad \text{(eq. 2.6)}$$

Notice in calm weather: $h_{con} = 5$.

2.1.3 Radiation

Unlike conduction and convection radiation does not require a medium. This is because radiation is thermal energy transfer by electromagnetic waves, which can

travel through a vacuum. All materials with a temperature above absolute temperature radiate thermal energy continuously in form of electromagnetic radiation from its surface at many different wavelengths. The electromagnetic spectrum covers an enormous spectrum of wavelengths from γ-radiation to radio waves (see figure 2.2). Notice that visible light also is a part of electromagnetic radiation.
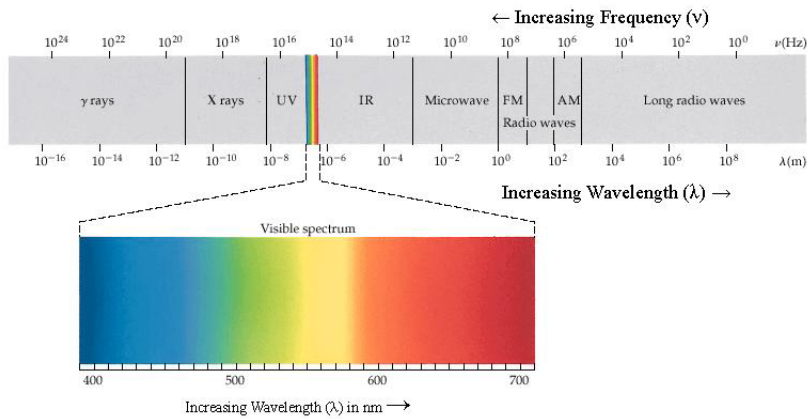
Figure 2.2 Spectrum of electromagnetic radiation. Picture taken from Wikipedia: The free encyclopedia on www.wikipedia.org

In practical cases we divide thermal radiation in two types; radiation from the sun and other sources of light that emits from sources of radiation with a high temperature (sunlight has approximately a black-body spectrum that indicates its temperature is about 6000 K) and has a short wavelength (q_{sw}), and thermal radiation from surfaces with a temperature range from approximately -100°C to 100°C and have longer wavelength (q_{lw}).

The maximum radiation (also called emissive power) a material can emit is given by the Stefan-Boltzmanns equation:

$$E_b = \sigma \cdot T^4$$
(eq. 2.7)

A material that absorbs all incoming electromagnetic radiation by this relation is called a black body. As seen from the above equation, the emissive power (same units as heat flow rate) from a black body is proportional to the forth number of the body's temperature and has therefore not a linear relationship like conductive and convective heat transfer to the temperatures. This means that radiation can be a very dominant heat-transfer mechanism if high temperatures are involved. As no material is "black" the emission from a materials surface at a certain temperature can not exceed the emission from a black body at the same temperature. When electromagnetic radiation hits a material surface different fraction of it will be absorbed, reflected and transmitted dependent of the material and the wavelength and the direction of the electromagnetic radiation. The portions of incoming thermal radiation that are absorbed, reflected and transmitted are called absorptivity (α), reflectivity (ρ) and transmissivity (τ), respectively (figure 2.3). According to the first law of

5

thermodynamics (energy conservation), the incoming radiation upon a surface must be equal to the radiation absorbed, reflected and transmitted:

$$\alpha + \rho + \tau = 1 \qquad \text{(eq. 2.8)}$$
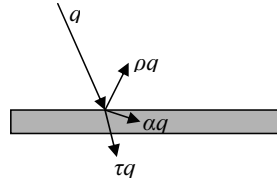
Figure 2.3 Illustration of absorbed (α), reflected (ρ) and transmitted (τ) parts of incident electromagnetic radiation emission by a material

2.1.3.1 Long-waved thermal radiation

As mentioned before, only a black body absorb all incoming electromagnetic radiation. The radiation property that enables us to compare a material with a black body is called is called emissivity (ε). Emissivity is a function of temperature, wavelength and direction of the emitted thermal radiation, but for simplicity, we regard ε as a average emissivity of all wavelengths and all directions. As emissivity is the ratio of thermal radiation emitted by a material to the thermal radiation emitted by a black body at the same temperature we have:

$$\varepsilon = \frac{E}{E_b} \qquad \text{(eq. 2.9)}$$

The emissivity is a strong function of surface condition. Some values from different building materials are given in Table 2.1.

Table 2.1 Values for the emissivity for different materials. Values taken from (Sandin, 1996)

Material	ε_{lw}
Gold, polished	0.02
Aluminium, polished	0.05
Aluminium, practical value	0.30
Steel, polished	0.27
Steel, corroded	0.61
Paint, white	0.85
Wood	0.90
Glas	0.92
Mortar	0.93
Paper	0.93

Measuring heat flux from long waved radiation (q_{lw}) the emissivity needs to be known as well as the absorptivity. In practical cases we determine the emissivity and the absorption coefficient to be equal by Kirchoff's law.

Kirchoff's law: $\alpha_{lw} = \varepsilon_{lw}$ \qquad (eq. 2.10)

Kirchoff's law of thermal radiation states that at thermal equilibrium, the emissivity of a body (or surface) equals its absorptivity. This is true for an opaque material ($\tau = 0$) at every temperature of the surface. Emissivity is a function of the surface temperature of the material whereas absorptivity is a function of the temperature of the thermal radiation source, but in practical cases where the thermal radiation radiates from a material with a certain temperature within the same range as the temperature in air we can determine Kirchoff's law to be valid in our cases also.

The heat flux from long waved thermal radiation of a surface at room temperature is given by the difference between absorbed and emitted thermal radiation.

$$q_{lw} = \alpha_{lw} \cdot I_{lw} - \varepsilon_{lw} \cdot E_b \qquad \text{(eq. 2.11)}$$

In cases of material surfaces with the temperature T_w we have the emission power E_b from equation 2.7:

$$E_b = \sigma \cdot T_w^{\,4} \qquad \text{(eq. 2.12)}$$

Analogously the incoming long waved thermal radiation is:

$$I_{lw} = \sigma \cdot T_f^4 \qquad \text{(eq. 2.13)}$$

T_f is a fictive temperature called the effective sky temperature that always has the same thermal radiation as the surroundings. At fully overcast T_f is equal to T_a, but at conditions with a clear sky the effective sky temperature can be measured by following approximation:

At horizontal surfaces:
$$T_f = 1.2 \cdot T_a - 14 \qquad \text{(eq. 2.14)}$$

At vertical surfaces:
$$T_f = 1.1 \cdot T_a - 5 \qquad \text{(eq. 2.15)}$$

In equation 2.10 we stated that emissivity equals absorptivity. By reorganize equations 2.11-2.13 we have the heat flux from long waved thermal radiation:

$$q_{lw} = \varepsilon_{lw} \cdot \sigma \, (T_f^{\,4} - T_w^{\,4}) \qquad \text{(eq. 2.16)}$$

In practical cases in building physics where temperature differences are a within a small narrow range, we make some mathematical approximations and thereby converting equation 2.16 to a linear equation with the use of a radiation heat transfer coefficient h_{lw}:

$$q_{lw} = h_{lw}(T_f - T_w) \qquad \text{(eq. 2.17)}$$

$$h_{lw} \approx 4 \cdot \varepsilon_{lw} \cdot \sigma \cdot T_m^{\,3} \qquad \text{(eq. 2.18)}$$

$$T_{\text{m}} = \frac{T_{\text{f}} + T_{\text{w}}}{2}$$
$$\text{(eq. 2.19)}$$

2.1.3.2 Short-waved thermal radiation

In practical cases the value of the emission from solar radiation (q_{sw}) can be determined without knowing the emissivity. The absorptivity for solar radiation is called α_{sw} and some values for normal used buildings materials are shown in Table 2.2. The values of α_{sw} correspond to what we understand as light and dark surfaces.

Table 2.2 Values of the absorptivity for different materials. Values taken from (Claesson et al., 1984)

Material	α_{sw}
White color	0.15
Surface with white lime	0.2
Red bricks	0.75
Concrete	0.6-0.7
Asphalt	0.93

The heat flux from short waved radiation is then:

$$q_{\text{sw}} = \alpha_{\text{sw}} \cdot I_{\text{sw}} \cdot \cos(\theta)$$
$$\text{(eq. 2.20)}$$

Radiation from the sun can cause high surface temperature. The color of the surface is decisive for the surface temperature. If a façade is white ($\alpha_{\text{sw}} = 0.3$) instead of red ($\alpha_{\text{sw}} = 0.9$) the sun absorption will decrease by 2/3, and the surface temperature will also decrease.

2.1.4 Moisture dependent heat transfer

The moisture dependent heat flux is given by:

$$q_{\text{moist}} = \Delta H_{\text{w}} \cdot g$$
$$\text{(eq. 2.21)}$$

The moisture dependent heat transfer is often neglected in heat balance calculations and will not be further described.

2.1.5 Total heat flux

At stationary conditions the heat flux balance at the outer surface is given by:
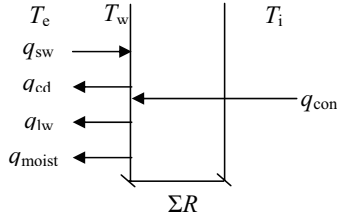
Figure 2.4 Heat balance of a construction at stationary conditions

$$q_{sw} + q_{con} = q_{cd} + q_{lw} + q_{moist} \qquad \text{(eq. 2.22)}$$

By combining the equations 2.3, 2.4, 2.17, 2.20 and 2.21 we have following equation for heat balance at an external surface:

$$\alpha_{sw} \cdot I_{sw} \cdot \cos(\theta) + \frac{(T_i - T_e)}{\Sigma R} = h_{con}(T_w - T_a) + h_{lw}(T_f - T_w) + \Delta H_w \cdot g \qquad \text{(eq. 2.23)}$$

From equation 2.23 we can calculate the surface temperature of an external surface:

$$T_w = \frac{\alpha_{sw} \cdot I_{sw} \cdot \cos(\theta) + \dfrac{T_i}{\Sigma R} + h_{con} \cdot T_a + h_{lw} \cdot T_f - \Delta H_w \cdot g}{\dfrac{1}{\Sigma R} + h_{con} + h_{lw}} \qquad \text{(eq. 2.24)}$$

2.2 Heat capacity

In non-stationary conditions we have to take a materials heat capacity (C) into account. C is determined by the amount of heat needed to change the temperature by 1K. The heat capacity of a material with the mass m is calculated by:

$$C = m \cdot c \qquad \text{(eq. 2.25)}$$

The heat capacity of a certain construction is the sum of the heat capacities of its parts and approximately, the heat capacity of a humid material is the sum of the heat capacity of the dry material and the heat capacity of the absorbed water. Though, this is not completely exact, because of the fact that there is an interaction between the water and the material that changes the heat capacity of the material. Compared to construction materials, water has a high specific heat capacity (4.185 J/g·K), and consequently the heat capacity depends on the moisture condition of a construction. The heat capacity of a material has a high influence on the materials response to for example temperature variations. A construction with high heat capacity can store a large amount of heat, and is said to have high thermal inertia (volumetric heat capacity), and then has lower temperature variations compared to a construction with lower heat capacity when the temperature varies. A construction with high heat capacity is therefore said to have a temperature dampening effect.

The T_w will also be influenced by the moisture content in the materials, as thermal conductivity and heat capacity increases with increasing moisture content and that

9

energy is used to evaporate moisture from the wall. These factors will have a reducing effect on the extreme surface temperatures.

Equation 2.24 is applicable in calculations of extreme surface temperatures on constructions with low heat capacity. If the heat capacity is high the construction will not manage to get in equilibration with the air (figure 2.5).
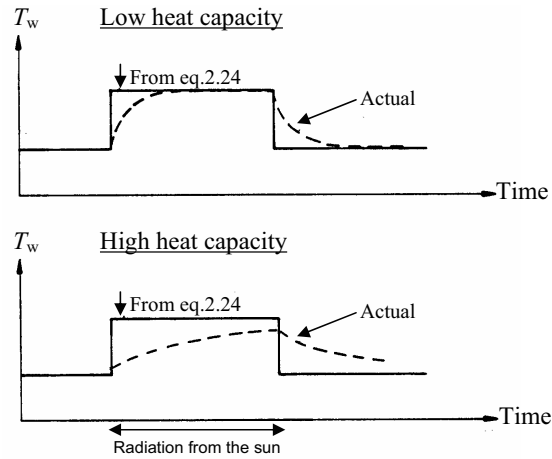
Figure 2.5 Influence of heat capacity on the surface temperature with incident radiation from the sun

Consider a night with a clear sky, when the air temperature decreases rapidly. On external façades the surface temperature with a high heat capacity will be significantly higher than the air temperature (figure 2.5). On external façades with a low heat capacity the temperature of the surface will be close or even lower than the air temperature. This means that the relative humidity on the surface of the external façade with low heat capacity will be higher and increase the risk for microbial growth. The lower the heat capacity of the façade is, the lower the temperature of the surface and the higher risk for high relative humidity or even condensation on the surface.

2.3 Moisture

2.3.1 Moisture in air

The air that surrounds us is a mixture of different gases and water vapour. The water vapour content (v) in air varies with the time of the year and the temperature and is normally measured as mass water vapour per volume of air. At a certain temperature the air can only contain a certain amount of water vapour, the saturation vapour content (v_{sat}). If the amount of water vapour exceeds this limit, the water vapour condenses as water drops. The temperature where the water vapour content equals the saturation vapour content is called dew point (T_{dew}). How much water vapour the air actually contains at a certain temperature in relation to the maximum possible amount at that temperature is called the relative humidity, RH (φ). The relative humidity is the actual water vapour content divided by the saturation vapour content at the temperature in question:

$$\varphi = \frac{v}{v_{sat}}$$

(eq. 2.26)

Relative humidity is often expressed as a percentage.
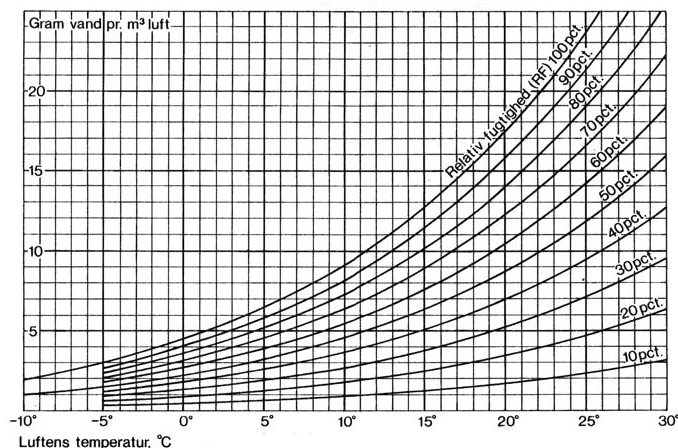
Fig 2.6 Relationship between water content, temperature and relative humidity

2.3.2 Moisture in materials

Most building materials contain some absorbed water, which can be more or less strongly attached to the material. From a building physical point of view the water is either chemically or physically bond to the material. The chemically bond water is strongly fixed to the material and should not be included in the concept of moisture. What we usually mean by moisture in materials is the physically bond water, which also can be called evaporable water. The evaporable bond water is can be determined as the water that can evaporate on drying at +105°C. However, for at material such as gypsum, the weakly bound crystal water molecules may be released at + 45°C. Water

11

vapour can be absorbed in materials by different processes. In wood hydrogen bonding between the cellulose and water is the most important process. In mineral based materials surface adsorption at low relative humidity and capillary condensation at high relative humidity are most important.

How much water a certain material contains is usually described either as moisture ratio (u) or moisture content (w). For materials that changes in volume with moisture content, such as wood, the moisture ratio is used:

$$u = \frac{m - m_{dry}}{m_{dry}} \qquad \text{(eq. 2.27)}$$

For rigid materials such as mineral materials the moisture content is used:

$$w = \frac{m - m_{dry}}{V_{dry}} \qquad \text{(eq. 2.28)}$$

The relation between moisture ratio and moisture content is:

$$w = \rho \cdot u \qquad \text{(eq. 2.29)}$$

The equilibrium between moisture content in the material and relative humidity in the surroundings can be shown in a sorption isotherm. For most building materials the sorption isotherm depends on whether the moisture is being absorbed or desorbed. If the material is in drying condition the sorption isotherm is above the sorption isotherm of the same material when it is absorbing moisture (figure 2.7). This effect is called hysteresis. In addition, some materials sorption isotherms are temperature dependent. A higher temperature causes lower moisture content at a certain relative humidity.
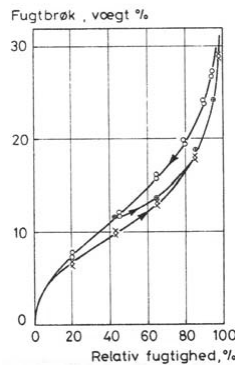
Figure 2.7 Sorption isotherm of a building material

2.3.3 Moisture transport
The flow of moisture in materials is possible both in the vapour phase through diffusion or convection or in the liquid phase by gravity, capillary suction and forces

from the wind. Moisture transport occurs often simultaneously in both vapour- and liquid phases.

2.3.3.1 Moisture diffusion

Diffusion is a process where water moisture molecules (and other gases as well) reduce differences in concentration. Diffusion of moisture in air is described by Fick's law:

$$J_{\mathrm{dif}} = -D\frac{\partial v}{\partial d} \qquad\qquad\qquad \text{(eq. 2.30)}$$

The diffusivity (D) is slightly temperature dependent and $\dfrac{\partial v}{\partial d}$ is the gradient in vapour content which is the driving force for vapour diffusion. In porous materials the diffusion flow rate is reduced, compared to diffusion in free air, but the process can be expressed analogously as:

$$J_{\mathrm{dif}} = \delta_{\mathrm{dif}}\frac{\partial v}{\partial d} \qquad\qquad\qquad \text{(eq. 2.31)}$$

In a homogenous construction with constant vapour permeability under stationary conditions, the flow is the same in every section in the construction and vapour content gradient will be linear through the wall (figure 2.7).
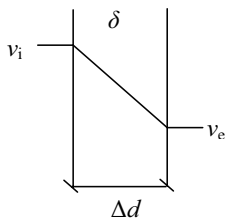
Figure 2.8 Distribution of vapour content in a homogenous material at stationary conditions

The flow rate through the wall is given by:

$$J_{\mathrm{dif}} = \delta_{\mathrm{dif}} \cdot \frac{v_{\mathrm{i}} - v_{\mathrm{e}}}{\Delta d} \qquad\qquad\qquad \text{(eq. 2.32)}$$

Analogously with the thermal resistances in heat transfer we can define a moisture transport resistance for a porous material, with the thickness *d*:

$$Z = \frac{d}{\delta} \qquad\qquad\qquad \text{(eq. 2.33)}$$

By using the moisture transport resistance we can describe the moisture transfer by diffusion as:

$$J_{\text{dif}} = \frac{v_i - v_e}{\Sigma Z}$$ (eq. 2.34)

The quantity of ΣZ consists of the vapour transport resistances both indoor (Z_i) and outdoor (Z_e) analogously to R_i and R_e, and the Z in every layer of a construction. Z_i and Z_e is often very small and is neglected.
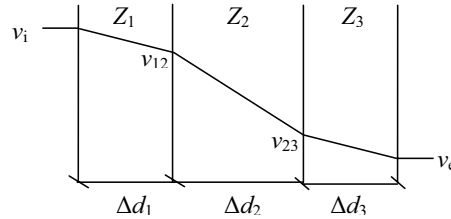
Figure 2.9 Distribution of vapour content in a construction with several layers

At stationary conditions in a multi layered construction the difference in vapour content over a specific layer is:

$$\Delta v_1 = \frac{Z_1}{\Sigma Z}(v_i\text{-}v_e)$$ (eq. 2.35)

The vapour content between two layers (figure 2.8) can be described as:

$$v_{12} = v_i \text{ - } \Delta v = v_i \text{ - } \frac{Z_1}{\Sigma Z}(v_i\text{-}v_e)$$ (eq. 2.36)

As temperature and vapour content values are approximately known from literature (Nevander and Elmarsson, 1994) the relative humidity can be calculated through the wall.

2.3.3.2 Moisture convection

The flow of moisture through convection involves water vapour being transported with an air flow. Differences in pressure on each side of a construction caused by wind, thermal forces and ventilation systems causes air and vapour to flow through the construction. The extent of convection of moisture is determined by the total pressure difference, the vapour content in air and the tightness of the construction. If an air stream flows from higher to lower temperatures the air will be cooled, which can lead to condensation and moisture accumulation in a construction part. In this process convection and diffusion normally acts together and increases the risk for condensation. If an air stream flows from lower to higher temperature the air will be warmed and the relative humidity will decrease. This type of convection leads to desiccation. In a building the risk for condensation only occurs if there is an overpressure indoors and condensation occurs if the moisture content indoors (v_i) is higher than the saturation vapour content (v_{sat}) outdoors.

2.2.3.3 Capillary suction

The most important moisture transport mechanism in liquid phase is capillary suction. The driving mechanism for this process is the underpressure in the meniscii of the material. The liquid moisture flow id given by:

$$J_1 = -\frac{k_p}{\eta}\frac{\partial P_w}{\partial x} = -\delta_1\frac{\partial v}{\partial d} \qquad \text{(eq. 2.37)}$$

2.3.3.4 Total moisture flow

The total moisture flow is given by adding the diffusion moisture flow and the liquid moisture flow:

$$J = J_{dif} + J_1 = \delta_{dif}\frac{\partial v}{\partial d} - \delta_1\frac{\partial v}{\partial d} = -(\delta_{dif} + \delta_1)\frac{\partial v}{\partial d} = -\delta_{tot}\frac{\partial v}{\partial d} = \frac{\Delta v}{Z} \qquad \text{(eq. 2.38)}$$

From equation 2.38 we see that the total moisture flow is independent of the temperature.

3 Buildings with mineral façades

The construction of a house can be made of a vast number of materials. Present project concentrates on façades of mineral materials and mostly rendered façades, following section will describe the render as building material. A rendering is a layer of mineral material on an external wall and has been used in house constructions since ancient time (Murerfaget, 2001). It was very early discovered that the use of rendering on a façade of a house, had a lot of beneficial effects thereby increased the worth of the building. In Sweden the rendering originally was applied on the outside of masonry. Later it became a practice to render façade systems of wood also. Because of the energy crises in the 1970 many Swedish buildings had to be additionally insulated by placing external thermal insulation on the existing wall. A layer of rendering was then applied directly on the thermal insulation. In the 1980's this type of rendering on thermal insulation was also started to be used on new buildings (*pers. com.* Kenneth Sandin).

3.1 Rendering

The most important functions of the rendering are to protect the under-laying wall against climatic and mechanic influences and against fire (SBI-anvisning, 1981). At the same time you want the façade to have an esthetically satisfactory surface. The types of renderings are numerous, but even if mortar compositions, thickness of different layers and working techniques are countless, all mortars have the same type of components: aggregates, binders, water and often some admixtures. Aggregate is the major component of mortar and consists of sand or crushed rock in different shapes and sizes. These particles will, when mixed with the binder material and water (mortar paste), form a more or less fluid mass: the fresh mortar. The fresh mortar has to have a good workability. The amount of mortar paste is therefore important, because the more mortar paste you add the better workability fresh mortar you get. The fresh mortar gets a good workability because the mortar paste act as a "lubricant" between the mineral particles and decrease the friction between them. If the right hardening condition is present, the fresh mortar will start to harden. When the mortar starts to harden the mortar paste has another function than in the fresh mortar. In the hardened mortar the binder will act as an adhesive that binds the mineral particles together and ensure a good bond between the mortar and the wall. As the binder material often is weaker, less durable and has a higher shrinkage, it is also important never to add more binder than necessary. Shrinkage or swelling in a mortar is always caused by movements in the mortar paste. Therefore it has been necessary to develop leaner mortars (with less mortar paste). The good workability the fresh mortar must have is instead obtained by a more intensive mixing process, by changing the particle size in the ballast and by addition of different admixtures (plasticizers).

A traditional rendering system consists of three layers, with different composition and function in each layer. It is important that all layers work together satisfactory, so that the overall rendering system works as one unit. In normal renderings the three layers are called: spatter dash, under-coat and final-coat. The spatter dash is applied in a very thin layer. The function is to obtain a good adhesion to the existing wall. In addition the splatter layer should regulate the suction from the substrate. After the thin splatter layer the under coat is applied in several layers until the wanted thickness is reached. The function of the under-coat is to make the surface plane and give mechanical

strength. The under-coat also regulates the suction from the final coat, so that the surface of the rendering gets a homogenous structure. As final treatment a final-coat is applied. Pigments in mortars are normally used in the final coat. These pigments have to be resistant to light and alkali resistance. The final-coat is chosen after which characteristics of structure, color, gloss and evenness one wants the wall to have. As it is a final layer it has to resists all influences from the environment.

3.1.1 Components in render

The binder materials used for renders can either be hydraulic or non-hydraulic. Hydraulic binders harden by a chemical reaction with water (hydration) and are for example Portland cement, hydraulic lime and masonry cement. Non-hydraulic binders harden by carbonation, a reaction with the CO_2 in the air, and are for example air lime In practical cases most binders for renderings in Sweden are combinations of cement and air lime.

In the practical use of mortar the different types are described by abbreviations of the binder used (Swedish abbreviations in parentheses):

L - Air lime (K)
L_h – Hydraulic lime (K_h)
C – Portland cement (C)
CL –Portland cement and lime (KC)
M – Masonry cement (M)
G – Gypsum (G)

3.1.1.1 L-mortar

In an L-mortar air lime is the only binder and therefore the material hardens by carbonation. But actually the hardening of an L-mortar consists of two processes. As the mortar needs to have a certain water content (between 0.5-6 weight% corresponds to a relative humidity of 50-80%) before carbonation can take place, the mortar needs to dry as the initial fresh mortar has a higher moisture level. As the mortar dries, the number of open pores increases that makes the mortar open for CO_2 diffusion. When the water content and number of open pores is suitable the carbonation, the actual hardening process, can take place. In the carbonation process the CO_2 in air reacts with the calcium hydroxide crystals and forms calcium carbonate ($CaCO_3$). Because of the low CO_2 content in air, the carbonation process is slow (and will stop if there is no CO_2 present).

3.1.1.2 C-mortar

Cement is the only binder in a C-mortar and hardens by hydration, a chemical reaction between the cement and water. The product of the chemical reaction between cement and water builds an extremely fine porous cement gel that surrounds the surface of the cement particles. As this reaction takes place, the original space between the pores between the cement particles will be filled up with cement gel. At the same time the mortar paste will be more tighten and stronger. The beginning of the hydration is dependent on a high water level. If the water in the fresh mortar is removed because of heavy suction or evaporation, the hardening process is slowed

down or inhibited. When the chemical process has started it cannot be stopped and normal C-mortar of Portland cement therefore has to be used within 3-4 hours after water addition. A high relative humidity in air does not influence the hardening and the cement cures well under water, as it is a hydraulic binder. The main advantages in C-mortars are the fast strength development and a high final strength if the product hardens under right conditions. Its disadvantages are not so god workability and tendency of bleeding. Up to a certain limit the strength of a C-mortar increases with the cement content, but at the same time this also increases the shrinkage.

3.1.2.3 CL-mortar

In a CL-mortar the binder is a mixture of lime and cement. Even though these materials are quite different, they work well together, and by combining different amounts of each material it is possible to either bring out or suppress each materials characteristics whatever suitable. When a CL-mortar hardens, there is actually two different hardening processes taking place at the same time: the lime carbonates and the cement hydrates. The carbonation is as earlier mentioned a slow process and the hydration is a fast reaction. Each reaction can take place without influencing the other reaction, but the hydraulic binder in a CL-mortar is not that dependent on the water content in the mortar, and the cement will harden even if the water content is so high so that the lime cannot carbonate. The strength of a CL-mortar increase with the cement content (within certain limits) and the hardening will be faster, but at the same time the workability and the water retention will decrease. In practical use CL-mortar in the Nordic countries contain at least 50% cement.

3.1.2.4 M-mortars

The hardening of M-mortars is in principle the same as for C-mortars and should be treated as such.

3.1.2.5 G-mortars

Many different mortars containing gypsum exist, but in the Nordic countries it is only very few types which are used and then only indoors. G-mortars are soluble in water and are therefore not used outdoors in Nordic countries. The advantages of using G-mortar are no shrinkage when hardening (minimal risk for cracks) and a fast development of strength. On the other hand G-mortars are porous and can promote corrosion if one uses steel reinforcement together with G-mortars. In addition G-mortars must not be used together with Portland cement or hydrated lime because the formed chemical products expand and causes spalling.

3.1.2.6 Admixtures in mortars

Different admixtures have been used for a long time in the manufacture of concrete. In recent years similar products are more and more used in mortar production also. The admixtures used in mortar production are air entraining agents (for increasing frost resistance), wetting agents, accelerating agents, retarders and water repelling agents. Admixtures improve certain properties of a mortar, but they might also change other properties for the worse. It is therefore important to know how an addition of a certain admixture will influence a mortar. Most admixtures have commercial names

which most often say nothing about the chemical composition and it can therefore be very difficult to predict the influences they will have on mortars properties.

4 Biological part

As present project combines different biological approaches the following section will give an insight in some biological concepts that could be interesting to know as a background for understanding the project.

4.1 Introduction

The diversity of biological organisms is astonishing. If one takes a look in any ecosystem, one will find the world teeming with different organisms. It is easy to recognize all the different plants and animals, but looking more carefully one will also recognize some fungi and lichens, and with the help of a microscope, bacteria and other minute life forms. But it is not only the ecosystems that teems with different life forms, also for example your skin, your mouth and your intestine is home for a diverse community of bacteria etc. But why does there exist so many different organisms? What decides why a certain organism exists and why in a particular environment? Natural scientists have in many centuries tried to explain the characteristics, the differences and similarities among organisms and above all the diversity of life. In 1973 a orthodox Christian and biologist Theodosius Dobzhansky wrote: "Nothing in biology make sense except in the light of Evolution" (Futuyma, 1998). Evolution is per definition: "the development of new types of living organisms from pre-existing types by the accumulation of genetic differences over long periods of time" (Lawrence, 1995). However, the idea of evolution in biology did first enter the Western world in the 19th century (Futuyma, 1998). Before that, the prevailing view of living organisms was that each organism were individually created in the present form by a creator's (God's) perfect idea and therefore could not become extinct or develop in any sense. In the middle of the 19th century Charles Darwin and Alfred Russel Wallace simultaneously came up with the theory of evolution that became one of the most revolutionary ideas in Western thought. The new idea of evolution in the biological world was that all contemporary species are products of evolution; they all are related to each other and all have descended with modifications from a common ancestor over billions of years. According to this new theory the biological world was suddenly not static, but organisms (species) were changing over time. The new idea explained discoveries of fossils such as dinosaurs and mammoths, and even if the geologists already did understand the dynamic change during the long history of the earth, it was Darwin and Wallace that extended the paradigm to living organisms (including humans). The mechanism behind evolution according to Darwin and Wallace was natural selection. Natural selection is the idea that organisms with certain favorable traits are more likely to survive and reproduce than organisms with unfavorable traits. Natural selection is still thought to be one of the main mechanisms in evolution together with genetic drift (the statistical drift over time of allele frequencies in a finite population due to random sampling effects in the formation of successive generations). Every organism's environment can be thought of as everything that may affect its development, survival or reproduction. These factors are of both abiotic and biotic origin. Abiotic factors, such as temperature, light, water, mineral nutrients and salinity affects the organism's activity, whereas the biotic factors, such as food, competitors, predators, mutualists and so on affects the probability of survival or reproduction. Which aspects of the environment that are important to an organism vary from species to species and depends on the organisms evolutionary history.

4.2 Biological kingdoms

In trying to describe, naming and systemize all species the Swedish botanist Carolus Linnaeus (1707-1778) introduced the binomial classification system. This is the system classification biologists uses today and is based on a hierarchical classification and binomial nomenclature. The hierarchical classification is based on every organism being categorized at different levels. Each of these levels is referred to as a taxonomic category with increasing specificity. The hierarchy of the nature was based on kingdoms that were divided into phyla and they were divided into Classes which were divided into Orders and so on into Families, Genera (singular: genus) and Species (singular: species) (often supplemented with different sublevels). An example of the hierarchical classification system (modern human) is shown in figure 4.1.

Kingdom Animalia	Characteristics: Eukaryotic, usually multicellular, heterotrophic organisms that lacks cell walls. Examples: sponges, jellyfish, slime animals, round worms, animals with vertebrae, insects, flatworms, rotifers, molluscs
Phylum Chordata	Characteristics (at least in embryos): a notochord, a hollow dorsal nerve code, pharyngeal slits, an endostyle, and a muscular tail extending past the anus. Examples: sea squirts, tunicate- and lancelet worms, and all animals with vertebrae
Class Mammalia	Characteristics: presence of mammary glands, hair or fur and endothermic bodies. Examples: monotremes, marsupials, rodents, whales, bats, primates and a lot of extinct species
Order primates	Characteristics: a unspecialized body plan, a generalized dental pattern, five fingers, fingernails, eye orbit characteristics (postorbital bar). Examples: lemurs, monkeys, apes
Family Hominidae	Characteristics: Genetically at least 97% similarity. Examples: humans, chimpanzees, gorillas, orangutans
Genus *Homo*	Characteristics: All species except the modern human (*H. sapiens*) are extinct. Examples: *H. neanderthalensis, H. floresiensis* and *H. sapiens*
Species *sapiens*	Characteristics: modern humans

Figure 4.1 Linnaeus' classification system exemplified by the classification of the species of modern human

Linnaeus made a classification scheme based on three kingdoms of "organisms" known at that time. He distinguished the organisms of plants and animals as two different kingdoms (Vegetabilia and Animalia) but in addition he also treated the minerals as a distinct kingdom (Mineralia). Minerals are not living organisms and have not been included in a scientific classification system since. Since Linnaeus' time, there has been made several improvements in the classification system, since more and more new organisms have been discovered and described. We do not have a perfect classification system and scientists still come up with new suggestions even on the level of kingdom and higher, especially after molecular studies became available. Today it is generally accepted to have a classification system based on three domains: Bacteria, Archaea and Eucarya. Both Bacteria and Archaea consists of prokaryotic organisms, but are highly evolutionary diverse. The domain of Eucarya consists of

eukaryotic organisms and includes the kingdoms of Fungi, Animalia and Plantae that is very close related compared to the diverse groups of bacteria and Archaea (figure 4.2).
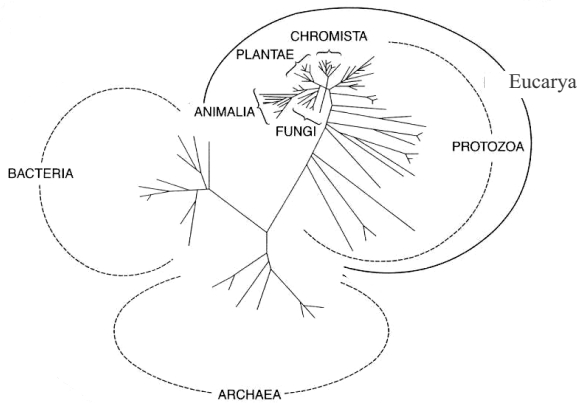
Figure 4.2 Phylogenetic tree of biological domains. The braches indicates evolutionary distances. Notice the compact group of plants, animals and fungi indication relatively close relationships compared with much greater evolutionary distances in the Protozoa, Bacteria and Archaea

The scientific name for every organism is based on the binomial nomenclature introduced by Linnaeus. This two-name system simply describes which genus and species an organism belongs to and is always given in Latin. For example the two living species of African elephants; the bush and the forest elephant, are much closed related and share the same genus name *Loxodonta*. But they are different species and therefore have different species names. The Latin names of the African bush and forest elephants are *Loxodonta africana* and *Loxonta cyclotis* respectively (the Asian elephant *Elephas maximus* is not so close related to the other two species and therefore belongs to another genus).

4.3 Metabolism

A key feature of living organisms is their ability to direct chemical reactions and organize molecules in specific structures. The term metabolism refers to all chemical reactions taking place within the cell. Cells are built up of different chemical substances and when a cell grows the chemcial substances increase in amount. The basic constituents of a cell come from outside the cell; the environment, and these substances are transformed by the cell to the characteristic constituents of which the cell is composed. On of the most important elements necessary in all knowing living systems is carbon, without it life as we know it could not exist. As metabolic processes are energy requiring, the cells must have means of obtaining energy. A lot of different strategies for carbon and energy metabolism have evolved and a reason for the enormous amount of living species is the different ways to optain and use different energy sources (Raven et al., 1992). It can be usefull to group organisms in metabolic classes, depending on the sources of energy and carbon metabolism they

use. Organisms using chemical compounds (respiration) or light (photosynthesis) as their primary energy source are called chemotrophs or phototrophs, respectively (see figure 4.3).

|		energy source		
		light	chemicals	
			inorganic	organic
carbon source	inorganic	photoautotrophs	chemolithoautotrophs	chemoorganoautotrophs
	organic	photoheterotrophs	mixotrophs	chemoorganoheterotrophs

Figure 4.3 Scheme of metabolic groups. As energy source both light and chemicals can be used and both organic and inorganic carbon can be used as carbon source

Chemotrophs can be further divided in chemolithotrops and chemoorganotrophs whether the carbon source used as energy source are inorganic (CO_2) or organic, respectively. Organisms capable of directly using CO_2 as carbon source in the carbon metabolism are autotrophs and organisms depending on an external organic carbon source is heterotrophs. Fungi uses organic carbon sources both for energy and carbon metabolism and are chemoorganoheterotrophs and green-algae using light for energy and CO_2 as carbon source are photoautotrophs.

4.4 Photosynthesis

Photosynthesis is the biochemical process in which autotrophic organisms convert light energy to chemical energy. The chemical energy is needed for maintenance, growth and reproduction. Photosynthesis is actually the route by which nearly all energy enters our biosphere, the only exception being some chemosynthetic bacteria (Raven et al., 1992)

The overall reaction in photosynthesis is:

$$CO_2 + H_2O + \text{light energy} \rightarrow CH_2O + O_2 + H_2O + \text{heat} \qquad \text{(eq. 4.1)}$$
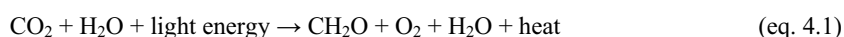
The CH_2O symbolizes a given carbohydrate that contains the chemical energy. The photosynthesis takes place in the chloroplasts in the cells, where chlorophyll and other photosynthetic pigments are arranged in light absorbing complexes called photosystems. The photosynthesis actually occurs in two stages, where only one stage needs light. In the light dependent reaction photons makes electrons in the photosystems move through a series of different complex reactions, thereby converting light energy to chemical energy. The electrons donated from the photosystems are replaced by oxidation of H_2O leaving O_2 as a waste product. In the light independent reaction the chemical energy harvested by the light dependent reaction is used to reduce CO_2 to organic compounds. The light independent reaction occurs through two processes; carbon fixation and the so called Calvin cycle. In carbon fixation CO_2 is fixed into larger carbohydrates. There a three different ways to do this among autotrophic organisms, but it all ends in the Calvin cycle, where the carbohydrate glucose is produced. Glucose can then be further converted to sucrose (for transport), cellulose (to build cell walls) or starch (for storage).

4.5 Respiration

All active cells respire continously, often absorbing O_2 and releasing CO_2 in equal amount, but the respiration process is actually a process that oxidizes organic compounds into CO_2 to generate energy by the use of an strong electron acceptor, normally O_2 (in aerobic conditions) which then is reduced to H_2O. The overall reaction in aerobic respiration is:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{heat} \qquad \text{(eq. 4.2)}$$

The respiration process is rather complex and consists of several distinct reactions. Most energy is released in aerobic respiration, but some organisms can use other electron acceptors such as NO_3^-, Fe^{3+}, SO_4^-, CO_3^- and even certain organic compounds. The respiration process is then called anaerobic respiration.

4.6 Gas exchange

One of the most used methods for measuring activity in autotrophs and especially lichens is measuring gas exchange. By measuring exchange O_2 or CO_2 in an organisms you can measure the physiological response to atmospheric conditions of moisture, temperature and light (Larson and Kershaw, 1975). Because of the relative low amount of CO_2 in the atmosphere compared to O_2, measurements of net photosynthesis and dark respiration in autotrophs have traditionally been carried out by means of CO_2 measurements (Nash III, 1996). In present project we have made literature studies of this method in lichen research. Numerous studies of gas exchange measurements have been carried out both in the laboratory and in the field for different lichens around the world (Brostoff et al., 2002; Kappen and Breuer, 1991; Larson and Kershaw, 1975; Reiter and Türk, 2000b, 2000a; Sundberg et al., 1999), especially by Lange and co-worksers (Bruns-Strenge and Lange, 1991; Hahn et al., 1993; Lange, Beyschlag et al., 1984; Lange, Kilian et al., 1984; Lange et al., 1985; Lange et al., 1990; Lange et al., 1991; Lange, Meyer et al., 1994; Lange, Büdel et al., 1994; Lange, Reichenberger et al., 1997; Lange, Belnap et al., 1997; Lange et al., 2004; Lange and Green, 2005). One disadvantage is however that gas exchange can be very difficult to measure, since growth rates of lichen thallus is extremely low and when studying lichen activity on a façade, the facade chemically characters has to be taken into account. Long-term studies of lichen photosynthesis production in nature are relatively rare primary because of the technical difficulties (Lange, 2002).

4.7 Chlorophyll fluorescence measurements

Another method for measuring activity in autotrophic organisms is to measure chlorophyll fluorescence. This alternative has been applied successfully for some time in photosynthesis research (Oxborough, 2004). The technique is based on the clear-cut relationship between chlorophyll fluorescence and the efficiency in photosynthetic energy conservation. When light is absorbed the photosynthesis pigment gets in an excited stage which results in either fluorescence chemical energy or heat, usually written by the equation:

$$\text{Incoming light} = \text{fluorescence} + \text{chemical energy} + \text{heat} \qquad \text{(eq. 4.3)}$$

Both fluorescence and heat is measured by the measuring technique and thereby the information of chemical energy can be obtained. If the autotrophic organism is photosynthetic active only a minor part of the absorbed light will emits as fluorescence.

4.8 Biological growth on a building façade

The genus of humans (*Homo* spp.) have over the last million of year increased incredibly in numbers and spread over the whole world, which have had a tremendous influence on the ecosystems on earth. Many biosystems have disappeared, but the human expansion has also created new "non-natural" biosystems. As some organisms can live on stones and vertical cliffs, the building of houses has then given new opportunities to expand by using buildings as habitats. These are often small organisms with low grow rate, but well adapted to these habitat. As for all other biological habitats the organisms growing on façades are dependent on different biotic and abiotic factors for their growth. The most important abiotic factor for growth on a façade is moisture (Sedlbauer et al., 2001). The organisms growing in this kind of habitat must be able to tolerate drought. There are in principle two ways in which organisms can survive drought. One is to store water and keep the biological processes running at a normal rate. The other way, which is used by organisms growing on façades, is to tolerate desiccation. During desiccation the biological processes are stopped, but they can be rapidly restarted when water is available again. The ability to tolerate desiccation (sometimes called anhydrobiosis) is not so common, but is widespread within all kingdoms (Alpert, 2006). It should be noted that desiccation tolerance is not the same as drought tolerance. Drought is low water availability in the environment of an organism, whereas desiccation is low water content in its cell (Alpert, 2005). The mechanism behind survival of desiccation is accumulation of disaccharides (mainly sucrose and trehalose), which enables the cells to stabilize the internal cell structure and maintain the cell integrity during the dehydration (Allison et al., 1999; Crowe et al., 1998).

4.9 Biofilm

The community of organisms we find on a façade is an accumulation of microorganisms at an interface forming a biofilm. A biofilm is an extremely complex microbial ecosystem that may consist of diverse amount of different microorganisms together with a matrix of organic and inorganic nutrient and extra cellular polysaccharide substances secreted by the cells (Kemmling et al., 2004). Formation of a biofilm often begins with the attachment of autotrophic organisms to a surface. These first colonist adhere to the surface initially through weak, reversible van der Waals forces, and if they are not directly separated from the surface again they can anchor themselves more permanently using cell adhesion molecules. The first colonists facilitate the arrival of other organisms by building a matrix that holds the biofilm together. It is the biofilm matrix rather than the organisms that is in immediate contact to the surface of the building material.

4.10 Biodeterioration

The publications of the ecological effects and biodeterioration of biological growth on stonework is numerous (Altieri and Ricci, 1997; Mansch and Bock, 1998; Piervittori et al., 1994, 1996; Piervittori et al., 1998; Sterflinger, 2000). Most researchers seems to be convinced that microorganisms can degrade stone and other similar substrates and that several organisms contain biomineralization products there may contribute to chemical weathering processes (Bjelland et al., 2002; Palmer et al., 1991; Shrivastav, 1998), but other researchers have daubed to what extent the organisms actually damage the façades on buildings (Gu, 2003; Prieto Lamas et al., 1995; Sterflinger, 2000). Some studies even shows that grow of lichens actually can protect the façade (Arino et al., 1995; Bjelland and Thorseth, 2002; Silva et al., 1999) or compensate for environmental stresses (Edwards et al., 1995; Edwards et al., 1997). Biodeterioration is defined as any undesirable change in the properties of a material caused by the vital activity of any organism (Morton and Surman, 1994) and can be mechanical, chemical (assimilatory or dissimilatory) or due to soiling. The mechanisms involved include acid and alkali production, alteration of surface properties, heat absorption and increased water retention, and direct penetration of filamentous microorganisms into the rock surface.

There has been a lot of work on identification and analysis of organism societies on historical monuments (Carballal et al., 2001; Crispim et al., 2003; Darienko and Hoffmann, 2003; Flores et al., 1997; Gaylarde and Gaylarde, 2000; Gaylarde and Gaylarde, 2005; Gorbushina et al., 2004; Lisci et al., 2003; Mansch and Bock, 1998; Ohshima et al., 1999; Ortega-Calvo et al., 1993; Ortega-Morales et al., 1999; Praderio et al., 1993; Prieto Lamas, Rivas Brea, 1995; Tomaselli et al., 2000; Zurita et al., 2005) and other stone substrates (Rindi and Guiry, 2003; Sanchez-Moral et al., 2005), but it is only within the last years the organisms on modern building façades are tried to be taxonomically investigated (Bagda, 2002; Hofbauer et al., 2003; Young and Urquhart, 1998).

4.11 Biological organisms on building façades

A short description of the different organisms you can find growing on building façades will be described in the following sections, but as lichens, algae and moulds are our main emphasis in this project, those organisms will be described more in details.

4.11.1 Mosses

Mosses belong to the kingdom of plants. They constitute a diverse group of rather simple, small plants that have many characteristics in common with green algae. In the classification system today, mosses are placed in a division of spore-bearing plants (Bryophyta). Mosses are photoautotrophic organisms; using light as energy source by photosynthesis. Mosses are found world wide, but often in rather moist and shadowed habitats. The moss lack the protective tissue (cuticula) to protect against sunlight which all plants posses, but desiccation tolerance is common within mosses (Oliver et al., 2005; Proctor and Tuba, 2002). Mosses do not have specialized conductive tissue like plants, but water absorption occurs directly and throughout the thin leaves and are like lichens poikilohydric organisms. That means the moss can

absorb water and mineral nutrition from the whole surface of the organism. In addition mosses do not have any roots, but uses small threads (rhizoids) to attach to a surface.

Figure 4.4 Grow of mosses on a façade

4.11.2 Algae

Algae are a polyphyletic group of eukaryotic organisms. They belong to several orders in the kingdoms of Plants and Protists. Most of them are aquatic, well known in freshwater and marine environments where they are completely dependent on liquid water. However, some algae, called terrestrial algae, can live in terrestrial environments as, for instance, in soil, on tree trunks or on building façades (Hoffmann, 1989). As they are autotrophic organisms they only need sunlight as energy source, and to be able to live in "extreme" habitats with frequent variations in abiotic factors, terrestrial algae have developed special morphological and physiological adaptations to cope with these stresses. For example have algae exposed to strong light developed pigmented materials to protect them against excessive sunlight. In addition, many terrestrial algae are also able to survive desiccation. The algae are then only metabolic active when appropriate combinations of abiotic factors are present. Some algae have developed symbiotic relationships with some fungi (then called lichens) and can therefore inhabit environments where unprotected algae would die. The algae we find on building façades are mostly green-algae, belonging to the division Chlorophyta, (Adam, 1990; Hofbauer, Breuer, 2003; Kastien, 1999). These algae form green to grey discolorations on façades, but a very characteristic red green-algae *Heamotococcus pluvialis*, which is a unicellular green-alga, who gets its red color from the pigment astraxanthin can also be found on façades. The coating of these algae gives the façade a reddish appearance (see figure 5.6 and 5.7).
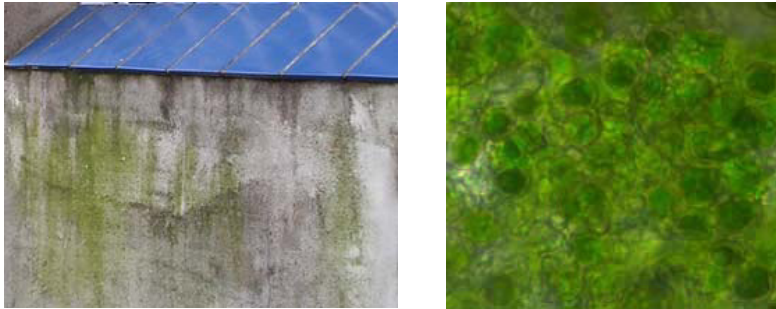
Figure 4.5 Left picture: growth of green algae on a wall. Right picture: green algae sp. seen in light microscope (x400)

4.11.3 Moulds

Moulds are an artificial group of microscopic, filamentous fungi. Fungi are not plants, and cannot do photosynthesis, but are heterotrophic organisms (like animals) and have their own kingdom. The most important factor for growth of mould is water availability, but they are also dependent on nutrients from the substrate. Different moulds have different requirements of water; some can live on a substrate with a water activity of 0.7, and survive long periods of desiccation (Ayerst, 1969). It is well known that many moulds can grow well on soiled substances if the right moisture conditions are available (Nielsen et al., 2000; Nielsen et al., 2004). The most common mould found on external mineral building façades are the black-colored mould *Cladosporium* spp. (figure 4.6), which is often found in air samples. Another common air-borne mould that can be found on building façades is *Alternaria* spp. Both these moulds are black because of the pigment melanin that protects them against strong UV-radiation.

Figure 4.6 Growth of moulds on a facade

Mould growing indoor is a well known problem because of the negative health effects of the inhabitants and a lot of models of assessing the risk for mould growth has been made (Ayerst, 1969; Smith and Hill, 1982). These models have most often been based on steady state conditions of temperature and moisture conditions). A german

scientist, Professor Klaus Sedlbauer, has made a lot of research to be able to predict spore germination and mycelial growth on various materials for a lot of different mould species as a function of temperature and relative humidity (Sedlbauer, 2001). Sedlbauer showed the correlation between temperature and relative humidity for spore germination and mycelial growth on different substrates in so called isopleth systems. An example for spore germination for different mould species is shown in figure 4.7. These isopleths it should be possible to predict the lowest risk for mould growth at a certain temperature and relative humidity on different building materials. As seen in figure 4.7 the correlation for spore growth between temperature and relative humidity differs between different species (and on different substrates). He divided the moulds into different hazardous classes after how hazardous they are regarded to human heath. The above figure on figure 4.7 is moulds which metabolic products are highly pathogen and the below figure is for moulds not dangerous to health. Such isopleths is only made for moulds in the indoor environment, but it is obvious that the germination and growth of moulds whether outside or inside a building is highly dependent on the right temperature and relative humidity conditions.

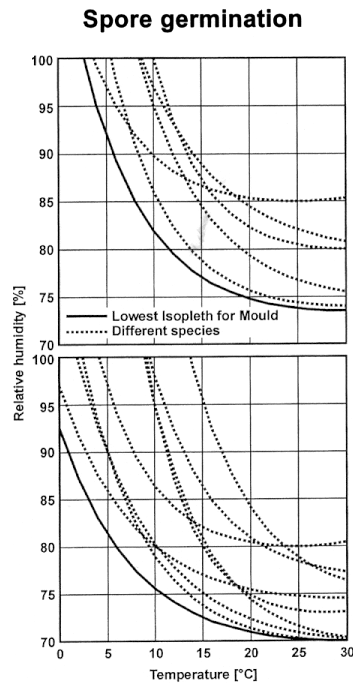*Figure 4.7 Isopleths for spore germination of different mould species. The above figure is moulds which has possible hazardous patogens for human health, the below figure is for moulds not dangerous for human health*

4.11.4 Lichens

Lichens are composite organisms, a symbiotic association of fungi (the mycobiont) and algae or cyanobacteria (the photobiont) that are lichenized in a unique

morphology. Lichens are by tradition described by the mycobiont and are therefore a part of the fungal kingdom (Greuter et al., 2000), but were in long time thought of as plants, just as fungi were. Linnaeus described them in 1775 as "poor trash of vegetation" (Ahmadjian, 1995), but as lichens are very advanced and well adapted to their environment this statement is not true. The lichen can grow where the fungi and algae alone can not survive, and they are found on almost every terrestrial substrate in the world and can tolerate different environmental stresses (Honegger, 1998; Kranner et al., 2003; Nash et al., 1990; Palmqvist, 2000; Smith and Molesworth, 1973) The unique morphology of lichens consists of several layers. The mycobiont forms a tissue within which the photobiont occupy a relative small volume in particular positions within the thallus. Figure 4.8 shows a cross section of a lichen thallus. At the top there is an upper cortex, a layer of fungal hyphae in a hydrophilic matrix (this structure can sometimes also be found in the bottom of the lichen, as seen on figure 4.8). Within this, the central part (medulla) provides a gas-filled zone of filamentous hyphae covered in a hydrophobic protein. The mycobiont is found in a layer at the lower side of the upper cortex. The medullary hyphae grow into the gelatinous sheath that surrounds the photobiont and the associated photobiont and hyphal cells become sealed together within the hydrophobic material.
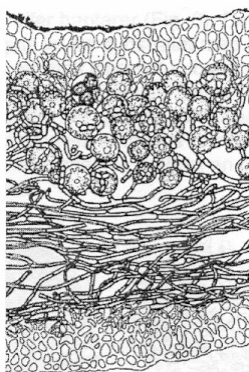
Figure 4.8 Cross section of a lichen thallus

In the unique symbiosis of lichens, the fungi surround and protects the algae against drought and excess light intensity, and the fungi get nutrients from the photosynthetically active algae (Nash III, 1996). The lichen symbiosis is considered obligatory for the mycobiont as regards growth and reproduction, but the significance for the photobiont is less clear. For some algae, the symbiosis may be obligatory for survival in a certain habitat, but in other cases, the symbiosis might not be an advantage for the algae. Therefore, it is not certain whether the lichen symbiosis should be referred as a mutualistic or a parasitic relationship.

Lichens are poikilohydric organisms, which means they react directly to changes in water availability in the surrounding environment (Nash III, 1996). Lichens do not, like leaves of higher plants, have an internal water supply through special transport tissue, but needs to remain exposed to their environment in order to allow natural moistening and drying. Lichens are desiccation tolerant and can therefore survive long periods of desiccation and return to an active, photosynthetic state within few hours with certain amount of water. Note though, that lichens with green-algae as

photobionts can extract moisture from non-saturated air and does not need the availability of free water (Lange et al., 1986). It is found that lichens respiration rate is highly influenced by thallus hydration, especially at the lower relative humidity, and does not occur in desiccated lichens (Lange and Green, 2005). The growth of lichens is often very slow, only a few mm per year (Nash III, 1996). Because whole lichens can not be readily grown in cultures, it is difficult to know the precise amount of different nutrients necessary for growth. Lichens living on mineral surfaces are in contact with inorganic nutrients but are also affected by dust from the air. Airborne dust can be incorporated in the lichen thallus and act as a nutrition source. Because many nutrients are affected by the pH of the substrate, the availability of nutrients can be very different from limestone to acidic substrates. As a consequence, we find very different lichen communities on different substrates. Mineral building façades are in general alkaline, and the lichens we find on building façades are therefore adapted to these conditions.

4.11.5 Bacteria

Bacteria are a group of genetic and metabolically diverse prokaryotic organisms that can be found in every ecosystem, some being chemotrophs others being phototrophs, but also many parasitic forms exists. Because of the very small size of bacteria (typically 0.5-5 µm in the longest dimension) they are easily spread by air. Bacterial coverings are usually not visible to the naked eye, but it is well known, that bacteria can establish growth on a mineral façade, where they can be present in large numbers on apparently clean surfaces (Gaylarde and Morton, 1999). Although bacteria seems to be common on mineral façades (Jahnke and priefer, 2002; Kiel and Gaylarde, 2006; Palmer et al., 1991) the study of these organisms are not a part of the present study.

4.11.5.1 Cyanobacteria

Cyanobacteria (formerly known as blue green algae) are a major kingdom of bacteria which are capable of fixing nitrogen from the atmosphere. On terrestrial substrates they are therefore often seen as pioneer organisms especially where the nitrogen level is low. Although cyanobacteria seemsto be common on mineral façades (Crispim, et al., 2003; Gaylarde and Gaylarde, 1998) the study of these organisms are not a part of the present study.

5 Experimental work

As present project is a multidisciplinary study within different disciplines of building physics and biology, a major part of this licentiate thesis have been literature studies. The experimental work described here, consists of both pilot projects and on-going long-term experiments to be presented in a doctoral thesis. I also describe investigations of building façades in Skåne, the southernmost province of Sweden.

5.1 Investigations of biological growth on building façades

We have investigated several buildings with discolored façades, mostly in Skåne, the southernmost part of Sweden. The discolorations on each façade were examined with a magnifying glass and samples were taken for further investigation under light microscope. The scope of these investigations is to identify which organisms we find growing on the façades. My personal identification skills include lichens, moulds, and to some extent algae, so even if other microorganisms grew on the façades (which they probably did) they are not included in this investigation. To look for other microorganisms, such as Bacteria and Archaea, demands completely different sample- and identifying techniques. In all cases the growth was always more widespread on the north- and west-facing façades and there was very seldom growth on the south-facing façade. The north-facing façade is more protected from the sun, and the moisture condition is therefore more suitable for growth. Therefore we always see more growth on the north-facing façade.

5.1.1 Höllviken

In Höllviken we had a case with newly built buildings with thin rendering on thermal insulation. After only a few years all facades had discolorations in varying degrees (figure 5.1). Generally the discolorations were more pronounced on the west- and north-facing façades compared to the south- and east-facing façade. The discolorations were more pronounced on some of the corners and at the first meter from the ground of the building, and were not covering the whole façade. It looked as if the growth was running down the façade in steps with increasing extent of discolorations. All discolorations were caused by unspecified uni-cellular green-algae (figure 5.2).

Figure 5.1 Façade of building with thin rendering on thermal insulation with green discolorations from a building in Höllviken

Figure 5.2 Picture of unicellular green-algae seen in microscope (x400)

5.1.2 Lund

In Lund we found an interesting building complex with houses of calcium silicate bricks, where almost all facades more or less covered with red discolorations (figure 5.3). The red discolorations are actually green algae (*Haematococcus pluvialis*) (figure 5.4). These algae produce a pigment called astraxanthin which gives the green-algae a red color.

Figure 5.3 Red discolorations on a façade from a building complex in Lund
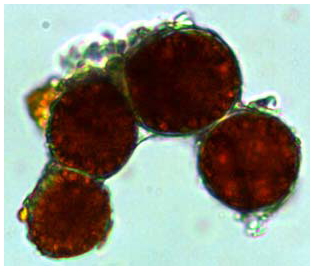
Figure 5.4 Haematococcus pluvialis *seen in microscope (x400)*

Closer investigations of the facades also showed a lot of other organisms growing on the facade (Figure 5.5). Some organisms grew only on the mortar, while others where growing on both calcium silicate bricks and mortar.

Figure 5.5 Calcium silicate brick wall with growth of several different organisms, mostly lichens

Some of the organisms were taken to further investigations under light microscope. A list of identified organisms can be seen in Table 5.1.

5.1.3 Läckö and Fågeltofta

The discolorations of the green-alga *Haematococcus pluvialis* can be very dominating on a façade as seen on the following pictures (figure 5.6 and 5.7) from the castle of Läckö, in the swedish province of Västergötland (the only objest in this study outside Skåne) and a building in Fågeltofta in Skåne. Notice the lack of growth under windows, due to the drier conditions.

Figure 5.6 Façade of castle in Läckö almost completely covered by Haematococcus pluvialis

Figure 5.7 Façade of building in Fågeltofta completely covered (except under windows) with Haematococcus pluvialis

5.1.4 Kristianstad

In Kristianstad we had a case with three buildings in the same area, all with rendered façades. Two of the buildings (building 1 and 2) was built with frames of aerated concrete and a rendering of 15 mm (figure 5.8 and 5.9) and the last building (building 3) was built with thin rendering on thermal insulation (figure 5.10).

Figure 5.8 Building 1 in Kristianstad with frames of aerated concrete. The yellow façade has dicolorations

Figure 5.9 Building 2 in Kristianstad with frames of aerated concrete. The red façade is without dicolorations

All buildings were built within the same time period and were around 5 years old in 2005. The only difference between building 1 and 2 was the color of the façade; building 1 is yellow and building 2 is red. As seen on the above pictures, the yellow building has discolorations on the façade, whereas the red building is clean. Investigations of the discolorations showed that unspecified lichen thallus was growing on the yellow façade.

The façades of building 3 were almost completely covered with discolorations, except under each window and at regularly placed small round "dots" approximately 10 cm in diameter (referred as "white dots").

Figure 5.10 Building 3 in Kristianstad with thin rendering on thermal insulation. The grey façade is almost covered with discolorations

We sawed circular holes in the rendering of building 3, both in areas with "white dots" and in the façade in areas with heavy discolorations. Underneath the rendering at areas with "white dots" appeared a plastic fastener with screws of steel (figure 5.11). The fastener is used to hold the thermal insulation to the structural wall behind. The fasteners were causing the "white dots" (see further information below).

Figure 5.11 Circular holes through the rendering of the façade of building 3. Left picture shows a fastener placed under a "white dot". The grey screw of steel holding the fastener plate is also seen. Right picture shows only thermal insulation at a place on the façade with discolorations

Another case in Kristianstad had the same problem with "white dots", but here we found a façade where the right half was very discolorated and with very distinct "white dots", but the left half had only minor discolorations (figure 5.12). Notice again the lacking discolorations under each window. We drilled holes in each half of the façade in areas of "white dots". Interestingly the fasteners in the right side were made of steel, whereas they were made of some black plastic material in the left side.

Figure 5.12 Façade of a building in Kristianstad. Left half of the façade with minor discolorations, right half completely discolorated and the "white dots" were very distinct

From our investigations we believe that the fasteners could be heat bridges in the construction, which then leads to a higher external surface temperature of the façade and therefore a lower surface relative humidity. The lower relative humidity could explain the decreased or lacking discoloration just in areas where the fasteners were placed.

The discolorations on both buildings in Kristianstad were caused by growth of unspecified lichen thallus (figure 5.13).

Figure 5.13 Growth of unspecified lichen thallus

5.1.5 Helsingborg

On the basis of a student project made in Helsingborg concerning biological growth on building façades we collected samples from various discolored façades in Helsingborg. One of the investigated buildings in Helsingborg was also a building with "white dots", but it was not possible to take samples from this building.

In Helsingborg ("Malen") we also found a morphologically different green-alga. Where most of the green-algae found were unicellular this one looked like a small package of four cells (Figure 5.14).

Figure 5.14 Green-algae sp. growing on wall from a façade ("Malen") in Helsingborg (left) and seen in light microscope (x400) (right)

5.1.6 Åkarp

In Åkarp we had an interesting case for 4 houses built in 2000 placed in a square as seen on figure 5.15. All these houses were with a construction of thin rendering on thermal insulation, and the houses were finished approximately one month after each other; beginning with house 1 in August 2000. House 2 and 4 have roof with projection, whereas house 2 and 4 have roofs that ends with the façade. House 2 is with a yellow façade, whereas the three other houses are in different white colours.
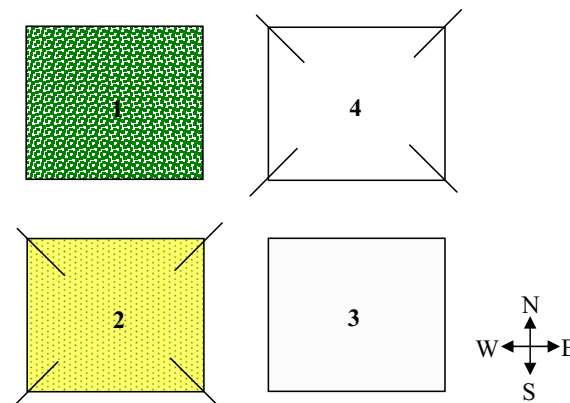
Figure 5.15 Overview of the four houses investigated in Åkarp. House 2 and 4 have roof projection. House 1 and 2 are heavily dicolored, whereas house 3 and house 4 only have minor discolorations. House 2 was built with a yellow façade, the others with white façades

House 1 had green discolorations covering the north-facing façade and a lot of growth could also be seen on the west-facing façade (see figure 5.16). The growth became very pronounced in 2004. At first sight and from a long distance house 4 looked clean, but on closer inspection it was possible to find growth on the north- and west-facing façades also, but not as pronounced as on house 1.

40

Figure 5.16 North-facing façades from two neighboring houses in Åkarp, built with same materials one month after each other in 2000. House 4 to the left, house 1 to the right

House 2 also had discolorations, mostly on the west-facing façade, though no growth was seen in a one meter zone from the roof and down on the façade, probably because of the roof projection. House 3 was not investigated. Interestingly the carport at house 1 was built later, but is also fully discolored.

5.1.7 Södra Sandby

In Södra Sandby we investigated a house with a lot of growth on almost every façade. Some discolorations were in addition seen in a somewhat strange pattern (see figure 5.17). Closer investigations of the discolorations showed that moulds were growing in cracks in the rendering. The rest of the discolorations were mostly caused by lichens and algae.

Figure 5.17 Façade of building in Södra Sandby

A full identification list of organisms found on the investigated buildings in Skåne is seen in table 5.1.

Table 5.1 List of all organisms found on investigated buildings in Skåne

Organism:	Latin name:	Found in:
Fungi	mould sp.	Södra Sandby
Green-alga	Green-algae spp.	Helsingborg, Höllviken,
Green-alga	*Haematococcus pluvialis*	Fågeltofta, Lund, Läckö
Lichen	*Caloplaca decipiens*	Lund, Södra Sandby
	Caloplaca holocarpa	Lund, Södra Sandby
	Candelariella aurella	Lund, Södra Sandby
	Catellaria lenticularis	Lund
	Lecanora albescens	Lund, Södra Sandby
	Leacanora campestris	Södra Sandby
	Leacanora conferta	Södra Sandby
	Lecanora dispersa	Lund, Södra Sandby
	Phaeophyscia nigricans	Södra Sandby
	Physcia tenella	Södra Sandby
	Verrucaria nigrescens	Södra Sandby
	Xanthoria parietina	Lund, Södra Sandby
	Lichen thallus spp.	Helsingborg, Kristianstad

5.2 Testhouse in Lund

A test house was built at the LTH area in Lund in 2004. The framework of the house and all interior parts consists of wood. The house is located with the longest façades facing north and south; each having 6 replaceable wall elements (1050 mm x 2100 mm).
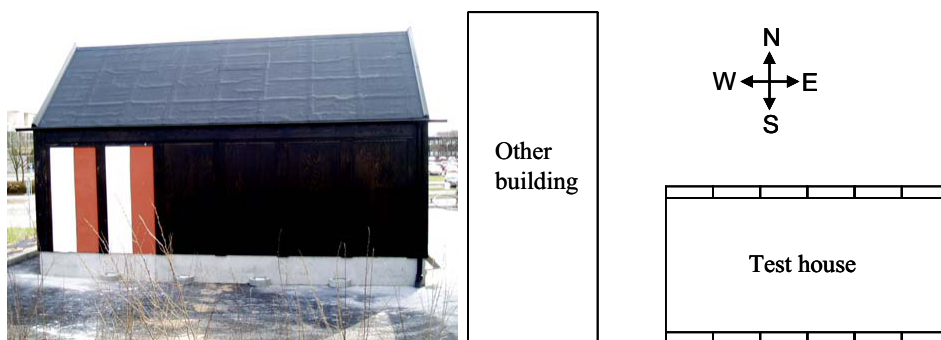
Figure 5.18 Test house in Lund. Picture to the left shows the north-facing side. To the right an overview of the test house seen from above

Figure 5.19 wall construction

5.2.1 Experiment 1

In April 2005 two façade elements on each side was built; one "heavy" and one "light" façade. The inner part of both façade elements were built up from a wooden construction of wood studs 45 mm c/c 600 mm with thermal insulation of mineral wool in between the studs and gypsum boards on each side. On the external gypsum board a 45 mm polystyrene thermal insulation was placed. Outside this, the heavy façade has a brick wall with a thin rendering layer applied on the brick wall, whereas the light façade has a thin rendering layer applied directly on the polystyrene thermal insulation. Both construction types have the same type of rendering system with a thickness of 3-5 mm. Half of each façade element has a final rendering layer with red pigments and the other half contains white pigments. For simplification following abbreviations for each façade element are used:

43

- **HR: red-colored heavy façade**
- **HW: white-colored heavy façade**
- **LR: red-colored light façade**
- **LW: light-colored white façade**
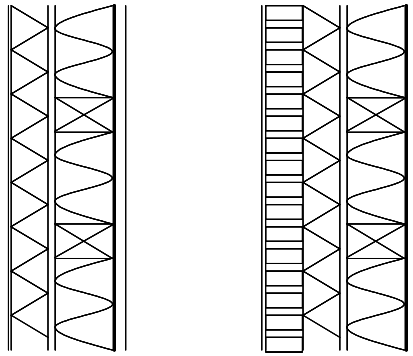
Figure 5.20 Sketch over the construction of the light (left) and heavy (right) façades.
The structure of the light façade from left (outside) to right (inside): 5 mm rendering,
50 mm polystyrene, 9 mm gypsum, 145 x 45 mm wood studs c/c mineral wool, 0.2 mm
vapour barrier, The only difference between the two constructions is the layer of
bricks between the rendering and the polystyrene thermal insulation in the heavy
façade

In each wall element sensors for measuring relative humidity and temperature was
mounted under the rendering, as close to the surface as possible. The ambient
temperature was also monitored with sensors placed above each façade element. The
relative humidity and temperature was monitored continuously every hour from April
2005 to September 2006 (still on-going measurements). In addition the temperature
inside the house was also measured.

To measure the effect of a strong heat bridge in the light façade, a self-constructed
"fastener" was produced of steel reinforcements and a plate of steel. In the light
façade temperature sensors were also placed on the surface of the fasteners.

5.2.1.1 Results of temperature measurements on south-facing façade elements
The surface temperatures on each façade element on the south-facing façade are
illustrated by the month of July 2006 (figure 5.21). The temperature distribution
between the different façade elements is similar throughout the year. Generally the
temperature varied more on the façades with thin rendering on thermal insulation than
on the brick wall façade. The temperature was always lower (difference up to 4 K)
during the night on the light façade than on the heavy façade. During daytime the red
façades reach the highest temperatures; the LR gets higher than the HR. The
temperature difference during daytime between the façades was more pronounced the
higher the air temperature was. In the winter months all façade temperatures were
almost the same day and night when the sun was not shining during daytime. The
highest difference between night and day temperatures was seen on the LR. In
October 2005 (data not shown) a temperature of 0.1°C was reached at 7:29 AM and at

13:29 PM the highest temperature for the day was reached of 60.6°C. The next morning the temperature was as low as -0.4°C. The highest temperatures on the façades was reached in July 2006 (see figure 5.20), where the LR reached a temperature during daytime up to 61.8°C. The LW reached a temperature of 44.6°C at maximum, also in July 2006. The lowest temperature on the LR and LW was -12.3°C for both façades reached in January 2006 (data not shown). During winter the LR reached a maximum temperature of 53.7°C (February 2006), whereas the HR only reached a temperature of 37.6°C.
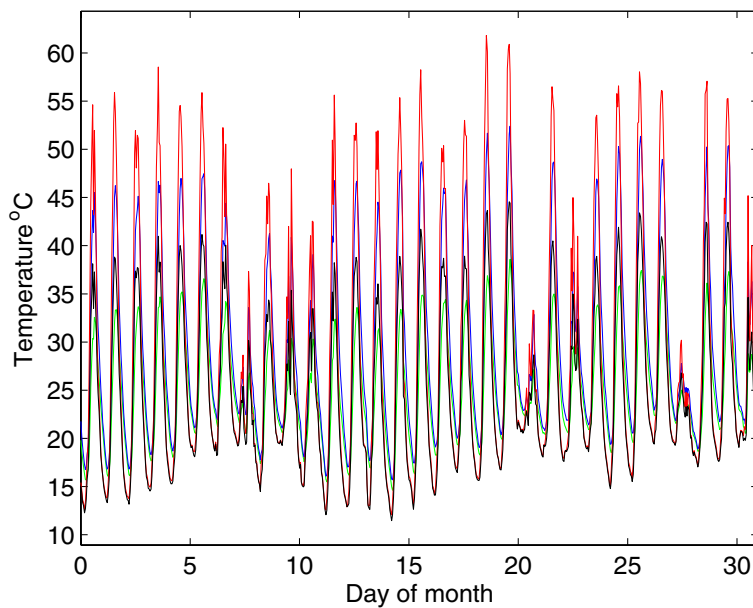
Figure 5.21 Results from temperature measurements from July 2006 on the south-facing façade. ___ HW; ___ HR; ___ LR; ___ LW

The temperature where the fasteners were placed was always a few degrees higher during night than the rest of the light façade. The difference was higher during winter than during summer. During daytime when it was not complete cloudy, it was still the red-colored facades that reached the highest temperatures, but the temperature on the fastener on the red-colored façade was lower than the red-colored façade itself. In wintertime during days with low temperature, the temperature distribution is the same as for nights.

5.2.1.2 Results of relative humidity measurements on south-facing façade elements
The results of the measurements of the relative humidity from July 2006 on the south-facing façades are shown in figure 5.22.

Figure 5.22 Results from relative humidity measurements from July 2006 on the south-facing façade. ___ HW; ___HR; ___LR; ___LW

The relative humidity showed similar patterns almost every day throughout the year. Typically the red-colored façades reached lower maximum relative humidity values compared with the white-colored façades both during day and night. Interestingly, when the temperature was low during daytime (compared with other days within same month), the relative humidity of the HR was lower than the relative humidity of the LR during night. During winter in cloudy days the relative humidity values of all façades were close to 100%, but when the sun was shining the relative humidity values declined significantly (data not shown). From November 2005 to January 2006 the relative humidity values of the LW were close to 100% day and night (data not shown). In the summer months, when the temperature during daytime was under 20°C, the relative humidity was above 90% day and night on the LW. For comparison, the HW often reached values of relative humidity below 80% during daytime in the summer months, even if the temperature was under 20°C. On warm days during summer the relative humidity on the red-colored façades was under 70% day and night. During daytime there was often a large difference in relative humidity between the white- and red-colored façades.

5.2.1.3 Results of temperature measurements on north-facing façade elements

On the north-facing façade the same temperature pattern during night was seen as for the south-facing façade; the light façade had lower temperature during night than the heavy façade. The temperature distribution in July 2006 on the north-facing façade is seen in figure 5.23. During daytime the red-colored façades reached the highest temperatures; the LR reached higher temperature than the HR. The HW reached the

46

lowest maximum temperature during daytime of all the façades. On the north-facing façade the difference in temperature during daytime between the HR and the LW was not as pronounced as on the south-facing façade. In addition, the difference between night and day temperatures on each façade was not as high as on the south-facing façade. Typically, the night temperature was higher the higher the temperature during daytime had been. The highest temperature we monitored on the north-facing façade was 36.7°C for the red-colored light façade in July 2006. The lowest temperatures on the north-facing façades were on the light façades in March 2006: -14.5°C and -14.2°C on the LR and LW respectively (data not shown). During winter when the temperature difference was small between day and night, the temperature differences on the north-facing façades were also small.
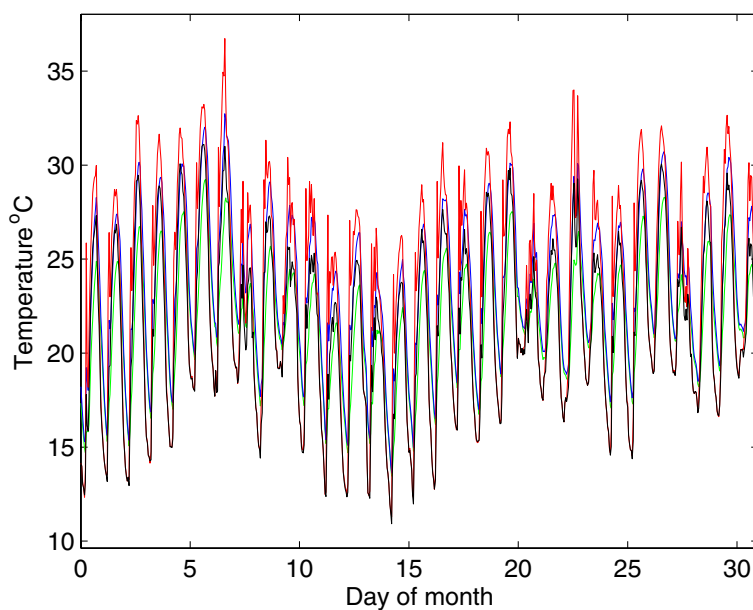
Figure 5.23 Results from temperature measurements from July 2006 on the north-facing façade___ HW; ___HR; ___LR; ___LW

The temperature distribution on the north-facing light façades with fasteners showed a similar pattern as on the south-facing façades. During night the temperature was a few degrees higher where the fasteners are placed than for the rest of the façade. During daytime the red-colored façades had higher temperature (up to 5 K higher) than the white-colored without fasteners, but during winter the temperatures of the HR were lower than the temperatures where the fasteners were placed (on both red and white façades) day and night. This means that the temperature of the fasteners were always higher than the temperature of the façades itself during winter.

47

5.2.1.4 Results of relative humidity measurements on north-facing façade elements

The results of the measurements of the relative humidity from July 2006 on the north-facing façade are shown in figure 5.24.
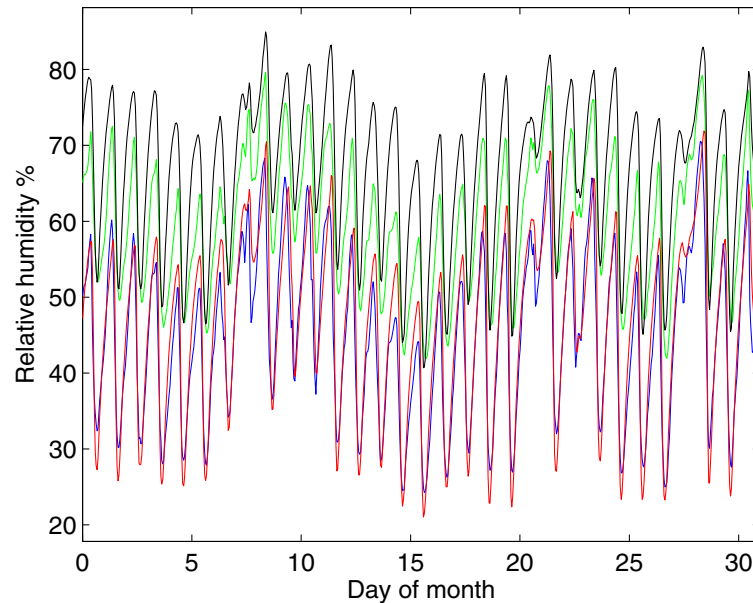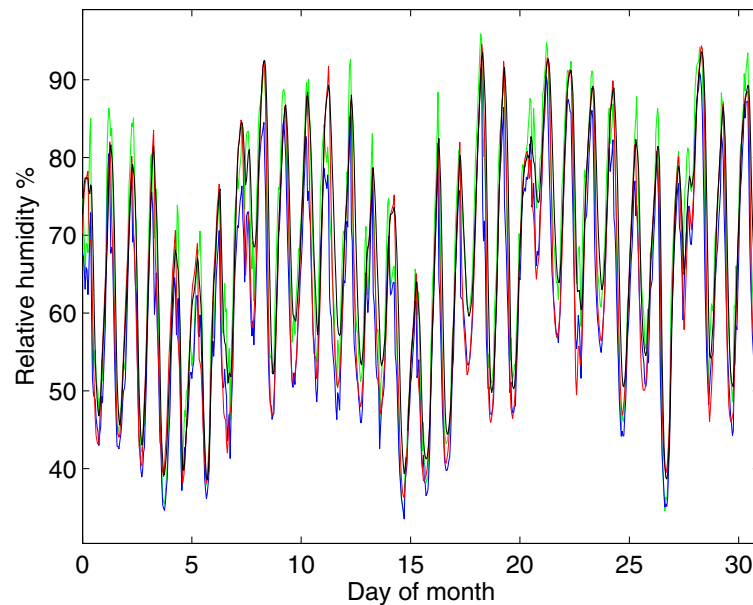

Figure 5.24 Results from relative humidity measurements from July 2006 on the north-facing façade. ___ HW; ___ HR; ___ LR; ___ LW

The relative humidity values are often lower for the red-colored façades during daytime, but there is no general pattern in relative humidity between the façades during nights other than the HR has a lower relative humidity than the other facades. All façades reached relative humidity values close to 100% almost every month (only exception is in July 2006, shown in figure 5.24) and the light façades have relative humidity values above 80% day and night from October 2005 to February 2006 (above 90% in November and December 2005). The HW had the largest temperature differences between night and day, with the highest relative humidity values during night and often the lowest values during day.

5.2.1.5 Discussion/conclusion –temperature measurements

The temperature and relative humidity measurements in experiment 1 show that light façades are more directly influenced by the weather conditions than the heavy façades. The temperature varied much more on the light façades than the on the heavy façades, especially on the south-facing facades, where the sun heats the surface by short-waved radiation. The color of the façades is also influencing the temperature conditions on the façade surfaces, especially during daytime. The LR gets warmer during daytime than the HW. This is not surprising, when we know that radiation from the sun causes high surface temperatures. As written in section 2.1.3, sun

48

absorption will decrease by 2/3, when the façade is white instead of red, and thereby the surface temperature decreases. The influence of solar radiation is also seen when we compare the south- and north-facing façades. The north-facing façades has lower maximum temperature than the south-facing façade all the year round, even the white façade. During nights there is no difference between the lowest temperatures on the light façades on the south- and north-facing façades. The light façades gets colder in the night then the heavy façades due to the lower heat capacity in the construction, whereas the heavy façades with the higher heat capacity can store the heat from daytime during night. Even if the HW reached the lowest maximum surface temperatures of all façades during daytime, it still has a higher night temperature than the light façades.

5.2.1.6 Discussion/conclusion –relative humidity measurements
During daytime the measured relative humidity values are in agreement with the temperature measurements; the red-colored façades, which had a higher temperature than the white-colored façades, have a significantly lower relative humidity with a difference of 20% relative humidity if it was not fully overcast. During night the heavy façades had higher minimum temperatures than the light façades, but if we look at the relative humidity values during night on the south-facing façades we see that the HW had a higher maximum relative humidity during night than the LR. The HW had the lowest maximum temperature during daytime, whereas the LR had the highest maximum temperatures, so even if the HW had a higher minimum temperature during night than the LR the maximum relative humidity values exceeds the maximum relative humidity values for the LR during night (approximately difference of 10% relative humidity).

The temperature measurements above the fasteners show that the fasteners are heat bridges that increase the façade surface a few degrees during night, but also in the winter on the north-facing façade during daytime. No relative humidity measurements have been made on the fasteners, but simulations of the relative humidity on façade surfaces with and without fasteners have been made and are described in section 5.2.3.

No growth has been discovered yet on the façade (November 2006) One of the factors we have not been looking at is how long time façades should have certain conditions to be suitable for growth. It will be interesting to take this into account also in future studies.

5.2.2 Experiment 2
In September 2005 the rest of the wall elements were built. These façade elements were built up from the same construction type as the first elements with a wooden construction with mineral wool as "skeleton" and with gypsum boards on each side. All new façade elements were applied with thin rendering on thermal insulation on the outside. The aim with experiment 2 is to follow any biological growth on façades with thin rendering on thermal insulation, when following different abiotic factors in the rendering is varied:

- Mineral or organic rendering
- With or without biocides
- Red or white surface colour

On each side (north and south) two façade elements were made with mineral rendering (element A and B) (with (A) and without (B) biocides) and the last two façade elements with an organic render (element C and D) (with (C) and without (D) biocides). Again the experiment is carried out with both red and white surface colour (figure 5.25).

Figure 5.25 Test house with four new façade elements (the south-facing side is shown); A: mineral rendering with addition of biocides; B: mineral rendering without addition of fungicides; C: organic rendering with addition of fungicides; D: organic rendering without addition of biocides

Because of a very cold autumn in 2005, the two last façades on the north side were not finished before April 2006. These wall elements were until then only covered with the polystyrene thermal insulation and the first layer of rendering (see figure 5.26).

Figure 5.26 The north-facing side of the test house in October 2005. The two façade elements without final rendering are completely wet

In September 2006 we discovered that the north-facing facades were completely wet (see figure 5.27) in the morning after a night with a clear sky. The relative humidity of the north-facing façade surfaces where then close to 100% day and night. Some mornings all elements were wet, some mornings only the east most ones were wet, probably because of the neighboring building protected the west most elements (see

figure 5.18) On the south-facing façades, the relative humidity were all under 100% RH (the red-colored façades are under 70% RH) during night.

Figure 5.27 The north-facing façade elements were wet as seen with a hand touching the façade the 14th of September 2006 at 8:30 AM.

We will observe these façades for signs on biological growth. Until now (November 2006) there is no visible growth.

5.3 Draft to article about fasteners in façades with thin rendering on thermal insulation

During the last years there has been reported considerable and rapid microbial growth on newly built rendered façades in Sweden. The problem has mainly occurred on thin rendering applied directly on thermal insulation, but apart from this, it is difficult to find clear indications of which façades that might be affected. The same problem has been reported from Germany (Bagda, 2002; Blaich, 1999; Karsten et al., 2005; Künzel and Sedlbauer, 2001; Sedlbauer and Krus, 2001) both where the old construction needed an additional thermal insulation and on newly built constructions. It is believed the problem occurs due to the decreased heat flow through the construction, thereby delaying the evaporation time of moisture on the outer surface and the fact of low heat capacity in the rendering. The thermal radiation from the surface to the sky especially occurring with a clear sky could cause a lower temperature on the surface of the façade than the temperature in the air and the risk of condensation on the surface is present. Together with climatic abiotic and biotic parameters this could lead to increased risk of growth of these kinds of constructions. To avoid the unwanted biological growth you have to understand the conditions necessary for growth. Investigations of temperature and moisture conditions of the outer construction of thin rendering on thermal insulation shows, that especially on the north side the moisture conditions are favorable for growth (Karsten et al., 2005). The Germany cases show that the most common growth is algae and moulds on the north or west side of the building (Bagda, 2002)

We have investigated building façades with organized patterns of small round areas where no growth occur on otherwise quite fouled façades. These small round areas appears then on the façade as "white dots". Interestingly this phenomenon could appear on one part of the construction while another, built at about same time with similar construction and facing the same direction, was not affected. Investigations of the façades show that the "white dots" appear at each fastener placed under the rendering to fasten the thermal insulation to the structural wall behind. All these buildings are built with thin rendering on thermal insulation, a common building practice in Sweden. We believe that the fasteners are heat bridges, with higher outer surface temperature and therefore a lower surface relative humidity at which no microbial growth occurs. Theoretical analysis has been made on this type of façade with the computer program HEAT 3. The HEAT 3 program can be used to calculate the three dimensional temperature distributions in a construction and the heat flow through a construction. We used the program to calculate the heat flow under stationary conditions.

Method
The simulations have been made when combining following parameters in the construction:

-150 mm concrete
-50 mm or 100 mm polystyrene
-5 mm or 20 mm CL-mortar
-fastener with a diameter 2 mm and 4 mm of steel or plastics
-outdoor temperature of -5°C and +5°C

The indoor temperature was set to +20°C.

We have made the calculations of the relative humidity on the surface by assuming conditions of a typical autumn in Skåne, Sweden. The relative humidity outside was set to 90% (Nevander and Elmarsson, 1994). The water vapour contents are then:

$v(-5°C) = 2.93$ g/m^3
$v(+5°C) = 6.12$ g/m^3

Results
The results of the simulations of relative humidity of surfaces with a fastener of steel are shown in table 5.2. The temperature outside the fastener and on the façade surface is called $T_{fastener}$ and $T_{surface}$ respectively. We find a larger difference in relative humidity between the surface and the fastener in cases with fasteners with a diameter on 4 mm compared to cases with the fasteners with a diameter of 2 mm. The relative humidity difference was also always higher in cases with an outer temperature on -5°C than if the outer temperature was +5°C. The biggest difference in relative humidity between the surface and the fastener was for a thin rendering on 50 mm thermal insulation in addition with the above mentioned factors.

Table 5.2 Results of temperature and relative humidity simulations shown for simulations with a fastener of steel

Thermal insulation (mm)	Render (mm)	Fastener diamenter (mm)	T_{out} (°C)	$T_{surface}$ (°C)	$T_{fastener}$ (°C)	ΔT (°C)	RH$_{surface}$ (%)	RH$_{fastener}$ (%)	ΔRH (%)
50	5	4	-5	-4.44	-2.73	1.71	86	75	11
50	5	4	5	5.34	6.36	1.02	88	82	6
50	5	2	-5	-4.43	-3.93	0.49	86	83	3
50	5	2	5	5.34	5.66	0.31	88	86	2
50	20	4	-5	-4.41	-3.56	0.85	86	80	6
50	20	4	5	5.36	5.86	0.51	88	85	3
50	20	2	-5	-4.38	-4.18	0.20	86	84	2
50	20	2	5	5.37	5.49	0.12	88	87	1
100	5	4	-5	-4.75	-3.61	1.14	88	80	8
100	5	4	5	5.18	5.84	0.66	89	85	4
100	5	2	-5	-4.69	-4.38	0.31	88	86	2
100	5	2	5	5.19	5.37	0.18	89	88	1
100	20	4	-5	-4.67	-4.08	0.58	88	84	4
100	20	4	5	5.20	5.55	0.35	89	87	2
100	20	2	-5	-4.67	-4.53	0.13	88	87	1
100	20	2	5	5.20	5.28	0.08	89	88	1

Discussion/conclusion
The results show that a construction with a thin layer of both thermal insulation and rendering had the highest difference in surface temperature between the point outside the fastener and at the surface. In simulations with an outdoor temperature of -5°C the difference in temperature was 1.71°C which made a difference in relative humidity of 11%. As we know that organisms need a high relative humidity to grow, these results could explain the uneven distribution of biological growth on the façades with "white dots".

6. Future studies

Some experimental studies are planned and will be described in following sections. We will also continue to study façades in the field. In addition we hope to get equipment to study the activity response of biological organisms (mainly lichens) to different abiotic factors *in-vitro* by chlorophyll fluorescence measurements.

6.1 Test house

Two activities are in progress on the test house:

- The monitoring of temperature and relative humidity on the façades from experiment 1 (section 5.2.1) will continue, thereby providing measurements to compare with results from computer simulations of surface conditions on façades with thin rendering on thermal insulation
- Investigation of any biological growth on the façades (experiment 2)

6.2 Test with samples of different rendering: "mortar experiment"

The aim with this experiment is to investigate different abiotic factors on samples of thin rendering on thermal insulation and the receptiveness to biological growth. Each sample is made of a PVC tube with a diameter of 25 cm, with 10 cm thermal insulation (mineral wool) and the mortar applied on both side on the thermal insulation. We will make samples with two different tube lengths: 10.6 cm and 14 cm. These two different sample lengths make it possible to have samples with 3 mm mortar on each side (sample size 10.6 cm) and with 20 mm mortar (sample size 14 cm). An example of each tube lengths is shown on figure 6.1.

Figure 6.1 Samples to the rendering-experiment. Each tube has thermal insulation inside the tube and mortar applied on each side

The mortar experiment will consist of samples with four different surface structures (see figure 6.2).

Figure 6.2 Mortar structures used in "mortar experiment"

The samples will be made of combining following abiotic factors:

- Surface structure –four different structures A-D (see figure 6.2)
- Mortar type
  - CL-mortar
  - Organic mortar
- Paint type
  - CL-paint
  - Organic paint
  - No paint
- Pigment
  - Titan dioxide
  - Zink oxide
- Biocides
  - Fungicides
  - Algicides
  - Poison
  - No biocide
- Weather condition
  - Dry
  - Wet
- Contamination in the form of soil

It is not possible to make samples with all combinations of the above factors, so we will make samples with starting point with basic samples (samples of mortar C+D in Table 6.1) with all mortar surface structures without biocides, but with both mortar types and in both wet and dry condition and with and without soil. With mortar A and mortar B we will make samples with different paint types, but only with titan dioxide as pigment, only in dry condition, but with and without addition of soil. With mortar D we will make samples with both mortar types, both pigments and with the four different biocides. An overview of all the samples is given in table 6.1. All the samples shown in Table 6.1 will be made in tubes with thin rendering (sample size 10.6 cm). The samples in bold font style in Table 6.1 refer to samples that also will be made with a thicker rendering (sample size 14 cm).

Table 6.1 Overview of different samples used in "mortar experiment"

mortar A+B

CL-mortar							organic mortar						
CL-paint		organic paint		-			CL-paint		organic paint		-		
titandioxide		titandioxide		dry		wet	titandioxide		titandioxide		dry		wet
dry		dry		soil	**no soil**	no soil	dry		dry		soil	**no soil**	no soil
soil	**no soil**	soil	**no soil**	1	3	1	soil	**no soil**	soil	**no soil**	1	3	1
1	3	1	3				1	3	1	3			

mortar C+D

CL-mortar			organic mortar		
no biocide			no biocide		
dry		wet	dry		wet
soil	**no soil**	no soil	soil	no soil	**no soil**
1	3	1	1	3	1

mortar D

CL-mortar								organic mortar							
CL-paint				organic paint				CL-paint				organic paint			
titandioxide		Zinkoxide		titandioxide		Zinkoxide		titandioxide		Zinkoxide		titandioxide		Zinkoxide	
4 biocide factors		4 biocide factors		4 biocide factors		4 biocide factors		4 biocide factors		4 biocide factors		4 biocide factors		4 biocide factors	
dry		**dry**		**dry**		**dry**		**dry**		**dry**		**dry**		**dry**	
1 1 1 3		1 1 1 3		1 1 1 3		1 1 1 3		1 1 1 3		1 1 1 3		1 1 1 3		1 1 1 3	

The samples will be put in north-south facing racks on the roof of the department building.

7. Wordlist

Abiotic factors: Non-biological factors in an organism's environment, such as temperature, relative humidity, pH etc.

Allele: One of a number of alternative forms of a gene that can copy a given genetic locus on a chromosome

Archaea: Domain of prokaryotic organisms. Differ from Bacteria in cell wall structure, membrane lipids and possession of introns in some genes

Autotroph: The ability of utilize CO_2 as the sole carbon source

Binomial nomenclature:
A method of naming species, a system based on giving each species a double Latin name; a generic name followed by a specific name

Biocide: A chemical substance capable of killing different forms of living organisms

Biofilm: Surface layer consisting of microorganisms and their extracellular products of metabolism

Biomineralization: The process by which living organisms produce minerals

Biotic factors: The influence on the environment of living organisms

Bryophyta: Division of spore-bearing plants, in which the mosses belongs

Chemotroph: Uses chemical compounds as energy source

Chlorophyll: Primary photosynthetic pigment of green plants and algae. Located in the thylakoid membranes of the chloroplast

Chloroplast: Semi-autonomous organelle found in cytoplasm, and in which the reactions of photosynthesis take place

Chordates: Phylum for animals having a notochord and gill clefts in the pharynx, and a hollow nerve cord

Cortex: the outermost layer of (in this contex) lichens

Cuticula: Layer of waxy material (cutin), on the outer wall of epidermal cells

Disaccharide: A sugar (carbohydrate) composed of two monosaccharides

Ecosystem: A biotic community and its habitat

Embryo: A multicellular diploid eukaryote in its earliest stage of development

Endostyle: Longitudinal groove in ventral wall of pharynx in urchordates and some primitive chordates

Endothermic: Ability to keep core body temperature at a nearly constant level regardless of the temperature of the surrounding environment

Eukaryote: Organisms with cell nucleus and other organelles

Evolution: The development of new types of living organisms from pre-existing types by the accumulation of genetic differences over long periods of time

Filamentous: Threadlike structure such as a fungal hypha

Genetic drift: the statistical drift over time of allele frequencies in a finite population due to random sampling effects in the formation of successive generations

Habitat: The locality or environment in which an organism lives

Heterotroph: Using organic carbon as carbon source

Hypha:	A long, branching filament forming the mycelium
Medulla:	Central part of (in this context) lichen, interior to the cortex
Mutualistic symbiosis:	
	The symbiosis is advantageous to both parts (+ +)
Mycobiont:	The fungal partner in lichens
Natural selection:	Favorization of certain traits in an organism that increases its chance of reproducing and survival
Notochord:	Slender rod of cells of mesodermal origin running along the back in the early embryo and which directs formation of the neural tube
Obligatory:	Limited to one mode of life or action
Oxidation:	The addition of oxygen, loss of hydrogen or loss of electrons from a compound, atom or ion
Parasitic symbiosis:	The symbiosis is disadvantageous or destructive to one of the organisms and beneficial to the other (+ −)
Pharyngeal:	From Pharynx –a part of the digestive system and respiratory system of many organisms situated immediately posterior to the mouth and nasal cavity
Photobiont:	Photosynthetic partner in a lichen, can either be a green algae or a cyanobacterium
Photosynthesis:	Synthesis of carbohydrate from CO_2 as a carbon source using light energy from the sun
Photosystem:	Light absorbing protein complexes involved in photosynthesis
Phototroph:	Using light as energy source
Phylogenetic:	The evolutionary history of biological groups
Poikilohydric:	An organism where internal water activity follows the external relative humidity
Polyphyletic:	Origins from several different lines of descent
Postorbital:	bone of vertebrate skull lying immediately behind the ear
Prokaryote:	Unicellular organism's without membrane-bounded cell nucleus and other membrane-bounded organelles
Protist:	A simple unicellular eukaryotic organism, such as unicellular algae, water moulds, slime moulds and protozoa
Rhizoid:	A filamentous outgrowth from prothallus that functions like a root
Symbiosis:	Close and usually obligatory association of two organisms of different species living together
Vertebrate:	Subphylum of the Chordata, animals characterized by the possession of the brain enclosed in a skull, ears, kidneys and other organs, and a well-formed bony or cartilaginous vertebral column or backbone enclosing the spinal cord

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The included papers

Paper I

Johansson, S., Li, Y. and Wadsö, L. (2005).
"Biological organisms on building façades". *Proceedings of the 7th symposium on Building physics in the Nordic Countries*, The Icelandic Building Research Institute, Reykjavik, Iceland, pp: 719-724.

Biological organisms on building façades

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Abstract

We have investigated rendered façades in the southernmost part of Sweden and identified which biological organisms that were growing on them. In order to fully understand the mineral façade as a biological habitat it is necessary to understand more about the organisms living there and which abiotic and biotic factors that control the growth. This article shortly describes the biological organisms found on mineral façades.

Introduction

If one takes a close look at almost any façade one will find biological growth. Just as there are organisms that can survive on vertical cliffs in nature, there are organisms that can do so on façades. The growth of biological organisms is determined by interactions of different abiotic and biotic factors (biological terms are explained in Table 1), which are very different from organism to organism. The most important abiotic factors controlling growth on a façade are relative humidity and temperature (Gaylarde and Morton, 1999). Every biological organism has different demands for growth, and where some are dependent on an organic carbon source from the substrate (heterotrophy) others are capable of using CO_2 as carbon source (autotrophy) and are therefore more independent from of substrate composition. Furthermore algae (and some bacteria) are capable of using sun light to utilize chemical energy by photosynthesis as we know it from plants (phototrophy). Fungi uses (organic) chemical compounds as energy source just like animals (chemotrophy). The most typical characteristic for all microorganisms growing on façades is their ability to endure repeated cycles of drying and rehydration (Gaylarde and Morton, 1999). As an example, fungi commonly found on leafs (*Cladosporium* spp., *Alternaria* spp. etc.) can dry out completely and then start growing again from their original growth points (hyphal tips) within an hour of being rehumidified (Deacon, 1997). Soil fungi like *Fusarium* spp. and food-spoilage fungi like *Penicillium* spp. can also sometimes regrow after desiccation, but not from the hyphal tips and the regrowth typically does not start until after 24 h. The fungal species described show these different characteristics because they are adapted to different environments, where leaf surfaces being an environment with daily extreme periodic wetting and drying is associated with the fungi that can tolerate such climate best. Similarly, different lichens, mosses etc. have different ability to endure repeated drying and the ones we find on façades are the ones most adapted to similar environments.

It is well known that some of these organisms can degrade stone and similar substrates (Gu, 2003; Sterflinger, 2000), but to what extent the organisms actually damage the façades on buildings is uncertain. By increasing our knowledge about the types of organisms growing on façades we will understand more about the parameters for growth and learn more about how to prevent the many-times undesired growth on façades. All building façades will most likely be discolored by time, but in Sweden we have discovered several cases of newly built rendered façades which have been discolored much more rapidly than has been seen earlier. We have investigated these types of building façades in southernmost part of Sweden and collected samples for identification of microorganisms. This paper will shortly describe the different types of organisms that have been found. Our work will hopefully result in a better knowledge about the biology on façades of buildings.

Table 1: Biological terms

Abiotic factors:	*Non-biological factors in an organism's environment, such as temperature, relative humidity, pH etc.*
Autotroph:	*The ability of utilize CO_2 as the sole carbon source*
Biofilm:	*Surface layer consisting of microorganisms and their extracellular products of metabolism*
Biotic factors:	*The influence on the environment of living organisms*
Chemotroph:	*Uses chemical compounds as energy source*
Eukaryote:	*Organisms with cell nucleus and other organelles*
Filamentous:	*Threadlike structure such as a fungal hypha*
Habitat:	*The locality or environment in which an organism lives*
Heterotroph:	*Uses organic carbon as carbon source*
Photosynthesis:	*Synthesis of carbohydrate from CO_2 as a carbon source using light energy from the sun*
Phototroph:	*Using light as energy source*
Phylogenetic:	*The evolutionary history of biological groups*
Polyphyletic:	*Origins from several different lines of descent*
Prokaryote:	*Unicellular organsim's without membrane-bounded cell nucleus and other membrane-bounded organelles*
Symbiosis:	*Close and usually obligatory association of two organisms of different species living together*

Biological organisms found on building façades

In our investigation of biological organisms on rendered façades we found algae and lichens were the most dominating organisms, but moulds were also found (at approximately 10% of the façades). Sometimes both algae and lichens were found growing on the same façade, but in other cases algae were found on the northern façade of the building while lichens were found on the other sides. In addition many façades had growth of mosses, e.g., close to the ground. This agrees with a Danish investigation of biological growth on masonry, tile- and concrete roofs (Frambøl et al., 2003) and Oshima´s (1998) investigation of concrete surfaces. We have identified the type of organisms by light- and stereo microscopy. Further identifications to genus or species level of the organisms were done when possible by ordinary identification literature. It was not possible to further identify algae, because of the necessity of difficult cultivation techniques.

Even though we only found algae, lichens, moulds and mosses growing on façades, it is well known that also bacteria and cyano-bacteria are also growing on facades (Gaylarde and Gaylarde, 1998). Bacteria are not a part of this project and mosses most likely do not grow on newly constructed façades. A short description of these organisms will however be included in this paper.

When we find microorganisms growing on a façade, we actually have the presence of a biofilm (Gaylarde and Morton, 1999). A biofilm contain active and dormant microorganisms and products of their metabolism, such as acids and polymeric materials, often polysaccharides. The weathering of materials is accelerated by the presence of a biofilm. The biofilm is highly diverse in both space and time. The polymeric material act as glues and trap dirt from the air which the microorganisms can utilize as nutrition source. The colonization often begins with autotroph organisms, which only requires inorganic compounds for growth. These organisms establish a primary biofilm providing growth for heterotroph organisms. For example, algae and lichen might be the primary colonizer on building facades due to they are autotroph and require little nutrient on substrate and can endure drought environment. They start growing and established their growth niches and formed the first layer of biofilm which can fix air born dust and also provide nutrient for later colonizers such as bacteria and moulds. If the right condition is available we can find a complex system of many different organisms in the biofilm.

Algae
Algae are a polyphyletic group of eukaryotic organisms commonly considered as photosynthetic organisms except plants. Different algae have very different appearances, life-styles and tolerance of variations in temperature, moisture etc. Most of them are aquatic, well known in freshwater and marine environments where they are completely dependent on liquid water. However, some algae, called terrestical algae, can live in damp terrestical environments as, for instance, in soil, on tree trunks or on building façades. These algae are spread by air, and their tolerance of variation in humidity, light intensity, temperature and in aridity is very high (Hoffmann, 1989). The algae we find on building façades are most green-algae, often belonging to the division Chlorophyta (Frambøl, 2003). These algae form green, light to very dark coatings on the façade.
We also found a very characteristic red green-algae *Heamotococcus pluvialis*, which is a unicellular green-algae, who gets its red color from the pigment astraxanthin. The coating of these algae gives the façade a reddish appearance (Fig. 1).

Figure 1 Coating of red green-algae on a masonry wall. Different lichen species can also be seen

Moulds

Moulds are an artificial group of microscopic, filamentous fungi. Fungi are not plants, and cannot do photosynthesis, but are heterotroph organisms and have there own kingdom. They absorb nutrients from the substrate, but the most important factor for growth of mould is water availability. Different moulds have different requirements of water; some can live on a substrate at water activity of 0.7, and survive long periods of drought. It is well known that many moulds can grow well on soiled substances if the right moisture conditions are available (Gravesen et al., 1994). The most common mould we found on external mineral building façades was the black colored mould *Cladosporium* spp., which is a mould very common in the air. Also another common air-borne mould *Alternaria* spp. can be found on external building façades (Frambøl et al. (2003). Both these moulds are black because of the content of the pigment melanin that protects the mould against strong UV-radiation. However there has been reported growth of *Penicillium* spp., which does not have this pigment (Johannesson, 2003).

Figure 2 The mould Cladosporium herbarum *(as seen in microscope)*

Lichens

Lichens are composite organisms, a symbiotic association of fungi and algae or cyanobacteria that are lichenized in a unique morphology. The fungi surround and protect the algae against drought and excess light intensity, and the fungi get nutrients

from the photosynthetically active algae. Lichens can survive long periods of drought and return to an active, photosynthetic state within few hours with certain amount of water (Nash III, 1996). The growth of lichens is often very slow, only a few mm per year. Because whole lichens can not be readily grown in cultures, it is difficult to know the precise amount of different nutrients necessary for grow in specific lichens. Lichens living on mineral surfaces are in contact with inorganic nutrients but are also affected by dust from the air. Airborne dust can also be incorporated in the lichen thallus and act as a nutrition source. Because many nutrients are affected by pH of the substrate, the availability of nutrients can be very different from limestones to acidic substrates. As a consequence, we find very different lichen communities on limestone and acidic substrates. Mineral building façades in general are alkaline, and the lichens we found on building façades are therefore adapted to these conditions. We found a large diversity of lichens growing on mineral façades. The species are listed in Table 2.

Figure 3 Rendered façade with at least five different species of lichens

Table 2: Identified lichen species found on mineral façades. The dominant species are written in bold

| |
| --- |
| ***Caloplaca decipiens*** |
| *Caloplaca holocarpa* |
| ***Candelariella aurella*** |
| *Catellaria lenticularis* |
| *Lecanora albescens* |
| *Leacanora campestris* |
| *Leacanora conferta* |
| ***Lecanora dispersa*** |
| *Phaeophyscia nigricans* |
| *Physcia tenella* |
| *Verrucaria nigrescens* |
| ***Xanthoria parietina*** |

Mosses

Mosses are a division of spore-bearing plants (Bryophyta) that, like other plants, can produce their own nutrients by photosynthesis. They require abundant water for growth and, but some species have evolved special methods of dealing with long dry periods. For example can the moss *Racomitrium languinosum* that is common in Sweden, can survive at least one year of total desiccation (Proctor, 1981). Mosses lack a real root, but are attached to surfaces by small threads (rhizoids). Water and mineral nutrients required for the moss to grow are absorbed, not by the rhizoids, but rather by the thin leaves of the moss. That means the mosses can absorb water and mineral nutrition from the whole surface of the organism.

Bacteria

Bacteria are a group of extremely different prokaryotic (unicellular organisms which lack a membrane-bounded nucleus and different organelles) organisms. They are highly diverse metabolically, and can be found everywhere in nature and can be parasitic or saprophytic on plants and animals. Because of the very small size of bacteria they are easily spread by air. Bacterial coverings are usually not visible to the naked eye, but it is well known, that bacteria can establish growth on a mineral façade, where they can be present in large numbers on an apparently clean surface (Gaylarde and Morton 1999).

Discussion

The organisms which can be found on building façades are from almost all kingdoms of the biological world. Figure 4 gives a short overview of a universal phylogenetic tree. Every branch consists of a biologically different group, and the length and the distance of the branches symbolize evolutionary diversity and distance, respectively. Notice the close relationship between animals, fungi and plants compared to the diverse group of bacteria.
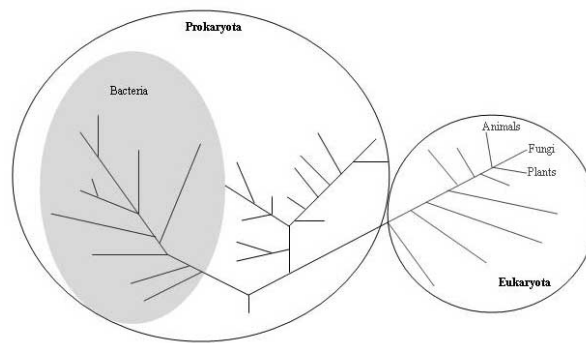
Figure 4 Phylogenetic tree of evolution. Note that mosses belong to the kingdom of plants, lichens are composite organisms consisting of algae (or cyanobacteria) and fungi and algae do not have their own kingdom, but some are part of the kingdom of plants

Conclusion

Moulds, algae, lichens, mosses and bacteria can be found growing on façades. These very different organisms thus seem to have similar environmental demands as they are

found growing side by side on the same façades. Most important for survival on a façade is the adaption to periodic desiccation, but other environmental parameters like UV-radiation and nutritional demands play a role. Only by understanding the influence of environmental conditions on the growth of the different organisms that can occur on a façade is it possible to reduce this growth.

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Paper II

Johansson, S., Wadsö, L., and Sandin, K. (2005).
"Microbial growth on building facades with thin rendering on thermal insulation".
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Microbial growth on buildings facades with thin rendering on thermal insulation

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Abstract

During the last years there has been reported considerable and rapid microbial growth on newly built rendered façades in Sweden. The microbial growth is mainly algae but also lichens and moulds are found. The problem is believed mostly to occur on thin renders applied on thermal insulation, but apart from this, it is difficult to find clear indications of which façades that might be affected.

We have investigated building façades with organized patterns of small round areas where no growth occur on otherwise quite fouled façades. These small round areas appears then on the façade as "white dots". Investigations of the façades show that the "white dots" appear at each fastener placed under the rendering to fasten the thermal insulation to the structural wall behind. All these buildings are built with thin rendering on thermal insulation, a common building practice in Sweden.

We believe that the fasteners are heat bridges, with higher outer surface temperature and therefore a lower surface relative humidity at which no microbial growth occurs. The aim of this project is to investigate this type of problems, understand why it occurs and to give advises on how to prevent them.

Introduction

All though discolorations of façades can be of non-biological origin, the most common discolorations are due to microorganisms (Gaylarde and Morton, 1999). Microbiel growth on painted wood façades has been a well known problem for a long time in the Nordic contries. During the last decade there have also been reported cases with considerable and rapid microbial growth on newly constructed rendered façades (Johannesson, 2003). A common building practice of façades in Sweden is a thin rendering applied directly on a thermal insulation (Fig. 1). Both mineral wool and polystyrene insulation are used and the rendering can be as thin as 3 mm in some cases. Even though most such buildings do not have the problem we are investigating, we have found several buildings with microbial growth on these types of construction (Johannesson, 2003).
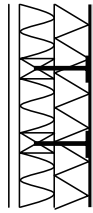
Figure 1 Construction of thin rendering on thermal insulation. The layers from left to right: inside wall, thermal insulation and wooden studs, thermal insulation, reinforcement mesh, render. Fasterners are fastened in the wooden studs

The problem of microbial growth on façades is a complex phenomenon of a number of interacting factors related to both abiotic and biotic conditions of the façade system. With abiotic and biotic factors we mean the influences of an organism's environment consisting of non-biological (eg. temperature, relative humidity, pH) and biological (organic nutrition, other organisms) factors, respectively. Growth of microorganisms is first of all dependent of high moisture levels (Gaylarde and Morton, 1999). Parts of a façade which are heavily exposed to rain are naturally wetter than other parts and will therefore be more exposed to microbial growth. Other factors have to be considered as well. For example temperature, thermal conductivity and heat capacity in the outer wall, nutrition availability, uses of fungicides, surface roughness, climate conditions, and UV-radiation are all factors that may have to be considered trying to avoid growth on façade constructions. The type of render could also influence the problem of microbial growth. Most types of render contain organic compounds. Even though the amount of these compounds is low they may be high enough to act as a nutrition sources for microbial growth.

General building physical considerations
The building physical design of a façade on a building can affect the surface microclimate in two ways; by the influence of temperature and moisture. In general, if you in a certain construction decrease the temperature of the surface by 1 K the relative humidity will be increased by 5% (Johannesson, 2003). The thermal insulation of the outer wall will therefore have a high influence of the moisture and temperature conditions of the surface of the wall. In addition we also have to consider both the thickness and the placement of the thermal insulation.

The thickness of the thermal insulation
The thickness of the thermal insulation influences the surface temperature. An increase of thermal insulation thickness decreases the heat flow through the wall. This results in a decreased external surface temperature, when it is cold outdoors. The surface temperature is affected mostly at small thicknesses of thermal insulation. At stationary conditions this is independent of the placement of the thermal insulation. The location of thermal insulation is significant in non-stationary state, when day and night variation in temperature and radiation is considered because the thermal inertia of the façade surface layer determines the surface temperature variation.

Heat capacity without consideration of radiation
The heat capacity of a material has a high influence on temperature variations. If the air temperature decreases rapidly (at nights), the surface temperature on the outer layer of a construction with a high heat capacity, will be warmer than the air

temperature. If the outer layer of the wall has a low heat capacity the temperature of this surface will be close to the air temperature. This means that the relative humidity on the surface of the outer layer with low heat capacity will be higher and increase the risk for microbial growth. Calculations of surface temperature on different walls show that the temperature on façades with low heat capacity is about 0.5 K lower at night compared with walls with high heat capacity (Sandin, 2002). The construction we primarily are investigating is a façade consisting of thin rendering on thermal insulation with low heat capacity in the outer layer. The above considerations could therefore lead to an increased risk for microbial growth. However the total influence of heat capacity in a construction is not obvious. We do not know if it is the higher temperature in day-time that is dominant or it is the lower temperature at night. Most likely it increases the risk for microbial growth if we have a low heat capacity in the outer layer, because of an increase of a few percent in relative humidity at night-times. Even if the influence of heat capacity is small it can have a high importance together with other influencing factors.

Heat capacity with consideration of radiation
The sun radiation also has a high influence on the surface temperature of the façade. In sunlight the façade absorbs large amounts of heat energy and gets a higher temperature than the air. A dark façade with low heat capacity can get temperatures as high as 30-40 K higher than the air temperature. This means that the relative humidity gets very low (if there is no high moisture capacity in the façade). The darker the color the façade has, the higher the temperature of the surface. Long wave thermal radiation (most commonly at nights) from a surface of a façade to the sky will lead to a lower surface temperature; sometimes even lower than the air temperature. The lower the heat capacity of the façade is, the lower the temperature of the surface. This means that thermal radiation of a façade with a low heat capacity results in high relative humidity on the surface or even condensation. We have used a computer program to simulate temperature distributions in constructions of two layers, where the outer layer is a thin rendering (10 mm). When we simulate long waved thermal radiation from the surface at night-time and a heating at day-time because of high sun radiation, we find that the surface temperature of a construction of thin rendering on thermal insulation changes faster than a rendered masonry wall. If the render is very thin, the heat capacity of the wall will be low. If this is the case the temperature of the outer layer could be as low as 2 K lower than the air temperature and that the relative humidity in the outer surface would be approximately 10%-units higher than the relative humidity in the air. This could indeed lead to a high risk for microbial growth if the relative humidity in the air at the same time is high.

Study of facades in Skåne (southernmost part of Sweden)
As a continuation of other studies (Johannesson, 2003; Sandin, 2002; Svensson and Williams, 2004) we have investigated microbial growth on mineral façades in the southernmost part of Sweden. The discolorations were different species of green algae, lichens and moulds. The microbial growth is often concentrated to those parts of the façade where the moisture load is thought to be high, like edges and next to balconies. Moreover the microbial discoloration is concentrated to the surface and has not penetrated the façade. When the render was painted, the growth did not seem to penetrate the paint.

At several occations we found an interesting discolored façade type. The façades was dicolored by microorganisms, but had a pattern of symmetrically placed "white dots", which were not (or very little) affected by microbial growth (Fig 2). Interestingly this phenomenon could appear on one part of the construction while another, built at about same time with similar construction and facing the same direction, was not affected.

Figure 2 Façade construction with thin rendering on thermal insulation, heavily affected by microbial growth on the right part of the façade. The white dots have no biological growth

By studying the constructions of these façades, we found that a fastener was placed behind every "white dot". This means that the fastener could influence the abiotic conditions of the façade construction in such a way that no growth could appear there. We have made a study of this by simulation the temperature on the surface of the facade of this construction both at the position of the fasteners and for the rest of the façade. We also simulated the temperatures on surfaces with different thermal insulation thicknesses, different in render thicknesses and with fasteners of different materials (steel and plastic). We found that the largest difference in temperature between the "white dots" and the rest of the façade was at constructions with thin rendering and a fastener of steel (1-2 K difference). This can lead to a difference in relative humidity of approximately 10% at normal weather conditions in the autumn in Nordic contries. This means that thin rendering combined with fasteners with high thermal conductivity could lead to inhibition of microbial growth just at the positions of the fasteners because of the lower relative humidity at these places. A similar German study (Blaich, 1999) also compared surface temperature and microbial growth on this kind of façade construction and showed that the temperature at the fasteners was 1 K higher than at the rest of the façade and that no microbial growth

occurred at these places. Therefore it seems that even small changes in surface temperature influences the abiotic conditions on the outer surface on the construction and may lead to a change in the probability of microbial growth.

Conclusion

In Skåne, the southernmost part of Sweden, we have experienced considerable and rapid microbial growth on newly constructed rendered façades (thin rendering applied on thermal insulation). We have made computer simulations of surface temperatures in such constructions to increase our understanding of which factors that are important for microbial growth on facades. Generally, thin renderings on insulation have lower night-time temperatures than thicker rendering or rendering on bricks walls. This is especially true if one takes radiation to the cold sky into account. Thin render on insulation will therefore have a higher relative humidity.

One special case of microbiological growth on facades are facades with "white dots", i.e., regularly spaced parts with less microbial growth on a facade otherwise covered with growth. Behind each "white dot" we found a fastener and computer simulations showed that the fasteners are heat bridges giving 1-2 K higher night-time temperatures than the rest of the facade. This small difference in temperature gives high enough differences in moisture state to almost prevent microbial growth above the fasteners.

It is difficult to predict the risk for microbial growth on a façade. In this paper we have discussed some factors that are necessary to understand the complexity of the problem.

Acknowledgement

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