Virpi Leivo - Jukka Rantala

MOISTURE BEHAVIOR OF SLAB-ON-GROUND STRUCTURES

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FOREWORD

The research report 'Moisture Behavior of Slab-on-Ground Structures' has been performed at the Laboratory of Structural Engineering and Laboratory of Earth and Foundation Structures of the Tampere University of Technology. The work was supervised by Professor Ralf Lindberg and Professor Jorma Hartikainen. The research report is a final report of a second research phase concerning Moisture Behavior of Slab-on-Ground Structures. Manuscript by Senior Researcher Jukka Rantala and Researcher Virpi Leivo. The research is financed by National Technology Agency (TEKES) and Lohja Rudus Ltd, NCC Finland Ltd, Rautaruukki Ltd, Linterm Ltd, City of Helsinki/Construction Management Division and Department of Geotechnics, City of Turku/ Tilalaitos, City of Tampere/Department of Building Supervision and Tilakeskus.

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Tampere, December 2002

The authors

ABSTRACT

The thermal and moisture conditions of slab-on-ground structures differ from other structures. The ground structure is in contact with warm and moist drainage and fill soil layers. The subsoil or drainage layer around the ground structures becomes a moisture source under normal thermal and moisture conditions. The bonding and transforming mechanism of moisture and especially the amounts of transformed moisture depend on the temperature field of the structure. Therefore temperature and moisture related phenomena should be examined together.

The drainage and fill soil layers are either in direct or indirect contact with large water storages of subsoil, ground water or upper ground water tables and gravitational water layers. Coarse soil layer containing fine fractions can convey large amounts of water from these water sources by capillary transformation not only vertically but also horizontally. The propagation speed of the horizontal capillary water front from the gravitational water layer in the drainage soil satisfying requirements of class 2 drainage material is about 30 cm per hour, and the amount of transformed water is up to 150 kg/m^3 . The capillary movement of water in soil layers contacting ground structures should therefore always be prevented using a coarse and sufficiently thick capillary breaking layer. The relative humidity of the pore air in drainage soil is always close to the saturated volume ($RH = 100\%$) because the pore structure of the soil is in contact with moisture sources and there is always some gravitational or capillary water transforming at the soil layers. The temperature of the drainage soil layer under the slab-on ground structure in a heated building is about $+15\ldots+17^\circ\text{C}$, depending on the used thermal insulation and indoor temperature. The temperature behavior of the drainage soil layer follows the temperature changes of the indoor air and ground slab quite precisely. Annual changes in outdoor temperature does not affect the temperatures of the drainage soil layer very much.

A temperature and moisture content difference forms between parts of a slab-on-ground structure. These differences tend to steady with flows through the structure. The water vapor content of the warm and moist drainage soil layer ($T_i \approx +16^\circ\text{C}$, $RH_i \approx 100\%$) is higher than the water vapor content of common indoor air ($T_s \approx +20^\circ$, $RH_s = 20\ldots 40\%$). Therefore the water vapor diffusion flow at the slab-on-ground structure is almost in every case upwards from the subsoil towards the dryer indoor air. Increasing diffusion flow increases the risk of saturation, or the critical moisture content of some material layers can be exceeded. In many cases the most critical part of the structure is the lower surface of the floor covering, especially if the used covering related has a too low water vapor resistance or it is too water vapor tight.

Three different states should be examined in the moisture design of slab-on-ground structures:

1. The drying phase when the structural moisture from the cast slab should be able to dissipate to the indoor air or subsoil. During this phase the moisture source is the structure itself.
2. The operating phase when the warm and moist subsoil and drainage soil layers are the moisture source of the slab-on-ground structure. The increase of relative humidity and the risk of saturation should be taken into consideration. The structure should be able to evaporate the moisture diffusing from the subsoil.
3. Damage situation (for instance plumbing leak) when the moisture source is inside the structure and the excess water should be able to escape either to the subsoil or indoor air.

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1 INTRODUCTION

This publication is a final report of a series of studies concerning the temperature and moisture behavior of slab-on-ground structures. The studies were performed at the Tampere University of Technology in Finland during 1999 – 2002 in co-ordination with the Laboratory of Structural Engineering and the Laboratory of Foundation and Earth Structures.

The background and motivation of this study were the numerous moisture related problems detected at the slab-on-ground structures in Finland. According to a study commissioned by the Ministry of Trade and Industry of Finland, in 25% of all detached, semi-detached or row houses the slab-on-ground structures have some degree of damages caused by the moisture. Another survey for the Federation of Municipalities of Finland reports that moisture damages detected in municipal office, school and health care buildings are related to slab-on-ground structures (26%) just as often as to roofs (26%).

Careful examinations of moisture damaged ground floors reveal that the temperature and moisture behavior of slab-on-ground structures is more complicated than commonly presumed. Almost inevitable changes in surrounding conditions of the ground slab are usually ignored or the moisture design is neglected altogether. The structural moisture in massive in situ cast concrete slabs, changes in indoor air temperature and humidity as well as the warming up of the subsoil caused by the steady heat flow from the heated building mass above can all change the moisture balance and behavior of the slab-on-ground structure dramatically and cause severe moisture damages, if not taken into consideration during the design of the structures.

The moisture and water transfer and setting mechanisms inside and across slab-on-ground structures and adjoining soil layers are various and strongly dependent on the current temperature field. Therefore moisture and temperature related phenomenon must be studied simultaneously. Besides the capillary rise, the lateral water flow caused by capillary forces and the water vapor diffusion in porous materials should also be considered. A coarse-grained drainage layer can effectively cut off the capillary rise but does not prevent the water vapor diffusion from the warmed subsoil towards the dryer indoor air. In the Finnish climate exterior water sources are numerous enough to keep the subsoil pore air humidity close to $RH = 100\%$ at all times.

The first part of this research series was concerned with the moisture and temperature behavior of coarse-grained soil materials and the related parameters determined by laboratory tests. The latter part of the series studied the slab-on-ground structure and its behavior under changing temperature and moisture conditions as a whole, including the adjoining drainage and subsoil layers. The temperature and moisture fields of the slab structures were determined by numerical methods, long term in situ surveys and studies of reported moisture damage cases.

2 MOISTURE AND TEMPERATURE CONDITIONS OF SLAB-ON-GROUND STRUCTURES

Potential moisture sources of slab-on-ground structures pertain to the outer boundaries of the structure and the prevailing conditions along these boundaries as well as to the moisture and temperature levels inside the structure. Seasonal and weather changes outdoors, alterations in ventilation volumes and temperatures of the indoor air, and the slow evaporation process of structural moisture cause changes in the operating conditions of slab-on-ground structures. Unlike the other parts of the building envelope, the slab-on-ground structure is partly or entirely in contact with the moist initial subsoil or another constructed soil layer, such as a drainage layer. Therefore the external moisture loads of slab-on-ground structure diverge considerably from the ones directed to the building envelope or the superstructures.

2.1 External temperature and moisture load

The external moisture load of the slab-on-ground structures pertain to the temperatures and moisture levels of the indoor air, outdoor air and the subsoil.

2.1.1 Outdoor air moisture and temperature

Outdoor air temperature has an impact on the temperature field and further on the moisture conditions of the ground floor particularly along the edge zones of the slab. Outdoor water vapor content has an indirect impact on the ground floor condition through the moisture level of the indoor air. Average monthly values of measured outdoor temperatures and relative humidity values from various Finnish locations are presented in Table 2.1. The statistics covers the years 1961 – 1990 /35/. Statistics show that the highest outdoor temperature is reached in July and the difference between the average annual peak temperatures in Southern and Northern Finland (Helsinki and Sodankylä) is approximately 3°C. The coldest month, in turn, is January when the difference between average lowest temperatures of Helsinki and Sodankylä is 10°C. It is noteworthy that while the measured average relative humidity RH of the outdoor air does not vary very much through the year (67 – 85%, Helsinki), the water vapor content of the air varies considerably (2,68 – 10,6 g/m³). The water vapor content of the air reaches its peak during July – August and the lowest value in January - February.

2.1.2 Indoor air moisture and temperature

The indoor air conditions of a building depend, among other things, on the occupancy of the space, leaks in the building envelope, insulation and ventilation. Technical target values for indoor air temperatures are shown in Table 2.3 /32/. Temperature target values are used to determine the required indoor air quality level during the building project planning. Target values refer to the occupied zone inside the room, in other words the space between the floor surface and the height of 1,8 meters above to floor and 0,6 meters from the walls.

Table 2.1 Average monthly outdoor air temperatures and humidity during 1961 – 1990 /35/.

		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Helsinki	T [°C]	-5,7	-5,7	-2,1	3,1	9,7	15,0	17,0	15,7	11,1	6,4	1,4	-2,9
	RH [%]	85	84	82	75	67	68	73	78	82	83	86	86
	p [Pa]	331	327	426	576	811	1161	1415	1393	1088	803	583	420
	υ [g/m ³]	2,68	2,65	3,41	4,52	6,21	8,74	10,6	10,46	8,30	6,23	4,61	3,37
Turku	T [°C]	-6,0	-6,2	-2,6	3,0	9,8	14,9	16,5	15,2	10,3	5,7	0,6	-3,6
	RH [%]	89	87	82	75	66	64	71	76	83	86	89	90
	p [Pa]	337	324	410	572	804	1086	1334	1315	1045	793	569	416
	υ [g/m ³]	2,74	2,64	3,29	4,49	6,16	8,18	9,99	9,89	8,00	6,17	4,51	3,34
Lahti	T [°C]	-8,4	-8,2	-3,6	2,6	9,8	14,7	16,3	14,5	9,3	4,5	-0,7	-5,5
	RH [%]	87	85	81	75	67	67	73	80	86	87	90	89
	p [Pa]	268	267	374	555	816	1123	1355	1324	1013	738	522	352
	υ [g/m ³]	2,20	2,18	3,01	4,37	6,25	8,46	10,15	9,98	7,78	5,76	4,15	2,85
Jyväskylä	T [°C]	-10,0	-9,5	-4,7	1,3	8,7	14,1	16,3	14,5	9,3	4,5	-0,7	-5,5
	RH [%]	88	87	81	73	65	65	73	80	86	87	90	89
	p [Pa]	234	243	342	491	735	1048	1355	1324	1013	738	522	352
	υ [g/m ³]	1,94	2,00	2,76	3,88	5,66	7,91	10,15	9,98	7,78	5,76	4,15	2,85
Vaasa	T [°C]	-7,8	-7,8	-3,9	1,7	8,3	13,7	15,7	13,9	9,2	4,6	-0,9	-5,5
	RH [%]	88	87	84	77	69	67	73	79	84	87	90	89
	p [Pa]	286	283	379	534	760	1053	1304	1258	983	743	513	352
	υ [g/m ³]	2,34	2,31	3,05	4,21	5,85	7,96	9,79	9,50	7,55	5,80	4,09	2,85
Lappeenranta	T [°C]	-9,4	-8,8	-3,8	2,3	9,8	14,8	16,7	14,8	9,5	4,2	-1,2	-6,2
	RH [%]	88	87	82	73	64	65	70	77	84	87	91	90
	p [Pa]	248	259	373	529	780	1096	1332	1299	1003	722	507	336
	υ [g/m ³]	2,04	2,12	3,00	4,16	5,97	8,26	9,97	9,79	7,69	5,64	4,05	2,73
Oulu	T [°C]	-11,1	-10,4	-5,8	0,5	7,5	13,5	16,0	13,7	8,4	3,0	-3,1	-8,2
	RH [%]	86	85	82	74	67	65	70	77	82	85	88	88
	p [Pa]	206	218	316	470	699	1009	1274	1210	909	648	423	276
	υ [g/m ³]	1,71	1,81	2,57	3,72	5,40	7,63	9,56	9,15	7,00	5,08	3,40	2,26
Joensuu	T [°C]	-11,6	-10,7	-5,4	0,7	8,3	14,2	16,4	14,0	8,6	3,2	-2,7	-8,2
	RH [%]	87	85	82	73	64	65	70	78	84	86	90	89
	p [Pa]	200	212	327	470	705	1055	1307	1250	944	665	447	279
	υ [g/m ³]	1,65	1,76	2,65	3,72	5,43	7,96	9,76	9,44	7,27	5,22	3,58	2,29
Sodankylä	T [°C]	-15,1	-13,6	-8,5	-2,1	5,0	11,6	14,1	11,2	5,9	-0,2	-7,4	-13,1
	RH [%]	85	84	80	72	66	65	69	77	84	87	89	86
	p [Pa]	138	158	244	374	579	892	1113	1029	785	524	299	170
	υ [g/m ³]	1,16	1,33	2,00	3,00	4,51	6,79	8,40	7,85	6,10	4,16	2,45	1,42

In Table 2.2 the target values are divided into three classes according to the indoor air categories.

S1: Individual indoor air quality

- Indoor air quality of the space is excellent and the temperature conditions comfortable during summer and winter months. The user of the space is able to control the temperature level individually and if needed to adjust the ventilation volume. Temperature and air quality in general satisfy the special requirements of the user, such as the elderly, allergic persons, people suffering from respiratory illnesses.

S2: Good indoor air quality

- Indoor air quality of the space is good and there is no draught. The peak temperature during the hottest summer months may rise above the comfortable level.

S3: Fair indoor air quality

- The indoor air quality and temperature conditions fulfill the minimum requirements of the regulations. The air might occasionally feel stuffy and a sense of draught is possible. Overheating is common during hot summer months.

Table 2.2 Target values of indoor air temperature /32/.

		Unit	Indoor air quality class Maximum values		
			S1	S2	S3
Room temperature*	Winter	°C	(21-22)*	20-22	20-23
	Summer***		(23-24)*	23-26	22-27 (35)
Temporary deviation from the target value **		°C	± 0,5	± 1	± 2
Temperature difference vertically		°C	2	3	4
Floor temperature		°C	19-29	19-29	17-31
Speed of air flow	Winter (20°C)	m/s	0,13	0,16	0,19
	Winter (21°C)	m/s	0,14	0,17	0,20
Speed of air flow	Summer (24°C)	m/s	0,20	0,25	0,30
Relative humidity	Winter	%	25 – 45	-	-

* In S1 class the room temperature must be adjustable individually in each space or apartment between the limit values 20 – 24 °C, if several persons occupy a single space or room, the base level of the room temperature during winter months is 21 – 22 °C and during summer 23 – 24 °C.

** The target value of room temperature must stay between "Room temperature" limits

*** Room temperature must not rise above +35°C on any account. If the outdoor temperature is below + 15°C, the room temperature must not rise above +27°C.

The moisture level of the indoor air depends on the outdoor air humidity, the occupancy of the space or building, moisture emission volumes inside the space, ventilation, hygroscopicity of the building materials, moisture flow through the building or room envelope and the amount of structural moisture evaporating during the drying period of the structures.

The indoor air water vapor content can be estimated as follows:

$$v_s = v_u + \frac{G}{n \cdot V} \quad (2.1)$$

v_s = indoor air water vapor content [g/m³]

v_u = outdoor air water vapor content [g/m³]

G = moisture emission rate inside the space or building [g/h]

n = ventilation rate [1/h]

V = volume of the space [m³].

Buildings and spaces in general are divided into three categories according to the moisture emissions rates inside the building:

- ordinary accommodation spaces, moisture regain compared to the outdoor air
3 – 4 g/m³ h depending on the use of the space
- office or other public spaces 2 – 3 g/m³ h
- industrial spaces, up to 6 g/m³ h or more.

2.1.3 Temperature and water content of the soil

The source of *surface water* is rainfall, and its annual average in Finland is 600 mm or 0,6 m³/m². The average monthly rainfall (1961-1990) in Jyväskylä, Sodankylä and Helsinki is shown in Figure 2.1 /37/.

Figure 2.1 The average monthly rainfall [mm] 1961-1990 under the climatic conditions of Jyväskylä, Sodankylä and Helsinki /37/.

The absolute volume of the surface water near each individual building depends on rainfall, topography, geographical location of the building, vegetation and materials of the soil surface near the structures. Approximately 30% of the rainfall flows above the soil surface to discharge ducts, rivers, lakes or sea and a major part, 5%, evaporates back to the air directly from the soil surface. Only about 2% of the rainfall actually soaks through the soil layers as a gravitational water.

Gravitational water drifts in soil layers freely by gravitational forces. Part of this slowly sinking water evaporates into the soil pore air and another part drifts through the drainage layers and drainpipes away from the building foundation and ground floor. In the gravitational zone the free water sinks downwards towards the ground water table, but part of the water has already adhered to the layers as capillary water or adsorbed water. The water vapor content of the pore air is also high thanks to the continuous evaporating from the gravitational water and ground water table.

Ground water: its volume and level in the subsoil at a particular time depends on the difference between the volumes of water drifting in and out of the ground water basin. Drain of the water basin is continuous due to the gravitational flow through the outlets below the ground water table to river and lake systems or swamps. The volume of the incoming water depends on the rainfall and further on the amount of gravitational water reaching the ground water basin. The difference and diversity between the drain and fill of the water basin causes variations in levels of the ground water table depending also on season, weather conditions and soil type. The water table is in its lowest during late winter as the frost has for months prevented water from soaking into the ground. The water table is at its highest right after the thawing period in spring. Below the ground water table the pore volume of the soil is fully saturated.

Above the ground water table up to a certain height there is the so-called *capillary zone*, where capillary forces raise water from the free water table. *The capillary rise* and the volume of raising water depend strongly on the soil type and density, especially grain size distribution. In porous material the pores between the solid grains form a complex continuous grid of small diameter ducts that function as capillary tubing. The shape, form and size of these tubes dictate the capillarity of each individual soil type. Gravity and viscosity resist the capillary movement. The capillary rise continues up to the point where the capillary forces causing the rise are equal to the gravitational forces opposing it (Chapter 3.1.2).

2.2 Internal moisture and temperature load

Structural moisture

One of the most important moisture sources of slab-on-ground structures immediately after the construction is the structural moisture of the in-situ cast concrete slabs. Ordinary structural concretes contain a large amount of mixing water and therefore the drying period of structures made from these concrete types is relatively long compared to the modern building schedules. An adequately long drying period of the concrete is especially important in structures where the drying process is possible in only one direction, such as composite slabs and slab-on-ground structures.

The relative humidity of the concrete refers to the relative humidity of the pore air. Concrete is a porous material that tends to reach the moisture balance with its

surroundings. The equilibrium moisture content depends on the characteristics of the concrete, such as water-cement ratio, pore structure, hydration degree and age, as well as current temperature field.

The water-cement ratio of normal floor concrete is 0,7...0,9. In the cast stage this kind of concrete contains water approximately $180 \dots 200 \text{ l/m}^3$. At this point the relative humidity of concrete is $RH = 100\%$. The total amount of water to evaporate from drying concrete varies depending on the setting mechanism of the excess water in a particular concrete type. A portion of the water forms a chemical bond during the hydration of cement. Another portion forms physical adsorption or capillary bond in the pore structure. The amount of the physically bonding water depends on temperature and moisture conditions of the surroundings. The rest of the original mixing water is structural moisture, that has to evaporate before the equilibrium moisture balance with the surroundings is possible. The amount of this excess structural moisture can be tens of liters of water per one cubic meter of drying concrete.

Figure 2.2 shows theoretical moisture division of three different grades of concrete at relative humidity $RH = 90 \%$. The original volume of mixing water is 180 l/m^3 /21/. Table 2.2 shows the effect of the curing of concrete, structural thickness and drying conditions on the drying time of different grades of concrete.

Figure 2.2 Theoretical moisture division in three different grades of concrete. Relative humidity of the surroundings is $RH = 90 \%$. The original amount of mixing water was 180 l/m^3 /21/.

Table 2.3 The effect of curing of concrete, structural thickness and drying conditions on drying time of different grades of concrete /21/.

Variable	Concrete 1 wcr 0,7	Concrete 2 wcr 0,6	Concrete 3 wcr 0,5
Curing:			
1 d in mold	0,7 ×	0,5 ×	0,5 ×
14 d in water	1,0 ×	0,9 ×	0,8 ×
28 d plastic sheet	0,8 ×	0,7 ×	0,5 ×
14 d in water+			
14 d plastic sheet	1,0 ×	1,0 ×	1,0 ×
28 d in water	1,3 ×	1,3 ×	1,0 ×
Thickness:			
10 cm	0,4 ×	0,4 ×	0,4 ×
15 cm	0,7 ×	0,8 ×	0,8 ×
18 cm	1,0 ×	1,0 ×	1,0 ×
20 cm	1,2 ×	1,1 ×	1,1 ×
25 cm	1,8 ×	1,5 ×	1,4 ×
Conditions:			
RH=35%	0,8 – 0,9 ×	0,8 – 0,9 ×	0,8 – 0,9 ×
RH=60%	1,0 ×	1,0 ×	1,0 ×
T=18°C	1,0 ×	1,0 ×	1,0 ×
T=30°C	0,6 – 0,7 ×	0,6 – 0,7 ×	0,6 – 0,7 ×

3 TEMPERATURE AND MOISTURE BALANCE OF POROUS MATERIALS

3.1 Bonding of water

All structural materials of a typical ground floor structure, including subsoil, are porous materials. The bonding mechanisms of water in a such material are

- hygroscopic sorption
- capillarity
- chemical bonding
- osmosis

3.1.1 Hygroscopic sorption

Porous hygroscopic matter can absorb or release water vapor directly from or into the moist air until a state of equilibrium is reached. The amount of absorbed water depends on the material, temperature and relative humidity of the surroundings.

The molecular traction forces in solid pore walls of porous media attract free vapor molecules from the pore air and form a thin water molecule layer on pore wall surfaces [22]. As the water vapor content of the pore air increases, the molecular layer thickens and vice versa. Water molecules bond with the pore structure with adsorption or capillary condense.

Hygroscopic equilibrium moisture content

Hygroscopic equilibrium moisture content denotes the water content level of the porous matter at a certain relative humidity and temperature. The equilibrium moisture content sorption curve for a material can be determined at a certain temperature by changing the relative humidity of the surroundings while the temperature remains constant (Fig. 3.1). Starting from dried material and slowly increasing the surrounding humidity, a wetting or absorption curve is achieved. Starting from fully saturated material and letting the surrounding humidity to drop in stages the resulting curve is called a drying or desorption curve. In this context absorption usually means both the adsorption and capillary condense behavior.

There are three distinctive stages in the hygroscopic moisture content curve due the bonding mechanism of water (Fig. 3.1). During the first deep stage of the curve at low relative humidity levels the individual water vapor molecules are attracted to the surface of the pore walls. During the second stage the adsorption of entire groups of water molecules is the dominant type of bonding. At the third deep stage the relative humidity is so high that the general formation of a meniscus is possible and the main bonding mechanism is capillary condense.

Figure 3.1 Hygroscopic equilibrium moisture content.

The equilibrium moisture content curves of the same material in wetting and drying display a strong hysteresis. Definite reasons for this phenomenon are yet unknown, but a few possible explanations are:

- Entrapped air in the pore structure of the wetting material. The dissolution process of these air bubbles into the water is very slow.
- The shape and form of the pore structure is such that drying occurs only at considerably lower relative humidity levels than wetting
- Too short equilibrium periods are used for the determination of sorption curves.

The tangent of the equilibrium curve determines the moisture capacity of a matter (ξ). The moisture capacity of a matter is high if only a small change in relative humidity produces a big change in the water content of the material.

As introduced before, temperature has a strong effect on the equilibrium moisture content of a material. The usual measuring temperature of equilibrium content curves for building materials is $+20^{\circ}\text{C}$. According to source [22] the equilibrium moisture content curves of common construction materials differ only slightly from one another if the temperature remains between $+20^{\circ}\text{C}$... $+50^{\circ}\text{C}$.

3.1.2 Capillary suction

The pore system inside a porous material forms a complex net of capillary tubes able to transport water from any free water surface by capillary forces. Capillary forces are produced by combined action of traction forces between water and solid grain molecules, surface tension and gravity, which form a convex surface or meniscus for the column of water inside any small tube. Along this convex surface, or meniscus as it is called, a pressure difference or underpressure develops that sucks water upwards along the tube. The smaller the diameter of the tube, the stronger the developing pressure difference. This water lifting underpressure is called capillary suction.

In soil materials the active capillary tubing is a net of linked pores between solid soil particles. There are no individual separate tubes inside these materials but a complex net of small caves connected to each other which together form a sort of continuous net of tubes whose diameter, form and direction changes constantly. Generally the average diameter of these tubes tends to increase as the grain size of the soil mass increases. Along with the grain size distribution the stratification, density and initial water content of the soil mass also have an effect on the intensity of the capillary suction. In addition, the capillary suction is a function of contact wetting angle i.e. the angle between the water meniscus and the capillary surface. The smaller this angle, the stronger the capillary suction. In hydrophilic or water-attracting materials the contact wetting angle is less than 90° and in hydrophobic or water-repelling materials the angle is between 90° and 180° .

The opposing force restricting the capillary rise is gravity. Inside an even capillary tube water rises up to a height where the capillary suction equals the weight of the formed water column at the level of the meniscus. As the diameter of a tube diminishes the water rises higher as the developing underpressure along the meniscus and therefore the force fighting gravity increases.

Capillary equilibrium moisture content

The capillary equilibrium moisture content denotes a water content level that the porous material reaches when the pore structure is in contact with a free water surface. The capillary moisture content is a function of distance from the water source. Especially in soil materials the water content tends to decrease radically as the distance from the water source increases. This is because the average pore diameter in granular soils is relatively large and the capillary suction is limited. The capillary equilibrium moisture content (w) of a certain material is usually expressed as function of distance from the water source or underpressure (Fig. 3.2).

Figure 3.2 Capillary equilibrium moisture content curves.

There is a strong hysteresis phenomenon linked to capillary wetting (capillary absorb). This is due to the complexity of the capillary tubing in porous materials and the

changing diameters of the ‘tubes’. Also in an initially dry sample there is no continuous water layer on the surfaces of the capillary tubing to prevent water from penetrating into the smallest micro pores of the material. As the moisture potential approaches an equilibrium inside the material, air remains entrapped in the pore structure. The dissolution of the air into the water is a very slow process. In addition there is a significant hysteresis involved in contact wetting angles of materials.

The capillary drying curve (capillary desorption) designates the moisture content distribution of a material after the initially fully saturated sample connected to the water source has dried out to the equilibrium state with its surroundings. In a single capillary tube the water meniscus sinks to the level that equals the equilibrium between underpressure and hydrostatic pressure. However in complex porous materials some of the smallest ducts remain full of water as the general water level lowers beneath their location. Forces like surface tension and capillary suction hold this so-called residual moisture in the smallest pores once filled with water. Drying of these micro pores is extremely slowly as the only possible drying mechanism is evaporation from the very small meniscus.

As discussed before, adsorption and osmosis also hold water near the solid walls of the pore structure. There is a distinctive difference between adsorption and capillary forces. Adsorption occurs between gas and solid particles whereas capillary suction is a bonding phenomenon between liquid and solid particles.

3.1.3 Chemical bonding and osmosis

Chemical bonding implies electrostatic or intermolecular bonding between water and solid particles. These bonds are extremely strong compared to other bonding mechanisms discussed earlier. Chemically bonded water, such as combined water is regarded as part of the solid material and usually ignored in moisture balance examinations of porous materials.

Osmotic bonding is a consequence of diffusive flow through a semipermeable membrane and the osmotic pressure caused by this flow. Osmotic bonding is typical in organic materials including semipermeable cell membranes and water-soluble components.

3.2 Transforming mechanisms of moisture

3.2.1 Diffusion

Diffusion is movement of gas molecules that seeks to equalize the differences in concentration or partial pressures of a certain gas in a gas mixture, for example water vapor molecules in air. The motive power of diffusion is a difference of contents as the diffusion transports molecules from a region of higher concentration to one of lower. The moisture content of air can be expressed as the water vapor content (v , [g/m³]) or a water vapor pressure (p , [Pa]).

As far as the pore structure of a material is initially dry and the diameter of each individual duct is bigger than the free distance of a single water vapor molecule, the equation of aerial mass flow of water vapor is (3.1) (Fick’s first law) /22/:

$$g = -\delta_p \frac{dp}{dx} \quad (3.1)$$

In equation (3.1) the potential is the difference between water vapor pressures. If the potential is expressed as a difference of water vapor contents, the following equation applies (3.2) /22/:

$$g = -\delta_v \frac{dv}{dx} \quad (3.2)$$

The association between water vapor permeability values δ_v and δ_p is (3.3) /22/:

$$\delta_v = 461.4 (273 + t) \delta_p \quad (3.3)$$

Under steady state conditions the moisture flow is not time-dependent and the moisture flow equation can be written as (3.4):

$$g = \delta_v \frac{v_2 - v_1}{L} = \frac{v_2 - v_1}{L/\delta_v} \quad (3.4)$$

where v_1 and v_2 are water vapor contents at opposite sides of the structure.

The term $L/\delta_v = Z_v$ is called water vapor resistance.

Under unstable conditions the moisture flow is time-dependent and the moisture flow (3.1) can be written as (3.5) /22/:

$$g = -D_w \frac{dw}{dx} \quad (3.5)$$

where D_w is the so-called moisture diffusivity determined by the equation (3.6) or (3.7) /22/:

$$D_w = \delta_v \frac{dv}{dw} \quad (3.6)$$

$$D_w = \frac{\delta_v v_s(T)}{\xi}, \quad (3.7)$$

where ξ is moisture capacity, (dw/dx)

The moisture flow under unstable conditions is usually calculated by numerical methods.

3.2.2 Capillary moisture flow

The capillary movement of water in porous materials is determined by Darcy's law, where the powering potential is the underpressure (p_c , [Pa]). According to Darcy's law the moisture flow is now (3.8) /22/:

$$g = \frac{k dp_c}{\eta dx} \quad [\text{kg/m}^2 \text{ s}], \quad (3.8)$$

where η is the viscosity and k permeability [kg/m]. Underpressure p_c is the opposite value of capillary suction p_{cap} ($P_c = -P_{cap}$).

Permeability depends on the underpressure p_c , which is further dependent on the water content of the material w . This way the equation (3.8) can be expressed in a form where the potential is the water content and therefore the equation has an equal form with diffusion flow equation (3.1)

Capillary movement can be estimated by assuming the wetting area to be a fully saturated advancing boundary whose speed in a porous medium is (3.9):

$$x = B \cdot \sqrt{t} \quad (3.9)$$

where x [m] is the depth of penetration and B [m/ $\sqrt{s}$] empirical coefficient of penetration. The value of coefficient B is dependent on the form of the meniscus, surface tension, contact wetting angle and the viscosity of the liquid. Further on, as the form of the meniscus is dependent on the initial water content of the material, the coefficient B is also a function of the initial water content w .

Assuming the capillary rise to be an advancing fully saturated boundary in soil mass, the total amount of absorbed water W [kg/m²] is:

$$W = A \cdot \sqrt{t} \quad (3.10)$$

where the infiltration coefficient A [kg/(m² $\sqrt{s}$)] is also an empirical value characteristic of each individual material.

3.2.3 Simultaneous diffusion and capillary movement

Simultaneous diffusion and capillary movement can be determined by combining the equations of diffusive and capillary flows. In theoretical studies and calculations the moisture gradient dv in a porous material is dividable into two parts: moisture changes caused by capillary forces v_{CAP} and the moisture changes caused by evaporation, diffusion and condense i.e. hygroscopic moisture changes δ_{EDC} (evaporation – diffusion – condensation) /24, 25/

$$dv = dv_{CAP} + dv_{EDC} \quad (3.11)$$

These two moisture gradients are powered by different mechanisms and can therefore be determined independently in numerical solutions and demonstrations. In part of the material where the moisture content of the medium is below a certain critical moisture level only the diffusion flow is considered. If the moisture content of the medium is above the critical level, only the capillary moisture flow is considered.

3.2.4 Gravitational movement of water

Water permeability determines the gravitational water flow in a porous medium. The grain and pore structure as well as the shape of individual grains and pore cavities have an effect on the water permeability and gravitational flow in a medium. Also the

characteristics of the liquid, such as viscosity and specific weight, have an effect on the permeability. Darcy's law describes the laminar water flow in a fully saturated porous medium (3.12) /26/:

$$v = k \cdot \Delta H , \quad (3.12)$$

where v is the flow rate of water [m/s], k is permeability [m/s] and ΔH is the hydraulic gradient [m/s].

Water permeability of different soil types is shown in table 3.1 /26/.

Table 3.1 Water permeability of different soil types.

Soil type	Water permeability k [m/s]
Gravel	$10^{-1} \dots 10^{-3}$
Sand	$10^{-2} \dots 10^{-6}$
Silt	$10^{-5} \dots 10^{-9}$
Clay	$< 10^{-9}$

3.2.5 Evaporation and moisture convection

The equation to determine the evaporation rate from the surface of a material is 3.13:

$$g = \beta(v_p - v_i) \quad (3.13)$$

$$\beta = \frac{\alpha_{ko}}{\rho_i c_i} , \quad (3.14)$$

where

α_{ko} = heat-transfer coefficient of the convection

ρ_i = density of the air = 1,2 kg/m³

c_i = specific heat of the air = 1010 J/kg °C

v_p = water vapor content of the surface

v_i = water vapor content of the adjoining air [g/m³]

$\alpha_{ko} \approx 2 \cdot \sqrt[4]{\Delta t}$, where Δt is the temperature difference between the surface and surrounding air.

Convection describes the water vapor movement with the current of air. The potential for the current is the air pressure difference at opposite sides of a structure. Possible causes for such a pressure difference are wind, temperature difference or ventilation fans. As the air flows between warm and cooler surroundings, part of the migrant water vapor condenses into liquid water if the water content of the air exceeds the saturation content at some point during the cooling process. Respectively the air flow between cooler and warmer space usually dries out the adjoining materials as the warming air is able to entrain some extra moisture from the surroundings. The convection through holes and gaps is a more important form of moisture convection than the natural convection inside the pore structure of porous material. The convection moisture flow is expressed as (3.15) /3/:

$$G = vR \quad (3.15)$$

where G is the moisture flow [kg/s], v moisture content [kg/m³] and R the current of air [m³/s].

3.3 Specific heat and thermal conductivity of soil

3.3.1 Specific heat of soil

The bulk density of all typical soil minerals found in Finnish soil types is approximately $\rho \approx 2650 \text{ kg/m}^3$ and the specific heat $C_p \approx 755 \text{ J/kg K}$. The density of water is about a half of that $\rho_w = 1000 \text{ kg/m}^3$, but its specific heat is more than twice compared to minerals. As the density of air is only a thousandth part of the one of water, it is usually ignored in the determination of overall specific heat of a soil type. The specific heat capacity of a soil type is the sum of those of its components weighted by their volume parts:

$$C = f_s \cdot C_s + f_w \cdot C_w \quad (3.16)$$

where

- C = specific heat capacity of the soil
- f_s = volume part factor of the soil minerals
- C_s = specific heat capacity of the soil minerals
- f_w = volume part factor of the water
- C_w = specific heat capacity of the water.

In addition to the actual mineral grains there is also some organic matter in an ordinary soil type, and the equation (3.16) can be written as (3.17):

$$C = f_m \cdot C_m + f_o \cdot C_o + f_w \cdot C_w \quad (3.17)$$

where f_o is the volume part factor of the organic matter and C_o the corresponding specific heat capacity. Table 3.2 shows the temperature parameters of typical soil minerals, water and air at the temperature $T = 300 \text{ K}$.

The sum of the volume part factors in equation (3.17) is:

$$f_m + f_w = 1 - f_a \quad (3.18)$$

where f_a = volume part factor of the air in soil pores. In typical inorganic soils the volume part factor of the solid particles varies between 0,45 ... 0,65 and the specific heat capacity of a soil mass from the value of dry soil $C = 1 \text{ MJ/m}^3\text{K}$ to the value of fully saturated soil $C = 3 \text{ MJ/m}^3\text{K}$.

Table 3.2 Temperature parameters of typical soil minerals, water and air at the temperature $T = 300$ K.

Matter	Density ρ [kg/m ³]	Specific heat capacity C_p [J / kg • K]	Thermal conductivity k [W / m • K]	Thermal diffusion coefficient $\alpha \times 10^{-6}$ [m ² / s]
Granite	2630	775	2.79	1.37×10^{-6}
Granular quartz	2640	1105	5.38	1.80×10^{-6}
Quartz	2660	755	8.8	4.38×10^{-6}
Organic matter	~1300	~ 1923	0.25	0.10×10^{-6}
Water	1000	4200	0.598	0.15×10^{-6}
Ice	920	2065	2.2	1.16×10^{-6}
Air	1.16	1000	0.025	22.6×10^{-6}

3.3.2 Thermal conductivity of soil

The thermal conductivity of soil λ , unlike the specific heat capacity, strongly depends on the air volume in soil pores. Air as a material is an insulation in comparison to water and especially to soil particles, and therefore a high volume part of air reduces the thermal conductivity of the soil mass significantly. As the specific heat capacity of soil may triple or quadruple as the volume part of water increases in the soil, the thermal conductivity of the same soil may increase by 100 times. Thermal conductivity is also dependent on the characteristics of the solid particles in soil mass, such as grain size, shape and distribution.

Equation (3.19) estimates the thermal conductivity of a soil mass composed of three ingredients: mineral grains, water and air. Soil is assumed to be a continuum water mass, in which air and solid particles are blended.

$$k = \frac{f_w \cdot \lambda_w + \kappa_s \cdot f_s \cdot \lambda_s + \kappa_a \cdot f_a \cdot \lambda_a}{f_w + \kappa_s \cdot f_s + \kappa_a \cdot f_a} \quad (3.19)$$

where λ_w , λ_a are λ_s are the thermal conductivities of water, air and solid particles respectively, κ_s is the ratio between temperature gradients of solid particles and water and κ_a the ratio between temperature gradients of air and water.

Thermal diffusion coefficient α [m²/s] determines the level of heat conductivity of a matter in relation to its capacity to store energy (3.20):

$$\alpha = \frac{\lambda}{\rho \cdot c_p} \quad (3.20)$$

Materials with a high thermal diffusion coefficient react rapidly to temperature changes in the surroundings. The smaller the coefficient, the longer it takes to reach thermal equilibrium in a changing environment.

3.4 Moisture conditions of the subsoil

3.4.1 Moisture content of typical coarse-grained fill and drainage materials

During the first part of this research [20] the capillary and hygroscopic equilibrium moisture contents for several coarse-grained materials were determined by series of laboratory tests. The objective was by determining the volumes of water able to drift or be stored in coarse-grained soil materials to provide means to estimate the source for moisture damage of slab-on-ground structures by measuring the water content or relative humidity of the subsoil and the slab itself. Another objective was to determine the limiting values for temperature and relative humidity of subsoil under ‘normal’ operating conditions for the moisture design of ground slabs.

Grain distribution curves of the studied coarse-grained materials from sandy till to macadam are shown in Figure 3.3. The grading characteristics and voids ratios of each soil type are shown in Table 3.3.

Figure 3.3 Grain size distribution curves of the studied materials.
a – 1- class drainage gravel , *b* – 2 -class drainage gravel
c – fine sand, *d* – coarse sand,
e – macadam, *f* –sandy till

Table 3.3 Grading characteristics of the studied coarse-grained materials.

Soil type	< 0.074 [%]	d ₁₀ [mm]	d ₂₀ [mm]	d ₆₀ [mm]	d ₁₀ /d ₆₀	e
A – 1 class drainage gravel	0	1.3	1.5	3.2	0.41	0.38
B – 2 class drainage gravel	1.3	0.6	1.1	2.8	0.39	0.31
C – fine sand	5.5	0.08	0.125	0.22	0.57	0.38
D – coarse sand	0.3	0.6	0.75	1.6	0.47	0.35
E – macadam	0.4	4.1	4.6	6.5	0.71	0.43
F – sandy till	15	0.038	0.125	4.0	0.03	0.21

Hygroscopic equilibrium moisture content

The volume of hygroscopic moisture in soil materials is significantly smaller than the volume of capillary suction and therefore hygroscopicity is usually ignored in geotechnical considerations. In moisture balance examinations, however, the knowledge of the hygroscopic equilibrium moisture contents of subsoil and fill materials is essential.

There have been a few studies concerning the hygroscopic equilibrium moisture contents of soil materials. Characteristics of the grained soil effecting on the moisture contents are

- grain size distribution
- impurities of the minerals; rust, salts
- mineral composition (not significant in Finnish soil types)

The hygroscopic equilibrium moisture content curves in wetting determined for the previously introduced materials are shown in Figure 3.4. The equilibrium moisture content at a relative humidity RH = 100% was less than one percent per weight. The highest value was detected with sandy till as its moisture content was $w = 0,8\%$. The coarse sand was up to some degree rusty and therefore the detected moisture content was almost as high as with the till sample. For all other studied materials the moisture balance content was less than $w = 0,5\%$.

The determined equilibrium moisture content values in drying were slightly higher from the hysteresis phenomenon (Chapter 3.1.1).

Figure 3.4 Hygroscopic equilibrium moisture content curves in wetting for the studied materials. Temperature $T \approx +20^\circ\text{C}$.

Source [31] determines the equilibrium moisture contents for gravel and silty till at the temperature $+20^\circ\text{C}$. The results show that the equilibrium moisture content of the gravel was approximately $w = 0,2\%$ in $\text{RH} = 100\%$ i.e. $8 \dots 10 \text{ kg/m}^3$. The same value for silty till was $w = 0,5\%$. The measured equilibrium moisture contents were nearly identical at the temperature $T = -18^\circ\text{C}$ and $\text{RH} = 90\%$.

According to laboratory tests, the hygroscopic equilibrium moisture content of typical fill and drainage materials, such as gravel, sand, coarse till or macadam, in wetting is less than two percent per weight ($\text{RH} = 100\%$). With fine-grained materials (fine sand, fine till), moisture contents up to $w = 3\%$ are in the limits of hygroscopic equilibrium values in drying.

The starting point of the moisture balance study of slab-on-ground structures is that the relative humidity of the pore air is $\text{RH} = 100\%$. The justification for this assumption is the following:

- The water content of the fill layers during construction period is usually very high ($\text{RH} = 100\%$) and the only possible drying direction is downwards into the subsoil. However, the natural moisture content of the subsoil is also high and the drying of the fill is extremely slow.
- The pore system of the soil mass is connected to the ground water table.
- Capillary movement, especially horizontal capillarity may occasionally raise the moisture content of the fill.

Capillary suction

Capillary movement of liquid water is a more significant moisture factor in subsoil and drainage layers where it occurs. Volume of water transforming into and through the soil layers by capillary forces and the ability of capillarity to hold moisture above ground

water table also in relatively coarse-grained materials is remarkable. The crucial factor for the capillary behavior is the relative amount of fine aggregate in the soil mass.

According to the performed tests and literature, the capillary water content of a soil layer depends on both the capillarity of the soil type and the distance from the free water source, i.e., the ground water table. The grain size distribution and especially the nature and density of the pore structure between the grains dictate the absolute volume, speed and height of the capillary migration. For example, in evenly graded fine sand the pore structure is relatively homogenous and the volume of capillary flow is almost even up to the maximum rise level. A capillarity test of the fine sand showed that the volume of rising water was over 300 kg/m^3 [20] and the maximum rise over 0,4 meters from the free water surface. By contrast, the volume of rising water in sandy till was only a half of that. The reason for this is the difference in porosity of the two materials: the porosity of evenly graded sand is notably higher than that of sandy till and therefore its potential capacity to raise water is respectively higher. On the other hand, the capillary rise of the till is significantly higher than the one of the sand because the average diameter of the pore structure in till is smaller and therefore the capillary suction is much stronger.

Horizontal capillarity was studied to determine the propagation speed and volume of the capillary front in initially dry soil samples (Figure 3.6). The horizontal capillarity and the volume of migrating water depends on the grain size distribution and distance from the water source. A clear linkage between the porosity and the volume of capillary migration was also detected. In evenly graded sand the volume of horizontally migrating water at the distance of 0,6 meters from the water source was $w = 200 \text{ kg/m}^3$. The speed of the advancing capillary moisture front in initially dry sample was almost equal in the measuring distance of one meter $v = 0,35 \text{ m/h}$. In the sandy till sample, however, the speed of the advancing front slowed down as the distance from the water source increased. The volume of migrating water was also lower than with fine sand, less than $w < 150 \text{ kg/m}^3$. In gravels and sand the propagation speed of the capillary front was more or less equal, $v \approx 0,35 \text{ m/h}$. In sandy till the flow resistance is much higher as the average pore diameter is smaller and the propagation speed of the front decreases as the distance to the water source increases.

Figure 3.5 Capillary rise and volume of migrating water in studied soil types.

Figure 3.6 Horizontal capillarity of the studied soil types.

Table 3.4 shows a summary of few capillary characteristics of the studied soil types. The volumes of capillary rise were measured at the height of 0,2 meters above the free water table and the volumes of horizontal capillarity at the distance of 0,6 meters from the water source.

Table 3.4 Capillarity of the studied coarse-grained materials.

Soil type	Voids ratio e	Vertical		Horizontal w_{60} [kg/m ³]
		w_{20} [kg/m ³]	h_p [m]	
Macadam	0,43	0	0	0
1 class drainage gravel	0,38	0	0	0
Fine sand	0,37	343	0,5	202
Coarse sand	0,35	192	0,2	126
2 class drainage gravel	0,31	145	0,5	57
Sandy till	0,21	110	> 0,7	169

Ground water

Under the ground water table the pore structure of the soil is assumed to be fully saturated.

3.4.2 Moisture flow through slab-on-ground structures

Reference /4/ studied the moisture flow rate through slab-on-ground structures during a 16 month drying period. In the tests the amount of evaporating moisture from the test specimens under steady surrounding conditions $RH = 30\%$ and $T = + 23^\circ\text{C}$. Test series examined the effect of under slab fill layer and vapour barrier on the moisture flow rate (Figure 3.7). The Figure 3.7 shows that the fill layer restrains the flow if the fill material is not capillary.

Figure 3.7 The effect of the under slab material on the moisture flow rate of the drying slab-on-ground structure.

3.4.3 Capillary flow through slab-on-ground structures

Slab-on-ground structures may have a direct capillary contact to ground water table or saturated subsoil. In this case the capillary flow through a concrete slab may be determined by equation (3.22):

$$g = \frac{B}{2d\sqrt{m}} \quad [\text{kg/m}^2 \text{ s}] \quad \text{where } d = \text{thickness of the slab} \quad (3.22)$$

The parameters m and B for different grades of concrete are shown in Table 3.6.

Table 3.6 The capillary parameters m and B in relative humidity, $RH = 90\%$ /3/.

Grade of concrete	B [$\text{kg/m}^2 \sqrt{\text{s}}$]	m [s/m^2]
K20 (w/c=0,8)	0,050 (max)...0,021 (RH90%)	$6 \cdot 10^6$
K25 (w/c=0,7)	0,028 (max)...0,012 (RH90%)	$17 \cdot 10^6$
K30 (w/c=0,6)	0,019 (max)...0,007 (RH90%)	$31 \cdot 10^6$
K40 (w/c=0,5)	0,013 (max)...0,005 (RH90%)	$48 \cdot 10^6$

The maximum capillary moisture flow rising through concrete slabs of different thicknesses and grades of concrete if the lower surface of the concrete slab is in direct contact with the free water table is shown in Figure 3.8. In practice the ground water table is usually much lower than the slab surface and the capillarity of the underneath fill and soil layers dictate the volume of water reaching the concrete surface. Especially if there is an impermeable insulation board under the slab, this layer performs as a final moisture barrier preventing capillary rise to the slab.

Figure 3.8 Maximum capillary moisture flow through a concrete slab.

3.4.4 Diffusion flow through slab-on-ground structures

The maximum diffusion flow through a non-isolated and uncoated concrete slab directly in contact with the moist subsoil ($RH = 100\%$) depends on the subsoil temperature, indoor air temperature and relative humidity, and the thickness and water vapor permeability of the slab itself. Figure 3.9 shows the diffusion flow through a 80 mm thick concrete slab under two different indoor air conditions ($RH = 25\%$ and $RH = 50\%$) and with two different water vapor permeability values of the concrete mass. The subsoil temperature varies between $+12 \dots 24^\circ\text{C}$.

Figure 3.9 The maximum diffusion flow through concrete slab.

4 TEMPERATURE AND MOISTURE BEHAVIOR OF SLAB-ON-GROUND STRUCTURES

The moisture behavior of slab-on-ground structures was studied theoretically under steady state conditions. In the analysis different types of ground floor structures and varying combinations of thermal and moisture parameters of the materials were used under changing surrounding conditions. The assumed moisture migration mechanism in all the calculations was diffusion.

In steady state comparisons the varying parameters were the water vapor permeability of the concrete, insulation and floor coating, as well as the relative humidity of the indoor air and the temperature of the subsoil. In addition the effectiveness of a common 'state-of-the-art' repair method, the so-called ventilated floor structure, was ensured by calculations under varying moisture conditions.

4.1 Slab-on-ground structure in steady state conditions

In steady state studies the principal assumption is that the heat and moisture flow are stationary and the temperature and moisture distribution across the structure can be determined by equations presented in Chapter 3.1. The calculations also include an assumption of linear dependence between saturated humidity and temperature although the dependence is really non-linear. The limit values for the calculations were the indoor air temperature t_i and relative humidity RH_i and the temperature and relative humidity of the subsoil t_s , RH_s . In all comparisons one variable was the temperature of the subsoil, varying between $t_s = +12 \dots +24^\circ\text{C}$ as the relative humidity remained constant $RH_s = 100\%$. A separate comparison was made to determine the effect of indoor air humidity on the moisture balance of the structures. The temperature of the indoor air and upper surface of the slab was constant $t_s = +19^\circ\text{C}$. The average values of thermal and moisture parameters of the structural materials used in the calculations are shown in Table 4.1. The extreme values of the variations are shown in brackets. In all comparisons the effect of the water vapor permeability of the floor coating was also concerned.

Table 4.1 The average moisture and thermal parameters of the materials /3/.

Material	Thermal conductivity λ [W/m °C]	Water vapor permeability δ_p $\times 10^{-12}$ [kg/m s Pa]	Water vapor resistance $Z_p = d/\delta_p$ $\times 10^9$ [m ² s Pa/kg]
Concrete	1,5	2,0* (1,5...5**)	-
Insulation board polystyrene	0,041	1,2 (1,2...7)	-
Insulation board polystyrene	0,037	1,2	-
Insulation board mineral wool	0,041	85	-
Expanded clay aggregate	0,12	20	-
Wood	0,14	1,0	-
Plastic film, 0.2mm	-	-	450
Construction paper	-	-	2
Filter cloth	-	-	2
*K30, RH 93%, ** value 5×10^{-12} corresponds to several years old concrete, with a water-cement ratio of 0.4			

The examined structural cross-sections were type structures from the Finnish building information file with codes AP 201, AP 204, AP 205 and AP 206 /30/. The type cross-sections, materials and layer thicknesses are shown in Figure 4.1.

Figure 4.1 The type cross-sections examined in steady state calculations.

Figure 4.1 shows only the structural layers of the slab-on-ground structures. In addition, the comparisons included a floor coating layer whose water vapor resistance varied between $Z_p \sim 20 \dots 180 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$. The relative humidity of the lower surface of the floor coating is usually critical for the behavior of the structure. The humidity should remain below $\text{RH} = 75 \dots 85 \%$ depending on the moisture endurance of coating materials and used adhesives. In general the relative humidity of $\text{RH} = 75\%$ is considered as a limit value after which fungus growth is probable.

The comparison calculations tried to determine what kind of water vapor resistance characteristics a floor coating material should have when used with a certain type of slab-on-ground structure. The examinations studied the temperature, saturation pressure and vapor pressure distributions across the slab cross-sections as a function of changes in the subsoil temperature.

4.1.1 Effect of the water vapor permeability of the concrete slab and floor coating on the moisture balance of slab-on-ground structures

In calculations the water vapor permeability of the concrete slab varied between $\delta_p \sim 1.5 \dots 5,0 \times 10^{-12} \text{ kg/m}\cdot\text{s}\cdot\text{Pa}$. The permeability $\delta_p = 1.5 \times 10^{-12} \text{ kg/m}\cdot\text{s}\cdot\text{Pa}$ corresponds to the grade of concrete K30 at the relative humidity $RH = 55\%$ and permeability $\delta_p = 5,0 \times 10^{-12} \text{ kg/m}\cdot\text{s}\cdot\text{Pa}$ an old concrete with water-concrete ratio 0,4 in relative humidity $RH = 80 \dots 90 \%$. The vapor resistance of the floor coating range was $Z_p \sim 50 \dots 180 \times 10^9 \text{ m}^2\cdot\text{s}\cdot\text{Pa/kg}$. Vapor resistance $Z_p = 50 \times 10^9 \text{ m}^2\cdot\text{s}\cdot\text{Pa/kg}$ corresponds the resistance of a typical linoleum sheet and resistance $Z_p = 180 \times 10^9 \text{ m}^2\cdot\text{s}\cdot\text{Pa/kg}$ equals the resistance of a typical plastic membrane used in public spaces.

Four cases **a** – **d** with parameter variations shown below were performed. Other temperature and moisture parameters are shown in Table 4.1.

Variations of the water vapour permeability:

a:	concrete	$\delta_p = 1.5 \times 10^{-12} \text{ kg/m}\cdot\text{s}\cdot\text{Pa}$
	floor coating	$Z_p = 50 \times 10^9 \text{ m}^2\cdot\text{s}\cdot\text{Pa/kg}$
b:	concrete	$\delta_p = 5,0 \times 10^{-12} \text{ kg/m}\cdot\text{s}\cdot\text{Pa}$
	floor coating	$Z_p = 50 \times 10^9 \text{ m}^2\cdot\text{s}\cdot\text{Pa/kg}$
c:	concrete	$\delta_p = 1.5 \times 10^{-12} \text{ kg/m}\cdot\text{s}\cdot\text{Pa}$
	floor coating	$Z_p = 180 \times 10^9 \text{ m}^2\cdot\text{s}\cdot\text{Pa/kg}$
d:	concrete	$\delta_p = 5,0 \times 10^{-12} \text{ kg/m}\cdot\text{s}\cdot\text{Pa}$
	floor coating	$Z_p = 180 \times 10^9 \text{ m}^2\cdot\text{s}\cdot\text{Pa/kg}$

Limit values: indoor air $t_s = +19 \text{ }^\circ\text{C}$, $RH_s = 50 \%$.
subsoil $t_u \sim +12 \dots +24 \text{ }^\circ\text{C}$, $RH_u = 100 \%$.

In comparisons the design limit value of the relative humidity for the lower surface of the coating was $RH = 75\%$. In Figures 4.2 ... 4.5 the curves end after the first condensation point occurs somewhere in the cross-section. Usually this happens somewhere inside the insulation. After the condensation the steady state diffusion examination is no longer relevant.

AP 201:

Relative humidity at the lower surface of the floor coating

The effect of the water vapour permeability of concrete slab
to moisture level at the lower surface of the floor coating

AP 201

Figure 4.2 The effect of the water vapor permeability of the concrete slab on the moisture balance of the slab structure. Section type AP 201.

AP 204:

Relative humidity at the lower surface of the floor coating

The effect of the water vapour permeability of concrete slab
to moisture level at the lower surface of the floor coating

AP 204

Figure 4.3 The effect of the water vapor permeability of the concrete slab on the moisture balance of the slab structure. Section type AP 204.

AP 205:

Figure 4.4 The effect of the water vapor permeability of the concrete slab on the moisture balance of the slab structure. Section type AP 205.

AP 206:

Figure 4.5 The effect of the water vapor permeability of the concrete slab on the moisture balance of the slab structure. Section type AP 206.

4.1.2 Effect of the relative humidity of the indoor air and the water vapor permeability of the floor covering on the moisture balance of slab-on-ground structures

The effect of the relative humidity of the indoor air on the moisture balance of slab-on-ground structure was studied by variations of the indoor humidity in the range $RH_i \sim 25 \dots 50 \%$. The vapor resistance of the floor covering varied between $Z_p \sim 20 \dots 180 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$.

All the section types were calculated in 12 different variation cases **a – l** as shown below. The other thermal and moisture parameters are shown in Table 4.1.

Variations of the indoor air relative humidity:

- a and i:** relative humidity of the indoor air $RH_s = 25 \%$ or $RH_s = 50 \%$
vapor resistance of the floor covering $Z_p = 20 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$
- b and j:** relative humidity of the indoor air $RH_s = 25 \%$ or $RH_s = 50 \%$
vapor resistance of the floor covering $Z_p = 30 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$
- c and k:** relative humidity of the indoor air $RH_s = 25 \%$ or $RH_s = 50 \%$
vapor resistance of the floor covering $Z_p = 50 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$
- d and l:** relative humidity of the indoor air $RH_s = 25 \%$ or $RH_s = 50 \%$
vapor resistance of the floor covering $Z_p = 75 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$
- e and m:** relative humidity of the indoor air $RH_s = 25 \%$ or $RH_s = 50 \%$
vapor resistance of the floor covering $Z_p = 100 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$
- f and n:** relative humidity of the indoor air $RH_s = 25 \%$ or $RH_s = 50 \%$
vapor resistance of the floor covering $Z_p = 125 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$
- g and o:** relative humidity of the indoor air $RH_s = 25 \%$ or $RH_s = 50 \%$
vapor resistance of the floor covering $Z_p = 150 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$
- h and p:** relative humidity of the indoor air $RH_s = 25 \%$ or $RH_s = 50 \%$
vapor resistance of the floor covering $Z_p = 180 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$

Limit values: indoor air $t_i = +19 \text{ }^\circ\text{C}$, $RH_i = 25$ or 50% .
subsoil $t_s \sim +12 \dots +24 \text{ }^\circ\text{C}$, $RH_s = 100 \%$.

An increase of the indoor air humidity increases the moisture level at the lower surface of the floor covering. The critical temperature of the subsoil was $t_s = +18^\circ\text{C}$ as the relative humidity of the indoor air was $RH_i = 50\%$. The critical temperature with drier indoor air $RH_i = 25 \%$ was $t_s = +21^\circ\text{C}$. At lower subsoil temperatures condensation did not occur in any cross-section type or parameter combination. The theoretical limit value for the permeability of the floor covering was $Z_p = 50 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$. With more permeable covering materials the relative humidity did not exceed the limit value $RH = 75\%$ at any parameter variation or cross-section. The decrease of the relative humidity of the indoor air allows the use of higher resistance floor coverings. The limit value for the vapor permeability of the floor covering was $Z_p = 125 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$ when the indoor air humidity was $RH_i = 25 \%$.

AP 201:

a)

Figure 4.6 Effect of the relative humidity of the indoor air and the vapor permeability of the floor coating on the moisture content of the surface structure. Cross-section type AP 201.

AP 204:

a)

b)

Figure 4.7 Effect of the relative humidity of the indoor air and the vapor permeability of the floor coating on the moisture content of the surface structure. Cross-section type AP 204.

AP 205:

a)

b)

Figure 4.8

Effect of the relative humidity of the indoor air and the vapor permeability of the floor coating on the moisture content of the surface structure. Cross-section type AP 205.

RH 206:

a)

b)

Figure 4.9 Effect of the relative humidity of the indoor air and the vapor permeability of the floor coating on the moisture content of the surface structure. Cross-section type AP 206.

4.1.3 Effect of the material of the insulation and the water vapor permeability of the floor covering on the moisture balance of slab-on-ground structures.

The effect of the insulation material on the moisture balance of the slab-on-ground structure was studied with variations of the vapor permeability and thickness of the insulation material. The variation range of the vapor resistance was $Z_p \sim 20 \dots 180 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$.

With both cross-section types AP 201 and AP 205 six different variation cases **a – f** were studied as shown below. The other thermal and moisture parameters were as in Table 4.1.

Variations of the insulation material and thickness:

- a:** water vapor permeability of the insulation $\delta_p = 1,2 \times 10^{-12} \text{ kg/m} \cdot \text{s} \cdot \text{Pa}$ (polystyrene)
thermal conductivity of the insulation $\lambda = 0,037 \text{ W/m} \cdot ^\circ\text{C}$
water vapor resistance of the floor coating $Z_p = 20 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$
- b:** water vapor permeability of the insulation $\delta_p = 85 \times 10^{-12} \text{ kg/m} \cdot \text{s} \cdot \text{Pa}$ (mineral wool)
thermal conductivity of the insulation $\lambda = 0,041 \text{ W/m} \cdot ^\circ\text{C}$
water vapor resistance of the floor coating $Z_p = 20 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$
- c:** water vapor permeability of the insulation $\delta_p = 1,2 \times 10^{-12} \text{ kg/m} \cdot \text{s} \cdot \text{Pa}$ (polystyrene)
thermal conductivity of the insulation $\lambda = 0,037 \text{ W/m} \cdot ^\circ\text{C}$
water vapor resistance of the floor coating $Z_p = 50 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$
- d:** water vapor permeability of the insulation $\delta_p = 85 \times 10^{-12} \text{ kg/m} \cdot \text{s} \cdot \text{Pa}$ (mineral wool)
thermal conductivity of the insulation $\lambda = 0,041 \text{ W/m} \cdot ^\circ\text{C}$
water vapor resistance of the floor coating $Z_p = 50 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$
- e:** water vapor permeability of the insulation $\delta_p = 1,2 \times 10^{-12} \text{ kg/m} \cdot \text{s} \cdot \text{Pa}$ (polystyrene)
thermal conductivity of the insulation $\lambda = 0,037 \text{ W/m} \cdot ^\circ\text{C}$
water vapor resistance of the floor coating $Z_p = 180 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$
- f:** water vapor permeability of the insulation $\delta_p = 85 \times 10^{-12} \text{ kg/m} \cdot \text{s} \cdot \text{Pa}$ (mineral wool)
thermal conductivity of the insulation $\lambda = 0,041 \text{ W/m} \cdot ^\circ\text{C}$
water vapor resistance of the floor coating $Z_p = 180 \times 10^9 \text{ m}^2 \cdot \text{s} \cdot \text{Pa} / \text{kg}$

Limit values: indoor air $t_i = +19 \text{ }^\circ\text{C}$, $\text{RH}_i = 50 \text{ } \%$.
subsoil $t_s \sim +12 \dots +24 \text{ }^\circ\text{C}$, $\text{RH}_s = 100 \text{ } \%$.

In addition, the effect of the thickness of the insulation layer, $h_{in} = 50 \dots 150 \text{ mm}$, was studied with cross-section type AP 205 (water vapor permeability of the insulation $\delta_p = 1,2 \times 10^{-12} \text{ kg/m} \cdot \text{s} \cdot \text{Pa}$).

Figure 4.10 The effect of the insulation and vapor permeability of the coating material on the relative humidity of the surface structure. AP 201

Figure 4.11 The effect of the insulation and vapor permeability of the coating material on the relative humidity of the surface structure. AP 203.

Figures 4.10 and 4.11 indicate that insulation with a low vapor permeability decreases the relative humidity at the lower surface of the floor coating approximately 2 ... 4% in comparison to structures with a high-permeability insulation layer. Furthermore, the limit temperature that induces condensation inside the insulation layer is lower when a high-permeability insulation material is used. This occurs most clearly in variations with cross-section type AP 205.

Figure 4.12 The effect of the vapor permeability and thickness of the insulation layer on the moisture balance of the slab-on-ground structure. Cross-section type AP 205.

Figure 4.12 indicates that doubling the insulation thickness decreases the relative humidity at the lower surface of the coating approximately by 5% units. The increased thickness of the insulation has also an indirect effect on the moisture balance of the structure by reducing the heat flow into the subsoil and lowering the temperature and partial pressure of the water vapor of the fill layers.

4.2 Ventilated slab-on-ground structure under steady state conditions

This chapter concerns one of the most common repair methods of moisture damaged slab-on-ground structures, the so-called ventilated slab structure, its theoretical behavior and design.

4.2.1 Ventilated slab-on-ground structure

One of the repair methods of the moisture damaged slab-on-ground structure is a ventilated slab structure constructed on top of the old damaged ground slab (Figure 4.13). In this method the floor coverings of the old slab are removed and a ventilation duct is created on top of the old structure by profiled steel bars, profiled plastic sheets, studs, macadam, expanded clay aggregate or some other suitable structure or material combination. If the ventilation is arranged properly, there is no limitation for the materials and permeability of the new floor covering material. The ventilation of the duct is arranged either gravitationally into the indoor air or by separate exhaust ventilation. The facts to be considered while designing this kind of slab structures are:

- the optimum thickness of the new floor structure (the space required for the door operations)
- the continuity of the ventilation duct through the separating walls (possible perforation)
- the sound reduction characteristics and requirements of the new structure.

Figure 4.13 Principle diagram of the repair method of the moisture damaged slab-on-ground structure. Alternative ventilation methods of the ventilated slab-on-ground structure.

The placing of the inlet and outlet ducts is convertible (Figure 4.14) and different places cause different theoretical currents of air inside the duct /14/. In alternative a, the inlet of the ventilation air is along three sides of the slab structure and the outlet is placed in the middle of the fourth side of the floor. In alternative b, the inlets are at the four corners of the slab and the outlet is in the middle of the slab span. In alternative c, the

air flows directly across the floor from one side to another. Figure 4.14 c presents the situation of the ventilation type c if the adjacent sides along the airflow are not airtight.

Figure 4.14 Ventilation methods of the air duct.

The joints between the new floor structure and the wall vary depending on the function of the interface. The joint may work as an inlet or outlet duct for the ventilation or as an airtight seal for the floor duct. The principle ideas of the inlet or outlet interfaces of the floor and the wall are shown in Figure 4.15.

Figure 4.15 The interface joints between the wall and the new floor structure.

The airflow in the duct carries moisture evaporating from the old slab surface. The limit condition for the airflow and the structural capacity of the new structure is that the relative humidity of the ventilating air remains below the saturated humidity or that the set limit value for the relative humidity is not exceeded. The required ventilation volume depends on the relative humidity and temperature of the air duct air, the initial humidity and temperature of the ventilation air and the subsoil temperature and moisture flow through the slab structure.

The moisture behavior of the ventilated slab structure has been studied in Sweden /14/. According to measurements, the ventilation of the slab-on-ground structure reduces the relative humidity of the slab surface. However the effect does not extend too deep into the slab, especially if the base of the concrete layer is connected with the free water surface and there is capillary flow through the slab structure.

This repair method is valid in cases where the moisture flow through the slab structure is relatively high (capillary flow) and the other repair methods have proved insufficient or uneconomical.

4.2.2 Principles of the design

The moisture rate passing through the ventilation duct (Figure 4.16) with the dimensions height b , width d and length l is according to equation (4.1) /22/:

$$G = R \cdot (v_a - v_a^0) \quad [\text{kg/s}] \quad (4.1)$$

where $R = b d u$ = air flow [m^3/s] and u = an average speed of air.

The moisture flow per width unit of a duct ($d = 1 \text{ m}$) changes the formula into the equation (4.2) /22/:

$$g = (b \cdot u / l) \cdot (v_a - v_a^0) \quad [\text{kg}/\text{m}^2 \text{ s}] \quad (4.2)$$

The current of air in the duct is 4.3 /22/:

$$Q_a = A \frac{b^2}{12\eta} \frac{\Delta P}{l} \quad [\text{m}^3/\text{s}] \quad (4.3)$$

where A is the cross-sectional area of the duct ($= b \times d$), b is the height, d is the width and l is the length of the duct. ΔP means the pressure difference and η the viscosity of the air [Ns/m^2] (Figure 4.19).

Figure 4.16 Design of the ventilation duct. The dimensioning variables.

According to the measurements of Harderup /14/ the pressure decrease along the ventilation duct is $\Delta P = 1 \dots 2 \text{ Pa/m}$. Assuming that the air temperature in the duct remains constant the water vapor content of the ventilation air is (4.4) /22/.

$$v_a = v_- - (v_- - v_a^0) e^{-kx} \quad [\text{g/m}^3] \quad (4.4)$$

where v_a = water vapor content of the ventilation duct $[\text{g/m}^3]$
 v_- = water vapor content of the subsoil (beneath the slab) $[\text{g/m}^3]$
 v_a^0 = water vapor content of the incoming air $[\text{g/m}^3]$ (highest during the summer months)
 $k = 1/b \cdot u \cdot Z = d/Q_a \cdot Z$
 u = average speed of the air (m/s) = Q_a/A
 Z = water vapor resistance of the slab structure $[\text{s/m}]$
 x = distance from the inlet duct

The limit value for the relative humidity of the duct air is usually $\text{RH} = 75\%$ or less. The required current of air in a certain duct can be determined by the equation (4.5):

$$Q_a = \frac{x \cdot (d/Z)}{\ln(v_- - v_a^0) - \ln(v_- - v_a)} \quad (4.5)$$

The required duct height with a certain current of air is (4.6):

$$b = \sqrt[3]{\frac{12 \eta Q_a l}{\Delta P d}} \quad (4.6)$$

Equation 4.5 gives the design value for the required airflow of the ventilated slab-on-ground structure when the form and shape of the duct is known. As an example we could consider the situation of an uninsulated slab-on-ground structure where the relative humidity of the subsoil is $\text{RH} = 100\%$. The temperature of the ventilation duct is equal to the indoor temperature $T_i = +20^\circ\text{C}$ and the initial vapor content of the ventilating air is equal to the indoor air content $v = 12 \text{ g/m}^3$ ($\text{RH} \approx 69\%$). The total distance of the floor duct is $x = 20 \text{ m}$ from the inlet to the outlet channel and the water vapor permeability of the concrete slab is $\delta_p = 6,76 \cdot 10^{-7} \text{ kg/m} \cdot \text{s} \cdot \text{Pa}$. If the limit value for the ventilation air is $\text{RH} = 75\%$, the subsoil temperature and thickness of the slab dictate the required volume of ventilation (Figure 4.17). The subsoil temperature under an uninsulated slab is usually equal to the temperature of the slab and indoor air $T = 20^\circ$, and the required volume of ventilation air $Q = 20 \dots 30 \text{ m}^3/\text{h}$.

The capillary flow through a slab structure can be significantly higher than the diffusion flow. The equation (4.3) also applies in this case if the flow through the slab is determined by the equation (3.22). The maximum capillary flow values through the slab are presented in Figure 4.18.

Figure 4.17 The required ventilation flow of an uninsulated concrete slab structure in a 20 meter long duct as the thickness of the slab and temperature of the subsoil varies. Relative humidity of the subsoil $RH = 100\%$ and the temperature and vapor content of the duct and ventilation air are $T_i = 20^\circ\text{C}$, $v = 12 \text{ g/m}^3$

Figure 4.18 The maximum capillary flow values through the slab structure as the thickness and grade of concrete changes.

The relative humidity of the ventilation duct in a case where a $h_s = 80$ mm thick concrete slab is connected to the free water table is shown in Figure 4.19. The figure shows that the duct height of 10 mm is sufficient with all grades of concrete except K20. With this grade the relative humidity of $RH = 75\%$ is achieved with the duct height of 13 mm.

Figure 4.19 Relative humidity of the air duct: 80 mm thick concrete slab with a direct capillary contact with water table

The effect of the grade of concrete and the thickness of the slab on the capillary flow through the slab structure is shown in Figure 4.20.

Figure 4.20 The effect of the grade of concrete and the thickness of the slab on the capillary flow through the slab structure.

5 IN SITU SURVEY OF SLAB-ON-GROUND STRUCTURES

Earlier in this report the moisture and temperature behavior of slab-on-ground structures were examined by moisture equilibrium characteristics of the structural materials determined by laboratory tests and theoretical calculations under different steady state conditions. However, the actual operating conditions and the true behavior of a structure under these conditions can only be verified by a long-term survey of a real structure under the true climatic conditions. Therefore this study included long-term surveys of three slab-on-ground structures of three different buildings in Tampere and Järvenpää regions in Southern Finland. These surveys performed during 2000 – 2002 measured the long term development in temperature and water content of the fill and drainage layers as well as changes in temperature and humidity of the structural layers: insulation and concrete slab.

The survey included a row building in Tampere region built during late fall and winter of 2001 – 2002. The heating of the building started in February of 2002. Another case was a detached house in Järvenpää, built during summer and fall of 2001. This house has a massive concrete slab ($h_c = 190$ mm) and a floor heating system including an exceptionally thick polystyrene insulation layer $h_i = 200$ mm. The third case was an office building in Hervanta region near Tampere, built during winter of 2002. The heating season of this building started in late spring of 2002.

Instrumentations in all of these survey cases were similar. The measured variables were the temperature and water content of the fill layers and relative humidity and temperature of the slab and insulation layer. The unique instrumentation and conditions in each individual survey case are presented in Chapters 5.1 – 5.3.

5.1 Detached house in Järvenpää

The detached house in Järvenpää region had a floor heating system and a massive concrete slab ($h_c = 190$ mm) with an exceptionally thick insulation layer ($h_i = 200$ mm). The floor heating system includes an air tubing cast inside the massive slab, an air heater and an air blower that circulates the heated air through the tubing. The tubing is separated in room units each of which has an independent control unit for adjusting the heat power by the indoor air temperature.

The plan and the structural layers of the slab structure are shown in Figure 5.1. The slab structure was identical in all three measuring points. The thickness of the concrete slab was $h_c = 190$ mm, thickness of the polystyrene insulation $h_i = 200$ mm and the thickness of the macadam fill layer $h_m = 300$ mm.

Figure 5.1 The plan and structural layers of the slab-on-ground structure. The detached house in Järvenpää region.

The calibration of used water content sensors was performed with crushed stone samples taken from the fill material in site. The grain distribution curve of the fill is shown in Figure 5.2.

Figure 5.2. Grain distribution curve of the crushed stone used as a fill layer in the detached house in Järvenpää.

5.1.1 Instrumentation

Two measuring points were chosen in two different heating circuits along the slab (Figure 5.3). The instrumentation in the *living room* measured temperatures of the slab and insulation as well as the water content and temperature of the crushed stone fill. The instrumentation in the *hobby room* measured temperatures of the fill, insulation and slab as well as water content of the fill. In addition the relative humidity of the slab and insulation as well as the relative humidity and temperature of the indoor air were measured from the cross-section in the hobby room. The outdoor temperature and relative humidity was measured with the sensors assembled through the wall at the north side of the building.

The temperature and water content sensors were assembled into crushed stone layers during the construction of the slab in early summer 2001. The water content was measured with the PTC sensors /20/ calibrated with the used fill material before assembly. The sensors were mounted to the plastic tubes together with the temperature sensors and placed into the crushed stone fill before the assembly of the insulation. The cast day of the massive slab was 26.6.2001 and the first measurements were performed 29.6.2001. At the same time before the cast the mounting tubes for the relative humidity and temperature sensors were assembled firmly into their positions and fastened to the reinforcement of the slab. Humidity and temperature sensors of the slab and insulation as well as the indoor and outdoor temperature and humidity sensors were assembled with the automatic data acquisition system in December 2001. The heating of the slab began on week 36 of year 2001.

The automatic data acquisition system included a HP 34970A data-logger and a portable computer together with the required cable work for the sensors.

Individual manual measurements were performed 29.6.2001, 15.8.2001, 30.8.2001 and 29.9.2001. The automatic measuring device was activated on 17.12.2001. After this date the sensor data was collected automatically three times a day every 8 hours. The types and assembly levels of each individual sensor at all three measuring points are shown in Figures 5.4 and 5.5 and in Tables 5.1 – 5.3. The 0 –level is the lower surface level of the concrete slab.

Figure 5.3 Detached house in Järvenpää: heating circuits of the slab and three measuring points: living room, storage and hobby room.

Table 5.1 Instrumentation, assembly levels and sensor types of the measuring point in living room. The detached house in Järvenpää. Lower surface level of the ground slab = ± 0 cm.

Measuring point: Living room				
Sensor code	Measuring variable	level [cm]	layer	Sensor type
JOT1	Temperature	+2	Slab	T
JOT2	Temperature	-8	Insulation	T
JOT3	Temperature	-16	Insulation	T
JOW4	Water content	-21	Insulation	PTC
JOT6	Temperature	-42	Insulation	T
JOW6	Water content	-42	insulation	PTC

Figure 5.4 Sensor types and levels of the measuring points in the living room.

Table 5.2 Instrumentation, assembly levels and sensor types of the measuring point in the hobby room. The detached house in Järvenpää. Lower surface level of the ground slab = ± 0 cm.

Measuring point: Hobby room				
Sensor code	Measuring variable	level [cm]	layer	Sensor type
JAT1	temperature		slab	HT/T
JARH1	RH		slab	HT/T
JAT2	temperature		slab	HT/T
JARH2	RH		slab	HT/T
JAT3	temperature		insulation	HT/T
JAT4	temperature	+4	slab	HT/T
JAW4	water content	+4	slab	PTC
JAT5	temperature	-4	insulation	T
JAW5	water content	-4	insulation	PTC
JAT6	temperature	-14	insulation	T
JAW6	water content	-14	insulation	PTC
JAW7	water content	-21	fill	PTC
JAT8	temperature	-40	fill	T
JAW8	water content	-40	fill	PTC

Figure 5.5..... Sensor types and levels of the measuring point in the hobby room. The detached house in Järvenpää.

5.1.1 Results of the in situ survey

Period 17.12.2001 – 25.10.2002

Table 5.3 shows the measured water content levels of the fill layer between 29.6.2001...10.1.2002.

Table 5.3 Water content of the crushed stone fill 29.6.2001 ... 10.1.2002.

Measuring point and level	Water content [weight -%]				
	Date				
	29.6.2001	15.8.2001	30.8.2001	29.9.2001	10.1.2002
Living room					
-41 cm	5,9 %	5,6 %	5,6 %	5,8 %	5,1 %
-21 cm	4,6 %	4,9 %	4,9 %	4,6 %	2,8 %
Hobby room					
-40 cm	5,8 %	5,8 %	6,1 %	6,0 %	5,5 %

Figure 5.6 shows the temperature changes over the slab cross-section during 17.12.2001... 25.10.2002 in the living room measuring point.

Months 2001 -2002

Figure 5.6 Temperature changes over the slab cross-section in the living room measuring point during 17.12.2001 ... 25.10.2002.

Figure 5.7 Water content levels at the fill layer in the living room measuring point during 29.6.2001 ... 27.11.2002.

Due to the heating system of the slab the temperature of the concrete was relatively high during winter months 2001... 2002 as the average measured value was $T \approx +26^{\circ}\text{C}$. Therefore the fill temperature was also relatively high $T \approx +14^{\circ}\text{C}$ all winter long despite the thick, $h_i = 200 \text{ mm}$, insulation layer. In April the slab temperature decreased about 5 degrees and the measured fill temperatures followed, but only about half a degree. These conditions remained through the summer 2002. As the heating period started again in fall 2002 the fill temperature rose rapidly to temperatures $T = +14 \dots +15^{\circ}\text{C}$.

The water content of the fill layer was monitored at two levels. At the level -21 cm the sensor was mounted close to the insulation board but yet inside the fill mass, and at the level -41 cm the sensor was approximately 10 cm above the subsoil surface (Figure 5.7). As the measuring started shortly after the in situ cast of the slab in summer 2001, the water content level of the fill was high, between $4,5 - 6$ percent per weight. During the fall and winter 2001 – 2002 the upper part of the fill layer dried out significantly. In early spring 2002 the water content level at the upper sensor level -21 cm varied between $w = 2,5 \dots 3\%$. The water content in the lower part of the fill also decreased, but only about one percent by weight, to the level $w = 5\%$. In late spring 2002 the thawing of the surrounding subsoil was obvious and also visible in measuring data. By the end of March the water content at the lower sensor level had increased about 1% and at the upper level about 0.5% . The summer 2002 was extraordinary dry in Finland. This is again readable from the measured water levels. By the end of the summer and in early fall the upper part of the fill dried up close to the hygroscopic equilibrium moisture content in drying, $w \approx 1 \%$, at the relative humidity $\text{RH} = 100 \%$. Closer to the subsoil surface the water content remained close to $w = 5 \%$ through the summer and fall 2002.

Figure 5.8 shows the temperature changes in hobby room measuring point during 17.12.2001 ... 27.11.2002.

Figure 5.8 Temperature changes at the slab cross-section in the hobby room measuring point during 17.12.2001 ... 27.11.2002.

Figure 5.9 Changes of the water content level at the fill layer in the hobby room measuring point over the period of 29.6.2000...26.5.2002.

In addition to the water content and temperature sensors of the fill and slab structure the hobby room instrumentation included the relative humidity sensors of the indoor air, polystyrene and concrete layers. The building envelope of the room was not perfectly sealed during the winter of 2001 – 2002 and the leaks to the outdoor air are clearly visible under the measured indoor air conditions. Moreover, the power of the heating circuit in hobby room was relatively low during the heating season, and therefore slab temperatures remained lower than the ones measured from the living room.

During the last months of the year 2001 the heating power of the hobby room circuit was high and the fill temperature rose to the value $T = +12^{\circ}\text{C}$. In the beginning of the year 2002, heating power decreased and the fill temperature lowered radically down to $T = +8^{\circ}\text{C}$. During the spring the average slab temperature started to increase and so did the measured fill temperatures. By the end of the exceptionally warm and dry summer 2002 the fill temperature had reached its peak value $T = +14,3^{\circ}\text{C}$. The corresponding average slab temperature was $T = +22^{\circ}\text{C}$.

The water content of the fill layer close to the subsoil surface remained at the same level as in the living room measurements. The water content of the fill decreased slightly during the winter, approximately $\Delta w = -0,5\%$, but the thawing in March 2002 increased the water content to its peak level $w \approx 6,1\%$ (Figure 5.9).

Changes in the relative humidity and temperature of the slab structure and indoor air are shown in Figure 5.10. The slab remained uncoated throughout the survey. The relative humidity of the lower part of the slab remained relatively high at all times, $\text{RH} > 93\%$, despite of the relative humidity changes of the indoor air and temperature changes of the slab. This indicated that there is still a lot of excess structural moisture in the lower part of the slab, and the drying process of the massive concrete slab is yet unfinished. At the upper part of the slab, the indoor air temperature and relative humidity had a clear impact on the measured humidity values. As the slab temperature rose to the maximum on February – March, the relative humidity of the slab decreased to $\text{RH} = 50\%$. The heating power decreased later on during the spring and the relative humidity rose about 5%. As the heating system was turned off completely during the summer months in June – August 2002, the relative humidity of the slab rose to the value $\text{RH} \approx 65\%$.

Figure 5.10 Relative humidity and temperature changes in slab and indoor air.

5.2 Row house in Tampere

The row house in Tampere presented a typical slab-on-ground structure, where an about one meter high block footing was filled with compacted gravel (Figure 5.11). The slab structure included a $h_s = 80$ mm thick concrete slab and a $h_i = 50$ mm insulation layer of polystyrene underneath (Figure 5.12).

Instrumentation was assembled in a single apartment at the end of the building in three measuring points shown in Figure 5.12. The measuring points were chosen along the slab structure, one under the living room floor, one under the bathroom floor and one in the outer corner of the building under the bedroom floor. The apartment was heated by radiators. The bathroom was an exception because it had a floor heating system.

The fill layer was gravel. The grain distribution curve of the fill layer material is shown in Figure 5.13.

Figure 5.11 Structural cross-section of the row house in Tampere region.

Figure 5.12 The plan of the instrumented apartment and a cross-section of the slab-on-ground structure.

5.1.2 Instrumentation

During the construction period in late summer of 2001, the temperature and water content sensors were assembled into the fill layer. The assembly levels and types of the sensors are shown in Figure 5.14.

Figure 5.14 Water content and temperature sensor levels and types at the fill layer.

Table 5.5 The type and levels of measuring sensors assembled in the living room measuring point at the row house in Tampere. The level of the lower surface of the concrete slab = ± 0 cm

Measuring point: Living room				
Sensor code	Measuring variable	level [cm]	Structural layer	Type of sensor
POT1	temperature	-10	fill	T
POW1	water content	-10	fill	PTC
POT2	temperature	-20	fill	T
POW2	water content	-20	fill	PTC
POT3	temperature	-30	fill	T
POW4	water content	-35	fill	PTC
POW5	water content	-45	fill	PTC
POT6	temperature	-55	fill	T
POW6	water content	-55	fill	PTC

Table 5.6 The type and levels of measuring sensors assembled in the bedroom measuring point at the row house in Tampere. The level of the lower surface of the concrete slab = ± 0 cm

Measuring point: Bedroom				
Sensor code	Measuring variable	level [cm]	Structural layer	Type of sensor
PMT1	temperature	-10	fill	T
PMW1	water content	-10	fill	PTC
PMT2	temperature	-20	fill	T
PMW2	water content	-20	fill	PTC
PMT3	temperature	-30	fill	T
PMW5	water content	-45	fill	PTC
PMT6	temperature	-55	fill	T
PMW6	water content	-55	fill	PTC

Table 5.7 The type and levels of measuring sensors assembled in the bathroom measuring point at the row house in Tampere. The level of the lower surface of the concrete slab = ± 0 cm

Measuring point: Bathroom				
Sensor code	Measuring variable	level [cm]	Structural layer	Type of sensor
PKT1	temperature	-10	fill	T
PKW1	water content	-10	fill	PTC
PKT2	temperature	-20	fill	T
PKW2	water content	-20	fill	PTC
PKT3	temperature	-30	fill	T
PKW4	water content	-35	fill	PTC
PKW5	water content	-45	fill	PTC
PKT6	temperature	-55	fill	T
PKW6	water content	-55	fill	PTC

5.2.3 Results of the in situ survey

Period 6.2.2002 ... 20.10.2002

The heating season of the row house in Tampere began in February of 2002. At this point the average temperature was near $T = \pm 0^{\circ}\text{C}$ and even below that at the sensor levels closest to the concrete slab. The development of temperatures at the fill layer after the beginning of the heating period is shown in Figures 5.15, 5.17 and 5.19. The changes in corresponding water contents are shown in Figure 5.16, 5.18 and 5.20.

Figure 5.15 The temperatures of the fill layer at the living room measuring point since the heating season started. Period 6.2.2002 ... 20.10.2002.

Figure 5.16 Results of the water content measurements of the fill in the living room measuring point. Period 6.2.2002 ... 10.1.2003.

Before the heating period of the row house started in February of 2002, the temperature of the fill in the living room measuring point was below zero at the upper part of the layer and approximately $T = +2^{\circ}\text{C}$ half a meter below the slab surface. Since the heating started, the fill temperatures began to increase rapidly. The increase was over 10 degrees in less than two months and the average temperature of the fill was $T = +12^{\circ}\text{C}$ in the beginning of April. At the same time the water content of the fill layer decreased to less than one percent per weight from initial values of $w = 1,5 \dots 2,5\%$.

The moderate elevation of the fill temperature continued throughout the early spring of 2002. In late May and early June the building was occupied permanently and the adjustment of the indoor temperature to fit the preferences of a new inhabitant shows in measurements as a rapid rise of the fill temperature. The fill temperature at the living room measuring point steadied to the level $T \approx +18,5^{\circ}\text{C}$ by the end of September 2002 as the heating period started. The water content of the fill simultaneously decreased to the level $w \approx 1\%$ (Figure 5.16) which corresponds to the equilibrium water content of this type of a material at the relative humidity $\text{RH} = 100\%$.

According to the parallel measurements in bedroom and bathroom measuring points the overall temperature and moisture behavior of the fill was very congruent anywhere under the slab. However at the bedroom measuring point there is a distinct temperature gradient between successive temperature sensors due to the placing of the sensors very close the salient corner of the building (Figure 5.12) and the heat flow through the slab into the surrounding subsoil. The measured initial water content values of the fill were also slightly higher at this measuring point, approximately $w = 3\%$.

The elevation of the fill temperature was similar to that in the living room, and so was the end temperature of the fill $T \approx 18,5^{\circ}\text{C}$. The water content of the fill reduced to the steady value $w = 2\%$ during the late summer and early fall 2002 (Figure 5.18).

At the bathroom measuring point the development of the fill temperature was similar to the other observations. However, the bathroom had an electric floor heating and its influence on the measured fill temperatures is clearly visible since the beginning of March of 2002. Between April and June the fill temperature increased rapidly: $\Delta T = 6^{\circ}\text{C}$ to $T = +19^{\circ}\text{C}$. By the end of August the fill temperature had steadied to the value $T \approx 22^{\circ}\text{C}$.

The water content of the fill at the bathroom measuring point was notably higher than at the parallel measuring points. The initial water content 0,5 meters below the slab surface was $w = 5\%$ and the intense warming-up decreased the content to an average value of $w = 3,5\%$ by the end of August. In the upper part of the fill closer to the slab the water content was significantly lower and the rapid drying of the fill due to the temperature rise is clearly visible. Here the end value of water content was again close to the hygroscopic equilibrium moisture content in drying, $w \approx 1\%$.

Figure 5.17 Temperature changes of the fill at the bedroom measuring point 6.2.2002...10.1.2003.

Figure 5.18 Water content changes of the fill at the bedroom measuring point 6.2.2002 ... 20.1.2002.

Figure 5.19 Temperature changes of the fill at the bathroom measuring point 6.2.200...3.12.2002.

Figure 5.20 The water content measurements of the fill layer at the bathroom measuring point 6.2.2002 ... 3.12.2002.

5.3 Office building in Hervanta

The office building in the Hervanta region was an annex of an older office complex. The construction period of the new wing was fall and winter of 2001 – 2002. The width of the wing was 15 meters and the total length approximately 35 meters (Figure 5.21). The heating period of the new annex began in early spring of 2002. The structure is founded on bedrock and gravel fill. The cross-section of the slab-on-ground structure is shown in Figure 5.21 and a detailed description of the instrumentation is presented in the following chapter.

Figure 5.21 Floor plan of the office building and the locations of three measurement points at the floor slab.

Measuring point 3 was placed close to the outer wall of the building where the thickness of the drainage layer was over 1 meter. The insulation thickness at this area was also greater, about $h_i = 100$ mm. Measuring points 1 and 2 were at the middle section of the slab and there was a 200 mm thick drainage layer (Figure 5.22) on top of the general fill material, which was coarse gravel.

Figure 5.22 The grain distribution curve of the fill layer of the office building in Hervanta.

5.3.1 Instrumentation

The temperature and water content sensors were placed in three measuring points along the slab surface (Figure 5.21) on levels shown in Figure 5.23. The types and levels of individual sensors are listed in Tables 5.10 – 5.12.

Figure 5.23 Types and levels of the measuring sensors in the office building in Hervanta.

Table 5.9 Sensor types and levels at measuring point 1. The level of the lower surface of the concrete slab = ± 0 cm

Measuring point 1				
Sensor code	Measuring variable	Level [cm]	Structural layer	Sensor type
H1T1	temperature	-10	drainage layer	T
H1W1	water content	-10	drainage layer	PTC
H1T2	temperature	-20	drainage layer	T
H1W2	water content	-20	drainage layer	PTC
H1W3	water content	-30	fill	PTC
H1W4	water content	-35	fill	PTC
H1W5	water content	-45	fill	PTC
H1W6	water content	-55	fill	PTC

Table 5.10 Sensor types and levels at measuring point 2. The level of the lower surface of the concrete slab = ± 0 cm

Measuring point 2				
Sensor code	Measuring variable	level [cm]	Structural layer	Sensor type
H1T1	temperature	-10	drainage layer	T
H1W1	water content	-10	drainage layer	PTC
H1T2	temperature	-20	drainage layer	T
H1W2	water content	-20	drainage layer	PTC
H1W3	water content	-30	fill	PTC
H1T4	temperature	-40	fill	T
H1W4	water content	-40	fill	PTC
H1W5	water content	-50	fill	PTC
H1W6	water content	-60	fill	PTC

Table 5.11 Sensor types and levels at measuring point 3. The level of the lower surface of the concrete slab = ± 0 cm

Measuring point 3				
Sensor code	Measuring variable	level [cm]	Structural layer	Sensor type
H3T1	temperature	-15	drainage layer	T
H3W1	water content	-15	drainage layer	PTC
H3T2	temperature	-25	drainage layer	T
H3W2	water content	-25	drainage layer	PTC
H3W3	water content	-35	fill	PTC
H3W4	water content	-40	fill	PTC
H3W5	water content	-50	fill	PTC
H3T6	temperature	-60	fill	T
H3W6	water content	-60	fill	PTC

5.3.2 Results of the in situ survey

The continual measurements at the office building were started in June of 2002. The results of the temperature measurements during the period 4.6.- 23.10.2002 are shown in Figures 5.24 – 5.26. Figure 5.27 shows the temperature and relative humidity changes over the structural slab cross-section at measuring point 2 including the temperature and relative humidity of the indoor air.

Figure 5.24 Temperature development of the fill layer at the measuring point 1 4.6. – 23.10.2002.

At measuring points 2 and 3 (Figures 5.24 and 5.25) the temperature changes were alike. The temperature rose from $T = +16^{\circ}\text{C}$ in early June to $T = +18,5^{\circ}\text{C}$ by the end of August. The distribution in depth at each measuring point was relatively even, the maximum measured temperature difference between the topmost and lowest sensor was only 2°C –degrees.

The temperature of the concrete slab was close to $T = +20^{\circ}\text{C}$ throughout the summer of 2002 and it follows the marginal changes of the indoor air temperature (Figure 5.25). The average indoor air temperature in the small computer room remained relatively high because of the several heat generating equipments in the space.

Figure 5.25 Temperature changes in the slab cross-section at the measuring point 2 during 4.6. – 23.10.2002

The relative humidity at the lower part of the insulation layer remained close to RH=95% throughout the measuring period (Figure 5.27). The relative humidity of the slab also remained in a steady state as the humidity at the lower part of the slab was RH= 80% and close to the surface RH = 65%. The slab was coated throughout the measuring period.

At measuring point 3 (Figure 5.26) there was an unidentified heat source at the level -30 cm below the slab surface that heated up the fill close to $T = +25^{\circ}\text{C}$. In early fall this source had disappeared and the temperatures of the fill had decreased to the same level with the parallel measuring points.

Figure 5.26 Temperature changes of the fill at the measuring point 3 4.6. – 20.9.2002.

Figure 5.27 Relative humidity changes of the slab cross-section at the measuring point 2 during 4.6. – 23.10.2002.

Figure 5.28 presents water content changes at all three measuring points during the measuring period of 4.6. – 23.10.2002.

Figure 5.28 Water content changes of the fill at all three measuring points during 4.6. – 23.10.2002.

According to the measurements the water content of the fill layer remained between 1–3% throughout the summer. The drying of the fill at the measuring point 2 is clearly visible. In early September the water content clearly increased due to the rain and voluminous irrigation of the surrounding plantation.

5.4 Evaluation of the results

Temperature behavior of the fill and drainage layers

Special attention was paid to the temperature changes of the fill layer due to the heating of the building and slab.

In the row house in Tampere the heating season began in midwinter of 2002 and the initial temperature of the fill was below zero degrees and the upper part of the layer was frozen. The elevation of the fill temperature during the heating period was rapid as the average temperature of the layer increased to $T = +13^{\circ}\text{C}$ by the end of March in only four weeks. The insulation of the slab was a 50 mm thick polystyrene board. After the permanent residents moved into the apartment in early June 2002 the temperature of the fill increased again rapidly to correspond to the increase of the indoor air temperature.

The sensors for measuring the temperature distribution in the fill at the bedroom measuring point were placed close to the external corner of the building. The heat flow through the slab and fill layer into the cooled surrounding subsoil is clear in this measuring point.

The floor heating of the bathroom floor had also a marked effect on the measured fill temperatures. The fill temperature under the bathroom floor was over $T = +22^{\circ}\text{C}$ during the summer of 2002, while anywhere else along the slab it remained well under $+20^{\circ}\text{C}$ – degrees.

Figure 5.29 The average temperature changes of the fill layer in all three measuring points in the row house in Tampere

The detached house in Järvenpää was built during summer and fall of 2001, and the building was already partially heated in winter of 2001. The heating system of the house was a floor heating that included an air tubing cast inside the massive slab, an air heater and an air blower that circulated the heated air through the tubing. The tubing was separated in room units, each of which had an independent control unit for adjusting the heating power by the indoor air temperature. The thickness of the massive in situ cast concrete slab was $h_c = 190$ mm and the thickness of polystyrene insulation underneath it was $h_i = 200$ mm. The measured temperatures of the fill under the heated building part remained relatively steady, $T = +14...+15^\circ\text{C}$, during the entirely measuring period 2001–2002. During the summer of 2002 the fill temperature decreased to $+14^\circ\text{C}$ due to the lack of heating but rose rapidly to the value $T = +15^\circ\text{C}$ as the heating period of the building started in fall of 2002. The fill temperature under the hobby room varied strongly due to the changes of the heating power in the room's heating circuit. The measuring point was also relatively close to the exterior wall, and the seasonal temperature changes in surrounding subsoil had also an effect on the measured temperatures. As the heating power settled by the end of the summer 2002, the fill temperature also rose to the same level as at the living room measuring point, $T \approx +14^\circ\text{C}$ (Figure 5.30).

Figure 5.30 The temperature changes of the fill layer in detached house in Järvenpää.

The office building in Hervanta had a shorter heating period than the other survey cases as the building was completed by the spring of 2002. The slab of the new annex consists of a 80 mm thick concrete slab and a 50 mm polystyrene layer as an insulation underneath it. Wind had an effect on the air conditioning system and during the hot summer of 2002 the indoor air was cooled in comparison to the high daytime temperatures of the outdoor air. The cooling is also visible in the temperature measurements of the fill layer. The fill temperature remained relatively low through

summer of 2002 until the cooling of the indoor air was stopped in August of 2002, and the heating period of the building started. Temperature changes in measuring point 1 and 2 are almost identical (Figure 5.33).

Figure 5.33 Temperature changes of a fill layer at the measuring points of the office building in Hervanta.

Water content of the fill and drainage layers

In the detached house in Järvenpää the water content measurements of the crushed stone fill began just one week after the casting of the slab in June of 2002. The results of the long term survey at two measuring points are shown in Figure 5.34. The grain size distribution of the crushed stone fill was such that the proportion of grains smaller than 1 mm in the mass was approximately 25%. This indicates that the fill material was capillary. The water content of the fill was relatively high immediately after the cast of the cast-in-situ concrete slab. The water content of the lower part of the fill layer was $w = 6\%$ and near insulation $w = 5.5\%$. During fall and winter of 2001-2002 the upper part of the fill dried out to the level $w = 2\%$, until in March there was a distinctive increase in water contents ($\Delta w = 0.5\%$) due to thawing of the surrounding subsoil. The dry and warm summer reduced the moisture content to $w \approx 1\%$, which corresponds to the hygroscopic equilibrium moisture content of coarse-grained materials in drying.

The measured water content changes at the hobby room measuring point were almost equal to those of the living room. Only the increase 2002 in late March – April was clearly stronger than in the living room due to the placing of the sensors closer to the outer wall and the stronger effect of the thawing waters near the footings.

Figure 5.34 Water content changes of the fill layer of the detached house in Järvenpää 29.6.2001 – 25.10.2002.

The row house in Tampere. The water content changes of the fill in all three measuring points are shown in Figure 5.35. The water content of the layer varied between $w=1\ldots5\%$. The water content of the fill layer near the insulation board had dried out to value $w\approx 1\%$, close to hygroscopic equilibrium moisture content again. In late summer 2002 a slight increase of water contents was detected due to the rains in the area.

Figure 5.35 Water content changes of the fill in the row house in Tampere during 6.2.2002 ...20.10.2002.

The office building in Hervanta. The water content changes of the fill at three measuring points are shown in Figure 5.28. The proportion of grains smaller than 1 mm was about 30 %, which indicates that the fill material was capillary. By the early summer of 2002 the water content of the measuring points 1 and 3 near the outer walls of the building had reached an equilibrium state as the water content in these points was approximately $w = 1...2$ %. By contrast, in the middle of the slab span at measuring point 2 the fill was still clearly drying during early summer of 2002. During the summer and fall the water content decreased about $\Delta w = 1\%$ to an average level $w = 1,5\%$. In mid September 2002 there was a clear increase in water contents of the fill layer, most intense in measuring points 1 and 2. At point 1 the content rose rapidly about 2% and a few days later at point 2 about 0,25 %. The reason for this is most likely the rains that occurred in the area at that time.

Temperature and moisture distribution at the slab cross-sections

The detached house in Järvenpää. The instrumentation of the structural cross-section was assembled at the hobby room measuring point. Since the beginning of the survey period in December of 2001 the slab temperature was high $T \approx +28^\circ\text{C}$ due to the drying process of the massive slab (Figure 5.8). During this heating period the temperature difference between the slab and indoor air was almost 10 degrees because the hobby room space was not yet completely insulated at that time. For the same reason the indoor air humidity was extremely low, only about $RH = 25\%$. The drying effect of these conditions was very high as the slab surface was not coated. Therefore the relative humidity of the upper part of the slab decreased down to the level $RH = 50\%$ during that period.

Figure 5.36 Relative humidity changes of the slab cross-section during 1.1.2002...20.10.2002. Detached house in Järvenpää.

In spring the heating power went down, and as the temperature of the slab decreased the relative humidity of the slab increased to the average value $RH = 70\%$. At the same time the average indoor air humidity rose to $RH = 55\%$. At the lower part of the massive concrete slab the relative humidity of the slab remained at the level $RH = 95\%$ throughout the survey period without any significant changes.

The row house in Tampere. The surveyed slab cross-section was at the boiler room. The indoor temperature of this space remained extremely high $T \approx 30^\circ\text{C}$ and so were the measured slab temperatures (Figure 5.37). The relative humidity of the indoor air varied between $RH = 20 \dots 40\%$ (Figure 5.37 and 5.38).

The relative humidity of the lower surface of the insulation layer was throughout the survey period over $RH > 95\%$. On the other hand, the relative humidity of the slab began to decrease during the fall 2002 as the indoor air humidity decreased. This indicated that the slab had reached the hygroscopic equilibrium moisture balance with its surroundings.

Figure 5.37 The temperature changes of the slab in boiler room during 6.2. – 20.10.2002. The row house in Tampere.

The office building in Hervanta. The slab instrumentation was located at measuring point 2 in the middle of the slab span (Figure 5.21). According to Figures 5.26 and 5.28 the structure had already reached the equilibrium moisture content by the time the survey started. Changes in the indoor air humidity are clearly visible in the humidity measurements of the concrete slab. The relative humidity of the lower part of the insulation remained clearly over RH = 90% throughout the survey period.

Figure 5.38 Relative humidity changes of the boiler room floor during 6.2. – 20.10.2002.

6 TYPICAL MOISTURE DAMAGES IN SLAB-ON-GROUND STRUCTURES IN FINLAND

6.1 Case study review

This chapter includes a summary of several case studies on moisture damaged slab-on-ground structures. The objective was to gather up the available information on previously detected moisture problems and to draw some conclusions of the typical moisture damages in slab-on-ground structures.

Some of the cases are not moisture damaged at all, but the inspection of the slab conditions was performed as a part of a general condition survey of the building. These ‘healthy structure’ summaries are included in this study as a valuable addition to the survey of the actual slab-on-ground conditions.

Usually the referred case study material included some sort of a damage or condition report of the structure, which was edited into the report card summary enclosed as an appendix to this report (Appendix 1). The report card information includes the general information of the building: age, purpose of use, size, repair history, detailed information on the slab-on-ground structure: structural layers and materials as well as the results of performed temperature and moisture examinations and an estimation of the possible cause or mechanism causing the moisture damage in each studied structure.

The reasons for moisture damages in slab-on-ground structures are diverse. The ultimate cause may lie in structural faults as well as in overall conditions or changes in occupancy of the space or building. To facilitate the management of these varying reasons a simple classification of the moisture damages of slab-on-ground structures is presented.

6.1.1 Classification of the moisture damages of slab-on-ground structures

The common causes for the moisture damages of the slab-on-ground structures may be divided as follows:

- **Design fault**
A structure or a combination of structural materials does not satisfy the standards under current surrounding conditions. The structure may have been built according to the valid standards of the construction time but does not behave correctly in the light of modern knowledge. Typical errors are the lack of capillary barrier under the slab, lack of drainage and wrongly placed moisture barrier inside the slab structure.
- **Construction fault**
The actual construction of a structure does not follow the plan or instructions. A typical mistake is premature coating of the concrete floor.
- **Repair fault**
A structure is repaired without precise knowledge of the reasons causing the moisture damage. The wrong repair method may produce more severe and more extensive problems with the slab. A repair fault is often caused by rashly

performed alterations in structure surfaces and coatings as the occupancy of the space or building changes. A classical example is the conversion of a basement storage into residential use.

- **Conditions and maintenance related damages**

Unexpected changes under surrounding conditions or negligence in maintenance may lead to an increase in the moisture load and a moisture damage. Typical unexpected conditions changes are pipe leaks or fire fighting waters as well as excessive use of water in cleaning processes. A common maintenance related damage is the plugging of drainage pipes or rainwater drains.

6.1.2 Case studies

Most of the studied cases (Table 6.1) deal with public buildings, such as schools, day-care centers, shopping malls, hospitals etc. This is due to the fact that most of the case reports were delivered by the municipal organizations responsible for the real estates of the towns and municipalities or institutions and companies mainly employed by the public offices. Moisture damages are also less common in detached and row houses than in public buildings and shopping malls with a large base area..

Table 6.1. The studied cases of moisture damaged slab-on-ground structures.

	Cases	
	number	%
Day-care centers	4	15,4
Other health care or social service buildings	2	7,7
Sport related buildings	2	7,7
Schoolings	11	42,3
Industrial buildings	1	3,8
Shopping malls	1	3,8
Other buildings - museum - library	2	7,7
Row houses	3	11,5
Summary	26	100

6.1.3 Analysis of the case studies

One of the focal reasons for moisture damages in slab-on-ground structures is the lack of insulation. Insufficient or absent slab insulation leads to extensive warming of the subsoil and an increasing diffusion flow through the slab structure. The increased flow may cause an exceeding of the critical moisture content in some structural layer, often at the lower surface of the floor coating. This type of problems is typically connected to the repair and conservation work of a building where a permeable floor covering is for some reason changed to a highly resistant material.

Another clear structural cause for moisture damages is the wrong placing of the vapor barrier. It is recommended not to place a vapor barrier in a slab-on-ground structure at all. The direction of the moisture flow varies during the lifespan of the structure as the

flow is directed downwards during the drying period of the concrete slab and is reversed towards the drier indoor air when the equilibrium state is attained. A vapor barrier is especially problematic in damage cases where a pipe leak wets the concrete slab and the barrier is placed underneath the slab. The excess moisture is now trapped between two high-resistance vapor barriers, the floor covering and the vapor barrier under the slab.

In several cases the fill layer under the slab structure does not form a sufficient or complete barrier against the capillary flow from the subsoil.

Often the increased moisture potential around the slab-on-ground structure is due to the ineffectiveness of the drainage layers and pipes around the building foundations.

Table 6.2 The most common structural faults detected in moisture damage cases.

Structural fault	Cases, number	Cases, %
Lack or insufficiency of thermal insulation	10	34,5
Lack of capillary barrier	11	37,9
Vapor barrier inside the slab structure	8	27,6
Total	29	100

Most common causes of moisture damages in studied cases

In most cases more than just one individual cause is responsible for the exceeding of the moisture capacity of the slab structure. Therefore it is usually impossible to point out the most significant factor among many probable causes.

The most probable causes of the detected moisture damages in the studied cases are here divided according to the classification presented earlier in Chapter 6.1.1:

- Design fault: about 80 % of all cases. Usually the structure is unfit in the light of present knowledge.
- Construction fault: about 15 % of all cases. In most cases the concrete slab is coated too early.
- Repair fault: about 35 % of all cases. Repairs are commonly performed without knowledge of the true reasons causing the trouble.
- Conditions and maintenance fault: about 30 % of all cases. Pipe leaks and insufficient drainage are very common.

7 PROPOSED DESIGN STANDARDS FOR THE MOISTURE BEHAVIOR OF SLAB-ON-GROUND STRUCTURES

7.1 Structural behavior

7.1.1 Limit values for the temperature and moisture design

The limit design values for the upper surface of a slab-on-ground structure are the current temperature and relative humidity of the indoor air. The indoor air conditions depend on the occupancy of the space or building. In Finland the indoor temperature in dwellings and office buildings is usually between $+19 \dots +22^{\circ}\text{C}$. The relative humidity of dwellings and offices varies between $\text{RH} = 25 \dots 60\%$, and the top values usually occur during summer.

The lower surface of the slab-on-ground structure is in direct contact with the subsoil or drainage layer. The temperature of the fill under the heated building depends on the temperatures of the indoor air and the concrete slab and the thermal flow through the slab structure. The thermal flow through the structure increases as the thermal resistance of the structure decreases. Up to some degree the heated building always warms the subsoil below. In normal slab-on-ground structures with a $50 \dots 100 \text{ mm}$ thick insulation layer (polystyrene) under the concrete slab, the fill temperature is usually around $T = +12 \dots +15^{\circ}\text{C}$ if the indoor temperature is around $T = 22^{\circ}\text{C}$. With uninsulated structures the subsoil temperature is almost equal to the slab temperature. Deeper in the ground the soil temperature approaches the temperature of the ground water table, $T = +5 \dots +7^{\circ}\text{C}$.

The limit design value of the fill and subsoil temperature in the moisture design of the slab-on-ground structure should be $T = +15^{\circ}\text{C}$. In addition the effect of higher temperatures ($T = +16 \dots +19^{\circ}\text{C}$) on the moisture behavior of the structure should be examined.

The basis of the moisture design of the slab-on-ground structure is that the capillary rise from subsoil to the structural layers (insulation and slab itself) is prevented, thus the water vapor concentration in the subsoil is the dimensioning factor. The assumption of the relative humidity of the pore air is $\text{RH} = 100\%$, because:

- The water content of the fill layers during construction period is usually very high ($\text{RH} = 100\%$), and the only possible drying direction is downwards into the subsoil. However, the natural moisture content of the subsoil is also high and therefore the drying of the fill is extremely slow.
- The pore system of the soil mass is connected to the ground water table.
- Capillary movement, especially horizontal capillarity may occasionally raise the moisture content of the fill.

The hygroscopic equilibrium moisture content of typical coarse-grained fill materials is $w = 0,5 \dots 2,0\%$ (percentage per weight).

7.1.2 Temperature and moisture conditions during the lifespan of a slab structure

The moisture conditions and behaviour of a slab-on-ground structure vary radically during its life cycle. Three divergent phases can be distinguished, all of which must be considered during the design process of a viable and healthy structure:

1. Construction phase involving excess structural moisture
2. Long-term use phase
3. Damage control and repair survey.

The excess structural moisture introduced into building materials during construction or installation, for instance the water contained by concrete, must be able to exit the structure without damaging connected structures and causing detrimental health effects to residents. The drying period of an in situ cast concrete slab can be remarkably long, several months or even years, and the amount of exiting water considerable, tens of liters per a cubic meter of concrete. The structure cannot attain a moisture equilibrium with its surroundings until the excess structural moisture has evaporated.

A slab-on-ground structure can emit moisture in two directions: up into the indoor air by evaporation, or down to the subsoil by water vapor diffusion and gravity flow of free water. The coating of the slab, depending on the water vapor transmission rate of the coating material, reduces or prevents evaporation into indoor air completely. Moisture can exit in the direction of the subsoil assuming that the structure does not include damp proofing under the drying concrete slab.

Construction phase design ensures that during and after the construction phase the new slab can emit the excess structural moisture. This can happen either upwards into the indoor air by evaporation, which requires an adequately long drying period before the application of the slab coating, or down into the subsoil by gravity flow and diffusion, which requires that the structure does not have damp proofing under the drying structural element.

In long term use, after a thermal and moisture equilibrium between indoor conditions and the subsoil has been achieved, the fill mass has warmed up close to the limit values presented earlier (+15°C ... +17°C). This means that water vapor diffusion flow is directed towards the drier indoor air. The moisture behavior of the structure depends on the vapor content difference across the structure and the water vapor resistances of the used materials. Although seasonal temperature changes and the variation in indoor air conditions affect the equilibrium, the long-term use conditions can be treated as steady state conditions.

Long-term phase design ensures that under thermal and moisture equilibrium conditions moisture cannot condense at any level inside the examined structure and that the critical relative humidity levels of the used materials are not exceeded (especially under the coating materials, Table 8.1).

‘Damage control’ refers to an unexpected moisture increase inside a slab-on-ground structure that raises the moisture content above the long-term phase equilibrium. The most common cause for the damage state is a pipe leak in built-in water or sewer pipes.

Part of the introduced excess water flows gravitationally downwards to the subsoil, part remains inside the structure by capillary and adsorption forces and dries off slowly by evaporation and diffusion. The situation is very similar to the one studied in the first design phase. Again, it must be possible for the excess water in the structure to dry out. In the same manner, damage-state design assures that excess water introduced into the structure can exit either towards the indoor air, which in practice usually means the removal of the slab coating during the drying period, or into the subsoil, if possible.

7.1.3 Standards for the moisture conditions

The potential risk of fungus growth in a structural material depends on the material itself, temperature and relative humidity (Figure 7.1) /22/. When determining the critical moisture content of a structural component one must consider the ‘normal’ equilibrium moisture content of the material and the consequences of exceeding the critical moisture value of this particular building element: does the possible fungus growth in this part of the structure have an effect on the indoor air quality or not? The most common wrong interpretation is that the high relative humidity of the fill and subsoil layer is always a sign of moisture damage and requires repair actions.

The accurate critical moisture values for typical floor covering materials are shown in Table 7.1 /13/. These values are determined as the limit values for the assembly but may also be used as the critical moisture content values in long term use conditions.

Figure 7.1 The risk of fungus growth under varying conditions /22/.

Table 7.1 The critical relative humidity of typical floor covering materials /13/.

Material	Critical relative humidity, RH %
Wood and wood based materials	80%
Plastic carpets, if the fungus growth is possible	80%
Glued floor coverings:	
- long term (over 6 months) moisture load	90%
- short term moisture load	95%
Cork sheets	80
Fillers*, moisture barriers, ceramic panels	almost 100%

*Critical humidity for fillers is almost 100%, but varies strongly between 80 ... 100 % depending on the components of the filler, lowest with organic fillers.

7.2 Insulation

The primary function of the slab-on-ground insulation is to reduce the heat flow through the slab structure and the overall energy consumption of the building. Considering moisture behavior the insulation has another important task by reducing the diffusion flow potential from the moist subsoil.

Under typical conditions around slab-on-ground structures, the water vapor content of the pore structure in subsoil is higher than the vapor content of the relatively dry indoor air. The potential of the diffusion is therefore from the subsoil towards the indoor air. Assuming that there is always enough moisture in the subsoil to keep the relative humidity of the pore air close to $RH = 100\%$, the temperature of the subsoil dictates the absolute vapor content and therefore the magnitude of the diffusion potential. The warmer the subsoil, the higher the diffusion potential and the flow through the structures.

According to a Swedish research /14/ the required temperature difference between subsoil and indoor air should be at least 2 ... 3°C. Figure 7.2 presents the required insulation thickness in different floor areas /14/.

Figure 7.2. Design graph of the slab-on-ground insulation /14/.

Optimal thickness of the slab-on-ground insulation:

The Finnish Building Regulations C3 defines the coefficient of thermal transmittance of the slab-on-ground structure to be equal or smaller than $0,25 \text{ W/m}^2 \text{ K}$. The regulation is based on the minimization of the energy consumption by minimizing the heat flow through the building envelope. A 100 mm thick polystyrene board as an insulation satisfies the new regulations. The insulation must cover the whole base slab area.

The slab-on-ground insulation must be placed mainly or entirely under the slab. This ensures a higher slab temperature and a lower moisture content than a structure where the insulation is placed on top of the slab.

7.3 Vapour barrier

The direction of the moisture flow changes during the lifespan of a structure i.e. during construction period, long term use and a possible failure state. Therefore it is safest not to assemble a vapor barrier in a slab-on-ground structure at all.

7.4 Water vapor permeability of the floor covering

Usually moisture damages of the slab-on-ground structures occur as unfastening or blistering of the floor covering or radical color changes as the critical moisture content of the materials exceeds.

The importance of the floor covering material for the overall moisture behavior of the structure is significant. The relative humidity at the lower surface of the floor covering increases as the diffusion potential, i.e. the partial vapor pressure difference over the structure increases. The relative humidity also increases as the vapor resistance of the floor covering increases.

Figure 7.3. Effect of the water vapor permeability of the thermal insulation on the relative humidity of the surface structure.

Surface structures and floor coverings can be divided into two categories according to their vapor permeability: permeable coatings and impermeable coatings. Permeable coatings include materials with an average vapor permeability of $50 \cdot 10^9 \text{ m}^2 \text{ s Pa/kg}$ (less than $400 \cdot 10^3 \text{ s/m}$). Impermeable coatings are materials with an average water vapor permeability of $150 \dots 180 \cdot 10^9 \text{ m}^2 \text{ s Pa/kg}$ ($1100 \dots 1400 \cdot 10^3 \text{ s/m}$).

Optimal water vapor permeability of coatings with common cross-section types

The evaluation of overall moisture behavior of different cross-section types using both permeable and impermeable coatings in the Finnish Building Information states that (Figure 7.4):

- Insulated slab types (AP 201, AP 205 and AP 206): the higher the thermal resistance of the insulation layer, the lower is the vapor content of surface structure.
- Insulated slab types (AP 201, AP 205 and AP 206): the limit subsoil temperature to exceed the critical moisture content of the coatings ($RH_{crit} = 85\%$) or condensation point inside a structure is $T = +19^\circ\text{C}$. With permeable coating materials the limit temperature is higher.
- Un-insulated slabs (AP 204): only impermeable coatings and surface structures are possible.

Relative humidity at the lower surface of the floor covering in various structures, water vapour resistance of the floor covering is $50 \cdot 10^9 \text{ m}^2 \text{ s Pa/kg}$ ($370 \cdot 10^3 \text{ s/m}$)

Relative humidity at the lower surface of the floor covering in various structures, water vapour resistance of the floor covering is $180 \cdot 10^9 \text{ m}^2 \text{ s Pa/kg}$ ($1333 \cdot 10^3 \text{ s/m}$)

Figure 7.4 Effect of the vapor permeability of the surface structure on the relative humidity of coatings with different types of slab cross-sections.

7.5 Design of the ventilated slab structure

A ventilated slab structure is usually the repair method for a damaged slab-on-ground structure. The structure includes a new vent duct above the old slab structure ventilated by gravitationally or artificial ventilation.

Several solutions for the construction of this vent duct are used, for example:

- A purpose-built carpet or mat (usually plastic)
- Profiled sheet or steel
- Wooden ribs
- Geotechnical composite reinforcement structures
- Some porous material, such as macadam or expanded clay aggregate.

The condition for a successful design of the ventilated slab is the relative humidity of the vent duct. The humidity of the vent air must remain below the critical humidity or saturated humidity at any point along the duct. The relative humidity of the duct air depends on the diffusion flow through the slab structure, initial humidity of the ventilation air (usually equals the relative humidity to the indoor air) and the total length of the air duct. The critical humidity of the duct air for design purposes should be $RH < 75\%$.

According to Figure 7.5, the height of the ventilation duct may remain relatively small, less than 10 mm. The calculation included a 80 ... 100 mm thick base slab with an average vapor permeability of a common cast-in-situ concrete (K30). The total length of the duct was 10 ... 20 meters. The initial vapor content of the vent air was 12 g/m^3 , which corresponds to the indoor air conditions $RH = 69\%$, $T = +20^\circ\text{C}$. The design value for the vent air humidity was $RH = 75\%$.

Figure 7.6 shows the required volume of the ventilating air in a certain size vent duct. The required flow rate doubles as the length of the vent duct doubles.

Figure 7.5 The required duct height of the example calculation and variations

Figure 7.6. The required volume of ventilating air of the example calculations and variations

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APPENDIX

Moisture damage report cards

12 p.

Structure, materials and conditions:

- o plastic floor covering or paint
- o concrete slab 100 mm (60 ... 100 mm)
- o 150 mm thermal insulation at the edge zone and 100 mm at the middle
- o subsoil sand

Building is 10-years old health center, build upper the hill, ground water is very deeply. Structure fulfills the demand of the current building standards, except there is no capillary breaking layer.

Observed failures:

There has been several sewer blockages under first use year when sewer water has raised several times to the floor. Observed moisture and mold problems at the center area of the slab where arisen RH-values at the slab has been previously measured.

Research and measurement results:

The temperatures of the structure at 10 measurement points in three depths (100 mm, 500 mm and 1000 mm from the slab surface) have been measured using thermo elements inside steel bar. Also the relative humidity of the slab at the 100 mm depth has been measured by Vaisala moisture and temperature meter. The covering material at some part of the slab has been removed before (slab has been dried).

Depth 100 mm: temperature: 15,0 ... 22,1 °C, RH: 52,2 ... 84,7%
 Depth 500 mm: temperature: 13,5 ... 19,8 °C
 Depth 1000 mm: temperature: 12,9 ... 19,9 °C

The moisture contents (weight-%) have been determined from the taken concrete and sand samples.

Concrete: moisture content: 1,9 ... 3,4 %, highest values at the middle of the slab
 Sand: moisture content, at the surface (under insulation): 1,0 ... 2,5 %
 at the bottom (500 ... 600 mm): 1,1 ... 4,3%

Probable cause of the failures: The structure has been moist by the pipe leaks and has not been able to dry out. Moreover the warming of the subsoil is causing water vapor diffusion to the structure.

Structure, materials and conditions:

- o wooden floor
- o wood support + sawdust insulation 150 mm
- o concrete slab 60 ... 80 mm
- o light-weight concrete 80 ... 1000 mm
- o sand

Sport hall of the school building.

Observed failures:

There were no observed failures at the structure. The owner wanted to examine the structure and its conditions.

Research and measurement results:

The temperatures of the structure have been measured at 12 drilled measurement holes in different depths (150 ... 2000 mm) and the relative humidity has been measured at 5 measurement points in depth 150 mm. The lowest temperature values have measured at the points, which are bordered, to the unheated space.

Depth 150 ... 200 mm: temperature: 12,3 ... 21,8 °C, RH: 55,0 ... 86,8 %
 Depth 650 ... 1000 mm: temperature: 12,7 ... 21,7 °C
 Depth 1250 ... 2000 mm: temperature: 13,5 ... 19,0 °C

The moisture content of the sand sample taken at the upper part of the layer was 2,8 weight-% (hygroscopic moisture) and moisture content of the concrete sample was 0,4 weight-% (hygroscopic moisture).

Probable cause of the failures: Failures can be caused by the diffusion from the up warmed subsoil if the wooden floor is replaced by floor covering which is more water vapor tight than the existing wooden floor.

K3

- plastic sheet floor covering
- concrete slab 100 mm
- bitumen spraying
- concrete slab 60 mm
- sand

The school building complex, which consists of three buildings, built at 1951, 1954 and 1961. The ground soil is capillary clay and silt and there are some very wet points at the building area.

Observed failures:

Research and measurement results:

The temperatures have been measured at the different buildings. Several measurements have been done in 1996 and 1997.
Temperature in 1 m depth: 15,6 °C ... 19,3 °C, RH in 350 mm depth 95,4%.
The ground water level is quite high, about 600 mm from the surface.

Probable cause of the failures: The capillary water from the soil is rising to the structure. Kapillaarinen kosteuden nousuminen rakenteeseen. Probable the high ground water level prevents the warming of the subsoil, which in otherwise can be a risk in un-insulated slab.

K4

Structure, materials and conditions:

- limestone plate
- plaster
- concrete slab 100 mm
- bitumen paper + bitumen spraying
- thermal insulation EPS 50 mm
- gravel fill 120 ... 200 mm
- double plastic sheet
- adjustment gravel
- subsoil

The underground cellar spaces of the museum have been built in 1980's.

Observed failures:

There have been observed some color changes at the limestone plates.

Research and measurement results:

The temperatures and relative humidity of the upper part of the concrete slab have been measured at the three measurement points. Also a temperature of the subsoil has been measured in depths 0,9 ... 1,3 m. At the same points the ground water level follow-up measurements have been done, which indicate that the ground water level is quite near the ground structure.

Concrete slab: temperature: 19,7 ... 19,8 °C, RH: 67 ... 84,3 %

Subsoil: temp. 12,6 ... 16,0 °C, highest at the point where ground water level lowest

Ground water level: 400 ... 1000 mm from the floor level, annual change small.

The capillary rise of the gravel samples were 300...370 mm.

Probable cause of the failures: The capillary rise of water and water vapor diffusion from the subsoil is dissolving minerals of the limestone which are depositing to the finishing of the plates. The problem is mostly visual. Problems can be developed if the floor covering is replaced with water vapor tight covering.

Structure, materials and conditions:

CASE 5

- o floor covering (plastic plastic plate or rubber plate)
- o concrete slab
- o subsoil

Over 20 years old, renovated extremely large (60 x 100 m²) school building. The part of the building was enlarged at the renovation when part of the floor structures was subjected to the rain for several months. Because the building is build on the gravel ridge there was not any capillary breaking layer, drainage layer or thermal insulation.

Observed failures:

At the renovation the second floor was build to the part of the building, also all the floor-covering materials were replaced. Soon (less than 1 year) after the renovation the floor coverings became to failure.

Research and measurement results:

The temperatures of the subsoil have measured at 9 measurement points. Also 7 soil samples of the three visually different sand materials have been taken from the opening hole. The moisture contents (weight-%) and capillary rise has been determined from those samples.

Subsoil, 900 ... 1100 mm depth:	temperature: 18,6 ... 22,5 °C
Subsoil, 1500 ... 2000 mm depth:	temperature: 15,4 ... 21,5 °C
Sand layer:	moisture content: 1,7 ... 3,0 % (hygroscopic moisture), capillary rise: 500 ... 820 mm
Subsoil:	moisture content: 1,5 ... 5,3% (hygroscopic), the depths of the samples 400 ... 1300 mm

Probable cause of the failures: The water vapor diffusion from the subsoil caused by the warming the subsoil. The capillary rise of the water from the subsoil is unlikely because of the building place and ground water level.

Structure, materials and conditions:

CASE 6

- o vinyl plastic plate floor covering
- o double magnesia mass layer
- o concrete slab 70 mm
- o bitumen spraying
- o concrete slab 90 mm
- o stony sand fill 500 mm
- o hard subsoil (till)

The ground floor of the library which is partly on the ground and partly underground.

Observed failures:

The floor covering plates were on the loose from the base and the magnesia mass layers were swelled creating even about 5 cm blisters.

Research and measurement results:

The moisture content and capillary rise has been determined from the sand samples.

Also the temperature of the subsoil has been measured at the 700 mm depth.

Sand fill: moisture content: 5,88 ... 6,11 weight-% (capillary moisture),

capillary rise: 0,19 ... 0,20 m

Subsoil, 700 mm depth: temperature: 19,2 ... 19,8 °C

Probable cause of the failures: The capillary risen water and the water vapor diffusion from the subsoil.

K7

Structure, materials and conditions:

- o plastic vinyl floor covering plates
- o concrete slab 100 mm
- o double plastic sheet
- o gravelly sand fill

Observed failures:

The floor coverings of the slab-on-ground structure in the 20 year old super market has been replaced. After that some of the plates have been loosen.

Research and measurement results:

The relative humidity of the indoor air has been very low, RH 20 ... 30%. The moisture content and temperature of the sand fill and subsoil has been measured up to the about 1100 mm depth. Moreover the relative humidity of the concrete slab and soil immediately under the slab has been measured by Vaisala moisture meter. The relative humidity of the soil layer was above the measurement range, over RH 100%, the relative humidity of the concrete slab was over RH 90%.

Soil fill, 100 mm depth: moisture content: 2,0 ... 3,4 weight-% (hygrosc.),
temperature: 20,3 ... 21,2 °C
Soil fill, 200 mm depth: temperature: 19,2 ... 20,8 °C
Soil fill, 400 mm depth: temperature: 19,6 ... 20,6 °C
Soil fill, 600 mm depth: temperature: 20,2 ... 20,5 °C
Soil fill, 800 mm depth: temperature: 20,2 ... 21,1 °C
Soil fill, 1100 mm depth: temperature: 20,2 ... 21,1 °C

Probable cause of the failures: The water vapor diffusion from the subsoil caused by the warming of the subsoil.

K8

Structure, materials and conditions:

- o bitumen spraying (broken)
- o concrete slab 60 mm
- o sand fill, 40 ... 160 mm (partly of two different soil material)
- o subsoil, fine clay/silt

Observed failures:

Classroom has been removed from use because of moisture and mold failures.

Research and measurement results:

At the ground water level measurements done earlier has been found that the ground water level is almost constantly at the level of the concrete slab. The temperature and the moisture content of the subsoil have been measured from the two measuring holes.

Measuring results:

Measurement hole 1: 700 mm depth: temperature 13,7 °C.
Visually observed that the subsoil is dry up to the level of 750 mm depth
Measurement hole 2: 1000 mm depth: temperature 18,1 °C.
Visually observed that the subsoil is dry up to the level of 350 mm depth

Probable cause of the failures: The high ground water level and the soil fill material capillary transforms water from the ground water.

Structure, materials and conditions:

- o matched board, 30 mm
- o membrane: impact sound insulation
- o support 100 mm, crossbar 40 mm, cross support 50 mm, air space n. 200 mm
- o concrete slab, 15...200 mm
- o sand and stones, partly about 10 cm loose of the concrete slab

Observed failures:

Mold and moisture problems at the wall and wooden floor structures and some odour problems at the classroom of the cellar in the school building. Drainage and leaking pipes has been repaired earlier, yet the problems have not removed. The examination was enlarged to the neighboring rooms which floor structure is: 150...200 mm concrete slab, covered with plastic floor covering, plastic plates or painting. The whole wooden floor will be removed and a new thermal insulated wooden floor will be build.

Research and measurement results:

The thermal and moisture measurements have been done from two measurement holes in two measurement tours, first measures were done after floor flooding caused by heavy rainfall. The relative humidity of the indoor air was RH 26,5...42,5%, highest at the first measurement time. Measurement results:

Under board, at the air space: temperature: 17,4...17,9 °C, RH: 80,4...88%,

At the bottom of hole, 400 mm depth: temperature: 15,4...16,2 °C, RH: 98,2...95,8%

Measurement done at the other rooms:

Room (plastic sheet)	T (°C)	RH (%)	Room2 (plastic plate)	T (°C)	RH (%)	Room3 (paint)	T (°C)	RH (%)
Under sheet	18,2...18,8	99,0...98,1	Under sheet	17,5...18,2	82,5...93,0	Concr. surface	16,3...17,4	72,1...78,3
Plaster	17,8...18,0	98,4...98,8	Concr. surface	16,6...17,1	86,5...89,0	20 mm depth	16,3...17,4	80,8...83,9
20 mm depth	17,8...18,0	100	20 mm depth	16,6...16,8	98,0...98,6	20 mm depth	15,8...16,8	95,9...95,6
120 mm depth	17,7...17,9	100...99,8	120 mm depth	16,6...16,8	98,3...100	120 mm depth	15,8...16,8	96,2...96,0
Subsoil (250 mm)	17,5...17,8	99,7...100	Subsoil (250 mm)	16,2...16,7	91,8...100	Subsoil (250 mm)	15,3...16,9	96...100
Indoor air	17,9...19,2	47,5...54,9	Indoor air	16,8...18,2	40,5...58,0	Indoor air	16,2...17,2	42,8...42,9

Probable cause of the failures: The missing thermal insulation has caused the warming of subsoil, which causes water vapor diffusion from the subsoil to the structure. Also capillary rise of water is possible. Moreover the drainage has not function properly and some rainwater has flooded to the floor.

Structure, materials and conditions:

- o plastic sheet floor covering
- o surface slab, concrete 60 mm
- o fill layer, partly sand
- o bitumen spraying
- o base slab

Observed failures:

The plastic sheet covering of schoolrooms is blistering, there are also strong odour of sewer. According to the plotting of drainage done a few years ago, the drainage is at quite high level.

Research and measurement results:

The relative humidity of indoor air was 25...29% and temperature 16...17,5 °C. The temperature and relative humidity of the structure has been measured from two different areas where arisen moisture contents have been measured by surface moisture meter. Measurement results:

Area 1:

Surface slab, 30...50 mm depth: temperature: 17,3...17,7 °C, RH 28...30 %.

Surface slab, n. 55 mm depth: temperature: 14,8 °C, RH 82 %.

Area 2:

Surface slab, n. 40 mm depth: temperature: 17,6...21,5 °C, RH 83...93%

Surface slab, n. 50 mm depth: temperature: 15,0 °C, RH 89 %

Soil fill layer: temperature: 21,4 °C, RH 81 % (?)

Probable cause of the failures: Sewer pipe leaks and un-functioning of the drainage.

Structure, materials and conditions:

- o plastic sheet covering
- o concrete slab 120...300 mm
- o expanded clay aggregate or gravel

Observed failures:

The plastic sheet covering and its glue in the schoolrooms has been failed because of moisture. Several measurements have been done in Room 3 during last 9 months. Last measurements has been done about 11 weeks after removing the floor covering and drying the structure. Also some drainage has been newly built.

Research and measurement results:

1. measure: The relative humidity of indoor air varied RH 38,8...43,6% and temperature 20...21,5 °C. Measurement results:

Room 1: (140...180 mm concrete slab, expanded clay aggregate)

Under the sheet: temperature: 20,1...20,3 °C, RH: 56,5...59,4%.

Expanded clay aggregate: temperature: 20,2...20,5 °C, RH: 43,5...58,2%.

Room 2: (120...130 mm concrete slab, expanded clay aggregate)

Under the sheet: temperature: 20,0...19,8 °C, RH: 56,7...60,3%.

Expanded clay aggregate: temperature: 19,2...20,4 °C, RH: 49,6...73,4%.

Room 3 (200...300 mm concrete slab, fine gravel) measurements:

	Mesur.1		Mesur.2		Mesur.3		Mesur.4	
	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
Room 3	22,2...22,8	84,1...88,9	21,4...23,0	60,0...93,1	23,2...23,5	73,8...78,2	23,3...23,8	47,7...79,9
Sheet			21,4...23,7	51,7...99,3	22,8...23,2	87,8...92,6	23,3...24,0	52,2...90,4
20 mm depth			21,0...23,3	60,9...99,9	22,6...23,2	96,4...97,6	23,0...24,0	55,6...96,8
50 mm depth			21,1	97,0...99,6	20,0...25,7	46,1...99,9	23,0...24,1	98,2...99,5
80 mm depth			21,5	38,8	21,8	51,7	23,7	54,9
Soil								23,3
Indoorair								58,5

Probable cause of the failures: The gravel fill soil material under Room 3 has probably too high capillary rise. The subsoil has warned because there is no thermal insulation at the structure, that causes water vapor diffusion.

Structure, materials and conditions:

- o plastic sheet covering plates
- o concrete slab 80 mm
- o bitumen spraying
- o expanded clay aggregate concrete 80 mm
- o expanded clay aggregate 150 mm, inglude some sand
- o plastic sheet
- o sand

Observed failures:

The floor of schoolroom has been flooded in the summer and it has been dried since then. It has been observed from the opening hole that the structure is not in accordance with the design plan.

Research and measurement results:

The relative humidity of the expanded clay aggregate sample was (in +20 °C) RH 70%. The temperature of the expanded clay aggregate layer was +2 °C and relative humidity RH 98%.

Probable cause of the failures: Flooding of the floor.

Structure, materials and conditions:

CASE 13

+

- o floor covering material
- o concrete slab
- o ?

Observed failures:

Moisture problems at the slab-on-ground structure and ground wall structure of the cellar in school.

Research and measurement results:

Holes for defining relative humidity has been drilled to the structures which moisture content is high according to the measurement done with surface moisture meter. Measurement results:

Room 1:

Surface slab:

temperature 16,8...20,8°C (average of 8 measures 19,2°C),
RH: 55,7...100% (average of 8 RH 92,5%).

Lower surface of slab:

temperature: 15,6...19,6°C (average of 8 measures 18,0°C),
RH: 86,9...100% (average of 8 RH 98,3%).

Room 2:

Surface slab:

temperature: 16,6...18,2°C (average of 8 measures 17,4°C),
RH: 76,3...100% (average of 8 RH 94,0%).

Lower surface of slab:

temperature: 15,7...17,9°C (average of 8 measures 17,0°C),
RH: 92,5...100% (average of 8 RH 98,9%).

Room 3:

Surface slab:

temperature: 16,2...22,4 °C (average of 12 measures 18,6°C
RH: 48,4...100% (average of 12 RH 76,2%).

Lower surface of slab:

temperature: 16,4...19,9°C (average of 12 measures 18,0°C)
RH: 49,0...100% (average of 12 RH 91,5%).

Probable cause of the failures: The water vapor diffusion caused of the warming of the subsoil.

Structure, materials and conditions:

CASE 14

+

- o paint
- o concrete slab
- o expanded clay aggregate/ mineral wool
- o concrete slab

Observed failures:

Some cracks have been occurred to the floor of the schoolroom a few months after renovation 1998. The building is built in 1960's.

Research and measurement results:

The temperature varied 24...26 °C and relative humidity RH 55...65%. Measurements results:

Surface slab, 20...30 mm depth: RH 68...87,6 %.

Surface slab, 35...60 mm depth: RH 70,4...95,9 %.

Surface slab, 105 mm depth: RH 70,3 %.

Probable cause of the failures: The capillary rise of the water from the soil is possible in the part of slab, which has mineral wool thermal insulation.

K15

- plastic plate floor covering
- concrete slab 80 mm
- plastic sheet
- expanded clay concrete 150...200 mm
- gravel

Observed failures:

The two school rooms of the enlargement which have ground floor have a bad, moldy odour. The rooms which have crawl space any problems was not observed.

Research and measurement results:

Some rotten construction waste was found at the pipe ducts under the structure. The ventilation system is sucking replacement air from the ducts.

Measurement results (measured under the floor structure, at the expanded clay concrete layer?):

- Hole 1: temperature: 17,5 °C, RH: 74,6%.
- Hole 2: temperature: 17,8 °C, RH: 74,8%.
- Hole 3: temperature: 21,2 °C, RH: 92,6%.
- Hole 4: temperature: 22,5 °C, RH: 93,1%.
- Hole 5: temperature: 21,4 °C, RH: 74,5%.

The highest temperatures and relative humidity have been measured from the center part of the slab.

Probable cause of the failures: The ventilation system function incorrectly. The rotten construction waste.

K16

- plastic sheet floor covering
- concrete slab 50 mm
- expanded clay aggregate 200 mm
- moisture barrier
- concrete slab 160 mm
- ?

Observed failures:

The floor and the brick wall up to high 400 mm have moisture failures. A large HPAC (heating, plumbing, air-conditioning) renovation has been done 12 year ago.

Research and measurement results:

The floor of the room is wet to the about 500 mm from the door according to the measurements done by surface moisture meter. In that area the water and sewer pipes of the toilets are passing through to the subjacent pipe duct. Measurement results:

- Hole 1: temperature: 18,8 °C, RH: 74,6%.
- Hole 2: temperature: 20,4 °C, RH: 98,2%.
- Hole 3: temperature: 21,9 °C, RH: 99,5%.
- Hole 4: temperature: 17,1 °C, RH: 72,8%.

The measurement holes 2 and 3 are in the failure area, others are reference points in neighboring rooms.

Probable cause of the failures: Pipe leak.

Structure, materials and conditions:

Structure 1:	Structure 2:
<ul style="list-style-type: none"> linoleum 12 mm plywood 30 mm old plank+ 280 mm support (pieces of fiberboard, card board, etc.) moisture barrier concrete slab sand 	<ul style="list-style-type: none"> linoleum 60 mm concrete 100 mm expanded polystyrene 90 mm adjustment sand moisture barrier 70 mm concrete fine sand

Observed failures:

Some water was flooded in 1999 to the floor from the above toilets. After that, the structures were mechanically dried and new linoleum floor coverings have been installed or a new structure (2) was built. Other parts except the slab-on-ground structures were renovated a few years ago.

Research and measurement results:

Measurement results:

Structure 1:

Under the floor sheet:
Insulation (support): temperature: 21,2...23,5 °C, RH: 38,4...78,3%,
Indoor air: temperature: 19,3...20,6 °C, RH: 52,2...74,5%,
Indoor air: temperature: 23,1 °C, RH: 57,05%,
RH: 90,4%.

Structure 2: (has not wetting in flooding)

Concrete surface:
10 mm depth: temperature: 21,7 °C, RH: 91,5%,
40 mm depth: temperature: 21,3 °C, RH: 92,5%,
10 mm depth in polystyrene: temperature: 21,0 °C, RH: 92,0%,
17,5 mm depth in polystyrene: temperature: 17,1 °C, RH: 95,8%,
Above moisture barrier (in sand): temperature: 16,9 °C, RH: 95,7%,
Below moisture barrier (concrete): temperature: 16,4 °C, RH: 96,9%,
500 mm depth (sand): temperature: 15,1 °C, RH: 98,6%,
Indoor air: temperature: 21,4 °C, RH: 65,0%.

Probable cause of the failures: There is possible a pipe leak under Structure 2. The renovated concrete slabs are possible covered too wet when the critical moisture content of the covering clues has been extended.

Structure, materials and conditions:

Observed failures:

A moisture failure has been occurred about 5 years ago in the ground wall of the 2-storey, 20 years old row house. The reason for the failure was blocking of the drainage. Now a one room (Room 1) has a stuffy odour and the baseboard has been microbe failures.

Research and measurement results:

Measurements are done at the ground floor and wall. Measurement results concerning ground floor:

Hole 1 (room 1, beside ground wall):

Indoor air: temperature: 20,3 °C, RH: 52,7%,
10...50 mm depth: temperature: 19,7...19,9 °C, RH: 88,6...95,6%.

Hole 2 (room 1, in the middle of floor):

Indoor air: temperature: 20,7 °C, RH: 48,7%,
10...50 mm depth: temperature: 20,1...20,3 °C, RH: 66,3...81,3%.

Hole 3 (neighboring room 1):

Indoor air: temperature: 18,9 °C, RH: 54,6%,
20...50 mm depth: temperature: 17,9...19,1 °C, RH: 74,6...91,2%,
Upper surface of insulation: temperature: 17,8 °C, RH: 91,9%,
Subsoil: temperature: 17,4 °C, RH: 93,3%.

Hole 4 (neighboring room 2, in middle of floor):

Indoor air: temperature: 20,6 °C, RH: 49,0%,
10...50 mm depth: temperature: 20,1...20,4 °C, RH: 48,3...56,7%,
Upper surface of insulation: temperature: 20,2 °C, RH: 76,2%,
Subsoil: temperature: 18,4 °C, RH: 97,5%.

Hole 5 (neighboring room 2, in middle of floor):

Indoor air: temperature: 20,7 °C, RH: 48,7%,
20...50 mm depth: temperature: 20,5...20,6 °C, RH: 48,5...62,5%,
Upper surface of insulation: temperature: 20,3 °C, RH: 97,9%,
Subsoil: temperature: 19,8 °C, RH: 100,0%.

Also some higher moisture contents have been measured from the ground outdoor walls of room 1 and neighboring room 1.

Probable cause of the failures: The water is rising capillary to the ground floor and wall of the room 1 and neighboring room 1.

Structure, materials and conditions:

	Building 1	Building 2	Building 3	Building 4
Covering	plastic sheet/ plates	Plastic sheet	plastic sheet/ plates	plastic sheet/ cork plates
Concrete	60...90 mm	80...130 mm	120...130 mm	60...100 mm
Thermal insulation	Expanded polystyrene (expanded aggregate)	Expanded polystyrene clay	expanded aggregate	Expanded polystyrene clay
Subsoil				Fine sand

Observed failures:

The object consists of 4 daycare center buildings. There were no observed failures or doubt of failure. The owner wanted to determine the condition of the slab-on-ground structures.

Research and measurement results:

Measurement results:

Building 1 (6 measurement points):	temperature: 18,4...20,8 °C, RH: 42,8...66,7%.
20 mm depth	temperature: 18,1...20,4 °C, RH: 56,7...75,8%.
40 mm depth	temperature: 18,5...19,0 °C, RH: 71,7...80,1%.
60 mm depth	temperature: 16,9...20,1 °C, RH: 61,9...78,9%.
Thermal insulation	temperature: 13,3...17,6 °C, RH: 73,7...96,2%.
Subsoil	
Building 2 (6 measurement points):	temperature: 16,1...20,1 °C, RH: 38,7...82,6%.
20 mm depth	temperature: 16,0...20,1 °C, RH: 63,2...82,9%.
40 mm depth	temperature: 16,0...19,7 °C, RH: 66,5...83,7%.
60 mm depth	temperature: 16,2...19,6 °C, RH: 66,8...78,4%.
Thermal insulation	temperature: 10,9...15,6 °C, RH: 82,9...98,6%.
Subsoil	
Building 3 (3 measurement points):	temperature: 15,6...18,4 °C, RH: 53,6...69,4%.
20 mm depth	temperature: 15,5...18,0 °C, RH: 67,1...74,4%.
40 mm depth	temperature: 15,8...18,3 °C, RH: 67,1...78,0%.
60 mm depth	temperature: 15,5...18,2 °C, RH: 53,7...80,2%.
90 mm depth	temperature: 14,6...17,9 °C, RH: 44,2...65,1%.
Expanded clay aggregate	
Building 4 (6 measurement points):	temperature: 17,9...19,9 °C, RH: 61,7...79,3%.
20 mm depth	temperature: 17,6...17,9 °C, RH: 71,4...85,2%.
40 mm depth	temperature: 17,9...20,1 °C, RH: 75,4...87,9%.
60 mm depth	temperature: 16,9...18,0 °C, RH: 77,3...90,3%.
Thermal insulation	temperature: 12,2...15,6 °C, RH: 85,8...99,4%.
Subsoil	

Probable cause of the failures: The moisture contents and temperature fields of all buildings are normal.

Structure, materials and conditions:

- o plastic sheet covering (moisture tight), in some part clinker plates (in bathrooms and kitchen)
- o concrete slab 45...90 mm
- o expanded clay aggregate (under bathrooms and kitchen)
- o rock?

Observed failures:

A pipe leak has been noticed one year ago in a school building built 1966. The floor covering at the dinner room was blistering and a odour indicating microbe failure was observed under the floor covering. The building was built in the hillside and some rainfall water is flowing down to the side of the building.

Research and measurement results:

Measurement results:

Dressing rooms (6 measurement points):	temperature: 15,5...16,9 °C, RH: 71,3...96,6%.
20 mm depth	temperature: 15,1...16,3 °C, RH: 84,9...97,9%.
Expanded clay aggregate	
Hall (6 measurement points):	temperature: 14,5...19,2 °C, RH: 45,6...95,5%.
20 mm depth	temperature: 14,2...20,9 °C, RH: 38,3...90,2%.
Expanded clay aggregate	
Dinner room (4 measurement points):	temperature: 15,5...18,4 °C, RH: 56,2...89,3%.
20 mm depth	temperature: 15,3...17,6 °C, RH: 53,8...90,8%.
Expanded clay aggregate	

Probable cause of the failures: Extended moisture load to the structures because of the pipe leaks and flowing rainfall water from the hillside.

Structure, materials and conditions:

- plastic sheet floor covering (different kinds), in some parts clinker plates
- concrete slab 100...140 mm
- expanded polystyrene insulation
- soil fill, in some parts sunk

Observed failures:

At the day care center (at the downstairs of the 1975 built apartment house, not designed for that purpose) observed odour indicating microbe failures and employees and children have symptoms. A pipe leak in a one room and a leakage in two rooms. The rainfall waters from the roof has been directed to the inside drain for rainwater.

Research and measurement results:

Measurement results:

Old plastic floor covering (not very moisture tight):
 20 mm depth temperature: 19,7 °C, RH: 39,9%
 60 mm depth temperature: 20,1 °C, RH: 59,3%
 120 mm depth temperature: 19,9 °C, RH: 65,7%
 Thermal insulation temperature: 19,9 °C, RH: 75,9%
 Subsoil temperature: 18,8 °C, RH: 84,9%
 Room where is pipe leak, newer plastic sheet (moisture tight):
 20 mm depth temperature: 18,4...19,9 °C, RH: 48,1...77,6%
 60 mm depth temperature: 18,6...19,9 °C, RH: 63,7...93,7%
 100...120 mm depth temperature: 18,3...20,0 °C, RH: 74,4...92,0%
 Thermal insulation temperature: 18,1...19,8 °C, RH: 75,7...93,6%
 Subsoil temperature: 17,8...20,2 °C, RH: 74,1...64,1%
 Newer plastic sheet (moisture tight):
 20 mm depth temperature: 16,7...20,2 °C, RH: 55,3...97,9%
 60 mm depth temperature: 17,1...20,2 °C, RH: 72,5...98,6%
 Thermal insulation temperature: 17,0...19,8 °C, RH: 86,0...98,3%
 Subsoil temperature: 17,0...19,4 °C, RH: 88,3...99,9%

Probable cause of the failures: The water vapor diffusion from the subsoil because of warming of the subsoil. Also possible pipe leaks in the inside drain for rainwater will increase the moisture load. The water vapor permeability of the newer floor covering is small compared to moisture load. Also it is possible that the floor is covered too soon and the new surface concrete was not able to dry out.

Structure, materials and conditions:

- paint and above it a thin epoxy layer
- concrete slab 150 mm
- thermal insulation at the edge area of the slab (1,2 m)
- gravel

Observed failures:

The paint floor covering in the 2 years old industrial hall has been loosened, mostly from most heavily strained areas, patched using epoxy. Also patching are loosening.

Research and measurement results:

Measurement results:

Thermally insulated slab part (2 measurement points):
 20 mm depth temperature: 20,3...20,5 °C, RH: 82,0...85,0%
 50 mm depth temperature: 20,0...20,3 °C, RH: 88,0%
 100 mm depth temperature: 19,6...20,3 °C, RH: 91,0%
 Insulation: 170...190 mm depth temperature: 19,3...20,1 °C, RH: 84,0%
 Subsoil: 330 mm depth temperature: 16,6...17,0 °C, RH: 95,0%
 Subsoil: 470 mm depth temperature: 15,8 °C, RH: 95,0%
 Un-insulated slab part (6 measurement points):
 20 mm depth temperature: 20,1...20,9 °C, RH: 80,0...85,0%
 50 mm depth temperature: 19,6...20,6 °C, RH: 82,0...90,0%
 100 mm depth temperature: 19,8...20,3 °C, RH: 91,0...95,0%
 Subsoil: 180...210 mm depth temperature: 19,5...20,2 °C, RH: 94,0...97,0%
 Subsoil: 300...350 mm depth temperature: 19,3...20,2 °C, RH: 93,0...96,0%
 Subsoil: 400...410 mm depth temperature: 19,5...20,0 °C, RH: 95,0%
 Subsoil: 480...500 mm depth temperature: 18,9...20,1 °C, RH: 94,0...95,0%
 The indoor temperature was 20,6...21,1 °C and RH 65...69%.

Probable cause of the failures: The floor coverings are probably loosening because of the extend moisture load. The reason for the loosening is the weakness in bonding of the covering.

MOISTURE BEHAVIOR OF SLAB-ON-GROUND STRUCTURES

This Research Report is a final report of a series of studies concerning the temperature and moisture behavior of slab-on-ground structures. The studies were performed at the Tampere University of Technology in Finland during 1999 – 2002 in co-ordination with the Laboratory of Structural Engineering and the Laboratory of Foundation and Earth Structures.

The research report defines the limit values for the temperature and moisture design of slab-on-ground structures. Knowledge of the surrounding thermal and moisture conditions of slab-on-ground structures are necessary in moisture design of these structures, in evaluation of the moisture behavior and in planning repairing methods. Also a few most common repairing methods of slab-on-ground structures and their moisture behavior have also been evaluated at this report.

The temperature and moisture fields of slab structures were determined both by long term in situ surveys and theoretical analysis. Based on large amount of reported moisture damage cases the most common causes of failures and in slab-on-ground structures has been evaluated.

Price of the research report 34 € + 8 % VAT

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