Moisture Behavior of Ground Floor Structures

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ABSTRACT

The aim of this paper is to present the results of a research series done during 1999-2000 at Tampere University of Technology concerning the moisture and thermal behavior of ground slabs under Finnish climatic conditions. The results show that the subgrade must be considered a moist material in moisture balance examinations. The pore air of a soil mass is usually saturated. The water content of the fill or drainage layer is increased by capillary rise and horizontal capillarity. The temperature field has a decisive impact on the moisture behavior of ground slabs. The temperature difference between indoor air and subgrade pore air determines the volume of water vapor flow through the floor structures. The moisture resistance characteristics of structural materials and the water vapor resistance of the entire floor structure dictate the performance of the ground slab structure at the prevailing temperature and moisture flow fields.

INTRODUCTION

Moisture and mold problems in ground floor structures are common in cold climates. According to the field research done at Tampere University of Technology, the problems are usually caused by the capillarity of the fill or drainage layer or the condensation of the hygroscopic moisture. In order to develop properly performing ground floor structures, the moisture behavior of the subgrade in changing temperature field should be known. Yet the hygroscopic behavior and capillary movements of drainage soil materials—especially the horizontal capillarity—are quite poorly known. Subgrades as well as fill and drainage layers are in direct contact with the water table through the open pore structure of the soil mass. The moisture movements in these layers are impacted by the characteristics of the soil material (particle size ratio, particle shape, degree of compaction), changes in temperature fields, changes in water vapor pressures, and capillarity. The water content of the drainage layers, especially the high relative humidity of the pore air of the soil, should be taken into consideration as a boundary value in moisture behavior examinations of ground slab structures. The key factor is the performance of the base floor as a unit under the prevailing moisture strain in the existing temperature field. The aim of this paper is to present the type and volume of moisture and temperature loads that are directed to the ground floor structures. Although the study is focused on frost-protected shallow foundations, most of the study results (hygroscopic, vertical, and horizontal capillary equilibrium moisture contents) are valid in all structures against the ground.

HYGROSCOPIC MOISTURE BEHAVIOR OF GROUND SLAB

The hygroscopic moisture behavior of ground slab structures depends on temperature and moisture conditions of the subgrade and the floor structure.

Hygroscopic Equilibrium Moisture Content of Subgrade

Adsorption of moisture in soil occurs mainly in the form of hygroscopic binding and capillarity. Particle size ratio and specific surface area of the grains, as well as the impurities of the material, such as rust, salts, or mineral composition, have an impact on the ability of the soil to adsorb moisture from moist air. The hygroscopic equilibrium moisture content of a material depends on the temperature and relative humidity (RH) of the ambient air. Usually in soil science, the hygro-

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scopic absorption in coarse soils is ignored because it is almost negligible compared to the capillary bonded moisture (Hillel 1971).

The hygroscopic equilibrium moisture contents of the most common fill and drainage soil materials used in Finnish conditions have been determined. It was done by the so-called "weighing method," where the desired relative moisture conditions in the climatic chambers were achieved with the help of saturated salt solutions of different hygroscopic characteristics. The hygroscopic equilibrium moisture contents were determined at +5°C (48°F) and +20°C (68°F). The determined sorption isotherms at the hygroscopic range (0% RH … 98% RH) in absorption (moisture content versus relative humidity, RH) at +20°C (68°F) are presented in Figure 1. The differences between hygroscopic equilibrium moisture contents (EMC) at +5°C (48°F) and +20°C (68°F) were small. At the upper limit of the hygroscopic range, about 98% relative humidity, the moisture content of the most common grain materials (sands, gravels, and macadam) was between w = 0.5 … 1.0% (wt%) or 10...20 kg/m^3 (0.625 … 1.25 lb/ft^3) (Figure 1). Parallel results have also been obtained from other Finnish research (Sandberg et al. 1987).

Temperature Conditions of Subgrade

The termic behavior of ground slab structures was studied by numerical modeling in order to determine how the temperature balance of the subgrade changes during the service life of a building. The initial temperature of the subgrade and structure masses was T_{init} = +5°C (48°F). The indoor temperature of the building was T_{out} = +21°C (70°F) and the outdoor temperature followed the average annual outdoor sinusoidal temperature curve typical for Finland. Temperature changes were predicted over 15 years (Figure 2).

The thermal material resistance values of the soil and structures used in the analyses are shown in Table 1. According to the numerical modelings, a building warms the subgrade to T_{sub} = +15°C (59°F) in the course of a few years if the indoor temperature of the building remains around T_{in} = +21°C (70°F) all year-round and the ground slab structure is properly thermally insulated (Figure 3). The thermal insulation board is a 100-mm-thick polystyrene board, with thermal conductivity of 0.040 W/m K (0.3 Btu in·/h ft^2 °F) or an R-value of about 15.

The numerical finite element modeling (FEM) above models the thermal behavior of the frost-protected shallow foundations, but the phenomenon that the heated building warms the ground around it is also present in buildings with a basement.

Water Vapor Diffusion in Ground Slab Structures

The following section simply illustrates how the different temperature fields at the different sides of the ground slab and water vapor resistances of the structure influence the thermal and moisture field of the ground slab.

The moisture field of the ground slab structure can be determined by using manual steady-state design tools such as the dew-point method, the Glaser diagram, and the Kieper diagram. Design tools compare the vapor pressures within a structure, derived from simple water vapor diffusion equations, with the saturation pressures, which are based on the calculated temperatures within the structure. Although these simplified design tools have many limitations (such as wetting and drying cannot be accurately analyzed and these tools ignore any moisture transfer mechanism other than diffusion), they are useful in comparing moisture behavior of one ground floor structure to another. The design tool used here is the simplified dew-point method. For the calculation, it has been assumed that the boundary conditions are stable and material properties (thermal and moisture resistances) do not vary with moisture content or temperature.

The water-vapor-diffusion behavior of a ground slab structure depends on the temperature gradient of the drainage layer and the subgrade, and the water vapor resistance of the ground slab structure. Temperature and water vapor content

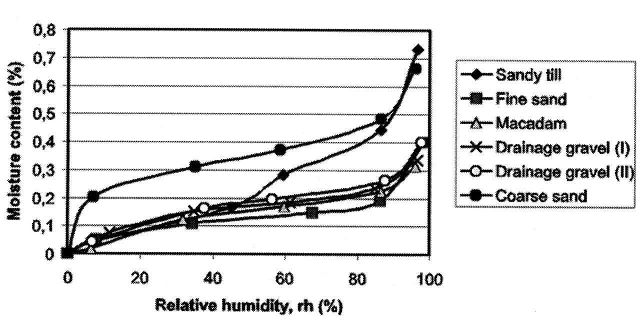

Figure 1 *Hygroscopic equilibrium moisture curve (absorption) of different coarse-grained soil types typically used as a drainage layer in Finland.*

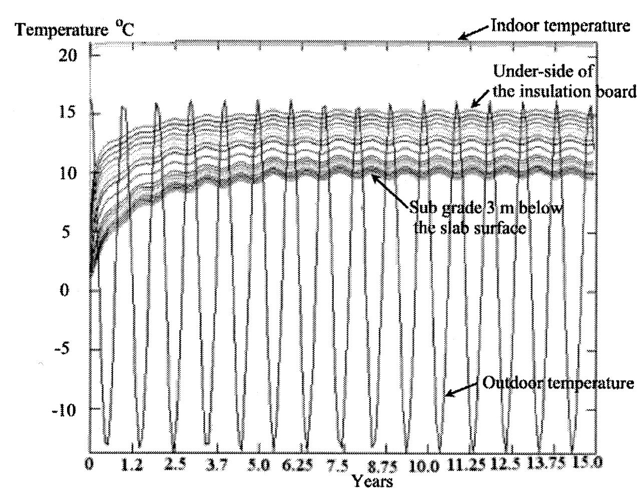

Figure 2 *Observed temperature changes at the subgrade and ground floor structures at the numerical finite element modeling (FEM).*

TABLE 1
The Thermal Material Values of the Soil Mass and the Structures Used in the Analyses

Material	Porosity	Dry Density kg/m^3 (lb/ft^3)	Degree of Saturation %	Melting Heat J/kg (Btu/lb)	Specific Heat J / kg·K (Btu·/[lb·°F])	Thermal Conductivity W/m·K (Btu·in./h·ft^2·°F)
Concrete	-	2400 (149)	-	-	880 (210)	1.4 (9.7)
Lightweight concrete block	-	650 (41)	-	-	650 (155)	0.22 (1.5)
Insulation board	-	16 (1)	-	-	1210 (289)	0.040 (0.3)
Gravel (Drainage layer)	0.30	1900 (119)	15	7704 (3.31)	771 (184) 676* (161*)	0.6 (4.2) 0.8* (5.6*)
Clay (Subgrade)	0.30	1700 (106)	95	47,811 (20.52)	1715 (409) 1117* (267*)	1.7 (11.8) 2.7* (18.8*)

* Frozen ground

differences across the slab structure tend to equalize through thermal conduction and diffusion. The basis of diffusion examination is the fact that the granular fill or drainage material is always moist; that is, the relative humidity of the pore air of the subgrade is around 100%. Also, the initial dampness of the fill material is usually relatively high because it is almost always exposed to rain at some point of the construction process, and the moisture can only exit by evaporation, which is a very slow process. Otherwise, the drainage layer is always in direct contact with the water table through the pore structure of the soil. Capillary attraction can also transport moisture to the drainage layer under the floor structures if the fine aggregate content of the material is too high.

As stated earlier, numerical modelings have shown that subgrade temperature is around T_{sub} = +15°C (59°F) if the indoor temperature of a building remains around T_{in} = +20°C (68°F) year-round and the ground slab has normal thermal insulation. The indoor temperature is usually between T_{in} = +20 … +21°C (68 … 70°F), and relative indoor humidity varies seasonally, being typically about 75% at a vapor pressure of 1754 Pa (0.52 in. Hg) in summer and 25% at a vapor pressure of 585 Pa (0.17 in. Hg) in winter in Finland. The direction and volume of water vapor diffusion depend on the temperature and relative humidity on different sides of the slab structure and the water vapor resistance of different layers of the ground slab structure.

The equation used to determine water vapor diffusion flux through materials is based on a form of Fick's law (Equation 1). The same type of equation also determines the heat flux in materials (Fourier's law).

$$w = -\mu \frac{dp}{dx} \quad (1)$$

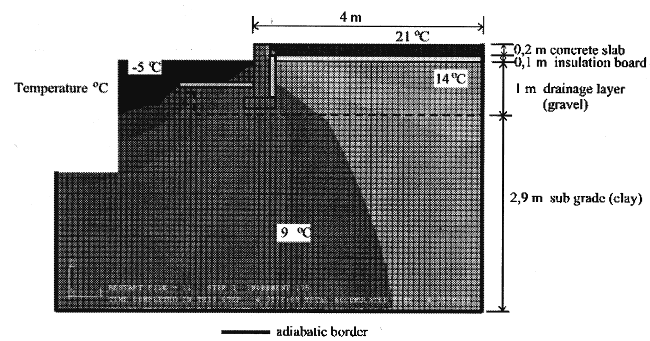

Figure 3 *The prevailing temperature field at the subgrade and ground floor structures after 15 years of thermal load caused by heated building.*

where

w = water vapor flux (flow rate per unit area), g/m^2 day (grains/h ft^2)

p = water vapor pressure, Pa (in. of Hg)

x = distance along flow path, m (in.)

μ = water vapor permeability, kg/m s Pa (per m in)

The temperature drop across each material layer is proportional to thermal conductivity (Equation 2).

$$\Delta T_x = \frac{R_x}{\sum R}(T_{in} - T_{out}) \quad (2)$$

where

ΔT_x = temperature change in one material layer x whose thermal resistance is R_x, °C (°F)

$R_x = d_x / k_x$ = thermal resistance of layer x whose thickness is d_x and thermal conductivity is k_x, K m^2/W (°F ft^2 h/Btu)

$R = \Sigma R_x$ = total thermal resistance of the structure

T_{in} = indoor temperature, °C (°F)

T_{out} = outdoor temperature, °C (°F)

Saturation pressure is determined by temperature according to an empirical function. Its values are calculated in many references, for instance, in the *1997 ASHRAE Handbook—Fundamentals* (ASHRAE 1997).

Vapor pressure drop across each material layer is proportional to the water vapor resistance (Equation 3).

$$\Delta p_x = \frac{Z_{px}}{\sum Z_p}(p_{in} - p_{out}) \quad (3)$$

where

Δp_x = vapor pressure drop in a material layer x whose water vapor resistance is Z_{px}, Pa (in. of Hg)

$Z_{px} = d_x / \delta_x$ = water vapor resistance of layer x whose thickness is d_x and water vapor permeability is δ_x, m^2 s Pa/kg (in. Hg ft^2 h/gr)

ΣZ_p = total water vapor resistance of structure

p_{in} = indoor vapor pressure, Pa (in. Hg)

p_{out} = outdoor vapor pressure, Pa (in. Hg)

The relative humidity (RH) of each layer is the ratio of vapor pressure to saturation vapor pressure.

Figure 4 presents the temperature, saturation vapor pressure, and vapor pressure distributions of a ground slab structure in a steady state when the temperature of the subgrade is T_{sub} = +5°C (48°F), +12°C (54°F), or +22°C (72°F).

The diffusion-driven moisture flow increases as the temperature of the subgrade increases. The risk of condensation occurring inside the structure or exceeding the critical moisture content of individual materials increases to the same extent. In buildings where the indoor temperature is about T_{in} = + 20°C (68°F) year-round, the subgrade should warm up to about T_{sub} = + 20°C (68°F) before water vapor can condense inside the most commonly used ground slab structures. At lower subgrade temperatures, T_{sub} = +12°C … +20°C (54 … 68°F), the critical moisture content of individual materials, such as floor coverings, glues, or timber structures, may be exceeded. That often leads to moisture and mold problems. Typically, moisture failure occurs after an old floor covering is replaced with a new one, which cannot evaporate the diffusing water vapor flowing through the floor structure. Mold growth on the bottom of the floor covering and in glued joints are usual signs of mold failure. Warming of this magnitude can occur if the ground slab is not thermally insulated at all, the

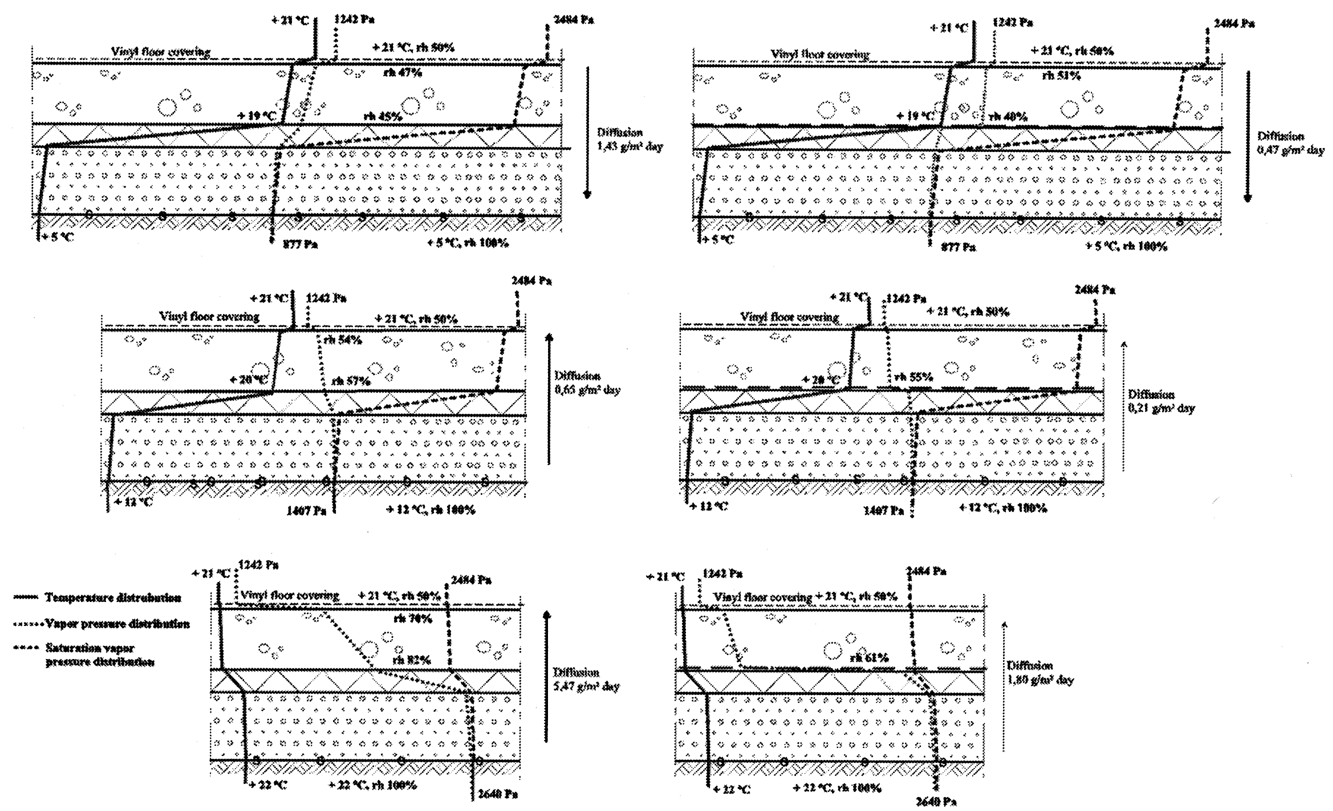

Figure 4 *Temperature, saturation vapor pressure, and vapor pressure distributions of a ground slab with and without vapor retarder beneath the insulation in different subgrade temperatures.*

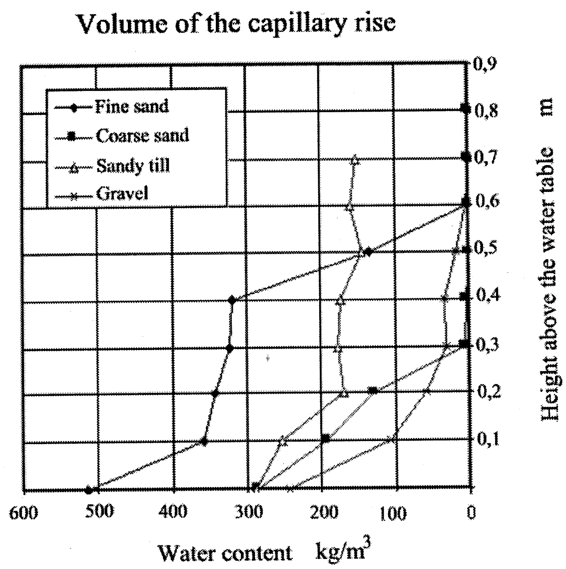

Figure 5 *Vertical capillary moisture equilibrium curve of different coarse-grained soil types typically used as a drainage layer in Finland.*

middle part of the slab with a large surface area has no insulation, or the subgrade contains heat piping. Subgrade temperatures as high as T_{sub} = +22°C (72°F) have been measured in Finnish ground slab structures that have suffered from moisture failure.

It should be noted that some water vapor diffusion will always occur due to temperature gradient and differences in water vapor contents across the ground slab structure. Excessive warming of the subgrade should be prevented by having effective thermal insulation under the slab. The volume of diffusion depends on the water vapor resistances of different sections of the slab structure. The ground slab structure as an entity should have the ability to evaporate the upward-diffusing water vapor of the subgrade.

CAPILLARY MOISTURE BEHAVIOR OF SUBGRADE

The ability of soil material to raise groundwater depends on particle size ratio, segmentation of the soil layers, degree of compaction, and prevailing temperature field. Capillary equilibrium moisture content depends on the surface area of soil particles and capillary pore structure of the soil mass.

Capillary Rise

The capillarity tests were made with one-meter-high test specimens of different granular materials packed inside an open-ended plastic tube and set up on an open water source. The volume and speed of the moist capillary front was measured with a series of PTC thermistors located inside the test specimen. Each individual thermistor was connected to a power source and a data logger. By measuring the required amount of voltage needed to heat up the PTC thermistor to its limit temperature, it was possible to define the thermal conductivity of the surrounding soil mass. By recording the thermistor readings at specific time intervals, one could define the speed and volume of capillary rise inside the specimen.

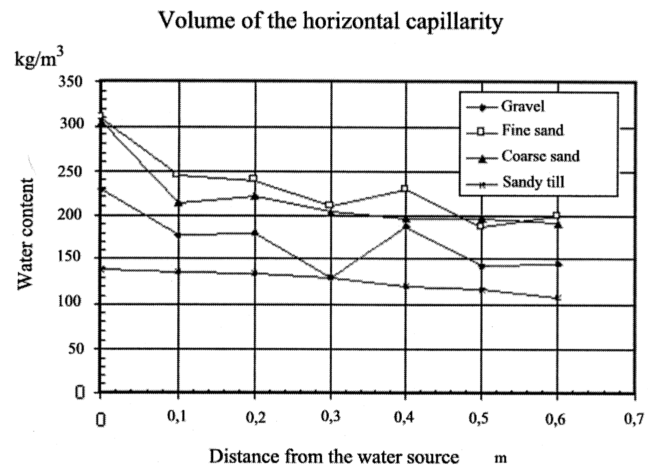

Figure 6 *Horizontal capillary moisture flow curve of different coarse-grained soil types typically used as a drainage layer in Finland.*

The volume of capillary rise depends on particle size ratio, shape of particles, and homogeneity of the pore system. The limit values of capillary rise for different soil materials (clay, sand, gravel) are presented in much soil science literature. There is a clear connection between the absolute value of the volume of capillary rise and the voids ratio of the material. The maximum volume of the rise was measured from even-grained sand, which had a characteristic void ratio e = 0.6 and total capillary rise volume of w = 20 kg/m^3 (20 kilograms of water in one cubic meter of soil or 1.2 lb/ft^3) at the height of h = 40 cm (16 in.) above the water table (Figure 5). The volume of capillary rise in moraine at the same height was noticeably smaller: w = 10 kg/m^3 (0.6 lb/ft^3) as the void ratio of the material was e = 0.3.

Horizontal Capillarity

Tests on horizontal capillarity were made with the same test equipment and coarse-grained materials as in the case of the capillary rise test series. This time, however, the test tube was placed horizontally and the water source was created by a gravitational water flow that passed by the other end of the open-ended tube.

Horizontal capillarity as a phenomenon is often a more significant cause of moisture migration in the subgrade and drainage layers than vertical capillary rise. Even in relatively coarse-grained materials, such as gravel and coarse sand from which the fine-grained particles had not been thoroughly washed away, the speed of the horizontal capillary flow and the volume of the migrating water were surprisingly high. The propagation speed of the moist front inside the test specimen was approximately v = 0.35 m/h (0.35 meters per hour or 1.1 ft/h) over a distance of l =60 cm (24 in.) from the water source as the volume of migrating water at this front was between w = 150 and 200 kg/m^3 (9.4 …12. 5 lb/ft^3) (Figure 6). References concerning horizontal capillarity of coarse soils are not found at the literature.

MOISTURE BEHAVIOR OF GROUND SLAB STRUCTURES

Based on laboratory testing and conducted analyses, it can be assumed that soils that are in contact with ground structures are always moist. The moisture content resulting from capillary rise and diffusion from groundwater is increased remarkably by horizontal capillarity. A capillary break layer of coarse-grained soil under the ground slab can prevent capillary moisture migration but not diffusive water vapor flow. The functionality of the ground slab structure with regard to water vapor diffusion depends on the temperature gradient between subgrade and indoor air. Warming of the subgrade should be prevented by using thermal insulation under the ground slab structure. Damage to ground slab structures lying on a warm subgrade can be avoided by using floor coverings of high enough water vapor permeance, which ensures that the critical moisture resistance of the various materials is not exceeded.

The water content of drainage layers and, especially, the high relative humidity of the pore air of the soil should be used as boundary values in studies on the moisture behavior of ground slab structures. In many cases, the ground slab structure functions properly even though the moisture content of the subgrade is high. The key factor is how the ground slab as a whole functions under the moisture load of the prevailing temperature field. If the temperature of the subgrade is low enough and the ground slab structure is capable of evaporating the moisture vapor flow, the moist subgrade should cause no problems.

The premises and initial boundary conditions for the design of new ground slab structures and the development of new repair methods for moisture-damaged ground slab structures should be as follows:

1. The relative humidity (RH) of the subgrade should always be assumed to be 100%.
2. The subgrade under the ground slab should not be allowed to warm considerably (there should always be a temperature gradient) because the water vapor diffusing toward the dry indoor air can raise the water vapor content within the floor structure and cause condensation.
3. The floor covering on the ground slab structure should be able to evaporate the water vapor diffusing from the subgrade.

CONCLUSION

The aim of this paper is to present the type and volume of moisture and temperature loads directed to the ground floor structures.

The hygroscopic equilibrium moisture content of grain materials (sands, gravels, and macadam) at the upper limit of the hygroscopic range, about 98% relative humidity, is quite small (between w = 0.5 and 1.0% [wt%] or 10 and 20 kg/m^3 [0.625 … 1.25 lb/ft^3]), compared to the capillary equilibrium moisture content. The total capillary rise volume varied between w = 20 kg/m^3 (20 kilograms of water in one cubic meter of soil or 1.2 lb/ft^3) in even-grained sand to w = 10 kg/m^3 (0.6 lb/ft^3) in moraine at the research. At the examinations of the horizontal capillarity, it has been noticed that even in relatively coarse-grained materials, such as gravel and coarse sand from which the fine-grained particles had not been thoroughly washed away, the speed of the horizontal capillary flow and the volume of the migrating water were surprisingly high. The propagation speed of the moist front inside the test specimen was approximately v = 0.35 m/h (0.35 meters per hour or 1.1 ft/h) over a distance of l =60 cm (24 in.) from the water source as the volume of migrating water at this front was between w = 150 and 200 kg/m^3 (9.4 …12. 5 lb/ft^3). According to the numerical modelings, the subgrade temperature rises up to around T_{sub} = +15°C (59°F) if the indoor temperature of a building remains around T_{in} = +20°C (68°F) year-round and the ground slab has normal thermal insulation in Finnish climatic conditions. The diffusion-driven moisture flow increases as the temperature of the subgrade increases. The risk of condensation occurring inside the structure or exceeding the critical moisture content of individual materials increases to the same extent.

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