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RESEARCH ARTICLE

Historical Overview of the Laboratory Measurements of Moisture Dependent Thermal Conductivity and the Integration of these Measurement Results into the Design of Hungarian Building Structures

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Abstract

The thermal conductivity of installed building materials can differ from the declared value, which is determined under specific laboratory conditions given in standards (Fülöp, 2007; MSZ EN ISO 10456, 2008). In this article, the author investigates moisture as a thermal conductivity modifying effect and the design of building structures in relation to this effect. In the first chapter, the international and Hungarian results of laboratory measurements of the value of moisture dependent thermal conductivity factors are summarized. In the next section, the application of these results in the design of Hungarian building structures is discussed, especially with regard to the flat roof, due to its increased exposure. With the framework of a historical overview, the most important flat roof layer combinations are described from the perspective of how thermal insulation material was protected against the different routes of moisture penetration. Concluding the article, a terrace restoration (a building constructed in the early 1900s originally without separate thermal insulation material) of Dr Zsuzsanna Fülöp is described to illustrate the points referred above.

Keywords

moisture dependent thermal conductivity, laboratory measurements, practice, flat roof layers, thermal insulation

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1 Problem identification

The thermal insulation capacity of building materials can be characterized by the thermal conductivity factor, the value of which depends, among others, on the material properties and measurement conditions. To ensure comparability, the value of the thermal conductivity of building materials must be determined under specific laboratory conditions; these can be found in the standards (MSZ EN ISO 10456, 2008); however, the real property of the installed materials can differ from this value. The different materials may respond to the modifying effects to varying degrees (MSZ-04-140-2, 1991).

In this article, the author investigates the changes in building materials' thermal conductivity due to moisture. The aim is to summarize the theoretical measurement results and to examine how these results are integrated into Hungarian building structure design (in practice), especially in the case of the flat roof (this building structure type has increased exposure to moisture) (Fülöp, 2007).

2 Laboratory measurements of the moisture dependent thermal conductivity factor

Lambert (for thin metal sheets) and Fourier (Fourier law, 1822) are considered the determining figures who laid down the most important principles relating to convection. At the beginning of the 20th century, researchers began making more detailed measurements in relation to moisture dependent thermal conductivity. Building physicist J. S. Cammerer (1892-1983) is considered one of the main representatives of these measurements; he was active in Munich, Berlin and Stuttgart. In his book, (Cammerer, 1936) he introduces the possible thermal conductivity values of different building materials as a function of the volumetric weight (Fig. 1); the standard deviation is because of the differences of occurring moisture in the practical application. The measurement results can be seen in Table 1. In his book, he also refers to the work of other authors: for example F. B. Rawley made measurements on the moisture dependent thermal conductivity factor of timber at 24 °C; Watzinger and Kindem (Trondheim) examined Masonite (made of wood fibres (Möller, 1929-1930)) and Celotex (made of beet sugar fibres (Möller, 1929-1930)) at 20 °C.

Table 1 The moisture content of building materials by volume. (Cammerer, 1936:p.18)

material group	the number of cases observed	moisture content observed (vol.-%)	moisture content normal value (vol.-%)	the most common value
brick and sandlime brick	22	0.2-0.3	0.2-1.0	0.5
concrete, gypsum	21	3.0-17.0	4-10	7
foam concrete	19	3.4-24.0	5-17	13
cob	17	4.2-14.5	4-10	7

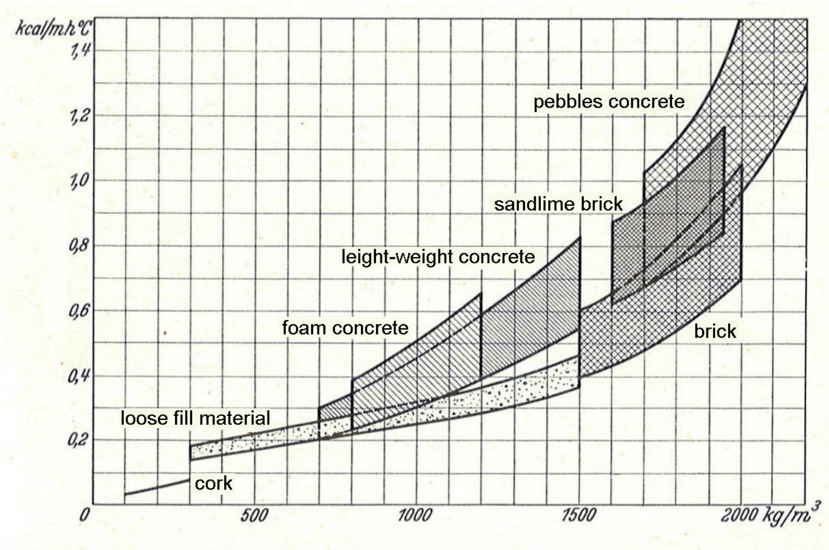

Fig. 1 The possible thermal conductivity values of more important building materials under practical conditions. (Cammerer, 1936:p.31)

A significant area of Cammerer's research was testing the moisture conditions of walls; he summarized his results in Table 2, and compared it with data of E. Raisch (München), Kreuger and Eriksson (Stockholm), Watzinger and Kindem (Trondheim). The influence of mortar and plaster were taken into account by assuming 1 % moisture content. Comparing the first and last line of Table 2, it can be seen that, in case of nearly identical volumetric weight, a 1.6 % moisture content resulted in a 29.76 % increase in the thermal conductivity factor. Cammerer mentions that a 25 % reserve should be required for the thermal insulation capacity of building materials. Later, in 1957, in his book (Cammerer and Schäcke, 1957) written together with H. Schäcke, extended thermal conductivity factor results for cork (as a thermal insulation material), brick walls, organic and inorganic building materials, as a function of moisture content, are discussed. In addition to his work, it can be established that as well as German research institutes, researchers in other parts of Europe also attached great importance to this question, mainly north of Germany: in Sweden, Norway and Denmark.

In Hungary, Károly Möller (1894-1945) carried out similar measurements; he began to publish his results (Möller, 1929-1930; Möller, 1942) from 1930. In his work, he refers to the measurements of Dr Hofbauer, Cammerer, Nusselt and Swedish researchers, furthermore, he made own measurements for cellular concrete. Möller summarizes the most typical insulation materials in his book (Möller, 1929-1930), and during their characterization, he highlights the differences between the dry and damp (having different moisture content level) samples (Fig. 2: brick wall, Fig. 3: cellular concrete). He establishes that the thermal insulation capacity (which he defines in his book as the

Table 2 Experimental results regarding the thermal conductivity factor of brick walls. (Cammerer, 1936:p.70)

	volumetric weight (kg/m³)	moisture content (Vol. %)	thermal conductivity factor (kcal/mh°C)	measured by
laboratory	1720	1	0.59	E. Raisch, München
laboratory	1900	1	0.63	Krueger and Eriksson, Stockholm
laboratory	1375	1	0.35	Watzinger and Kindem, Trondheim
house	1600	1.0	0.63	Cammerer, Berlin
house (inwall)	1600	0.4	0.65	Cammerer, Berlin
house (new build)	1750	2.6	0.84	Cammerer, Berlin

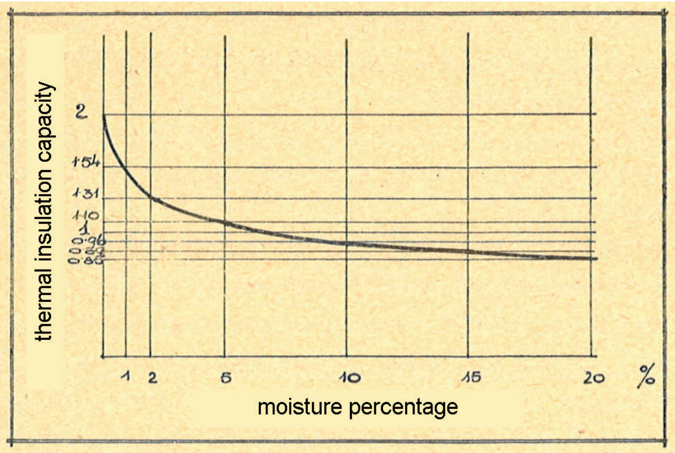

Fig. 2 The decrease in the thermal insulation capacity a fired brick wall as a function of moisture content according to Dr Hofbauer. (Möller, 1929-1930:p.6)

reciprocal of thermal conductivity factor (Möller, 1929-1930)) of peat/turf is 25 (from aquatic plants, its density after pulping is between 180-200kg/m^3) having the density of 190kg/m^3 at 0 °C, but if the material contains 0.5 % water, the value reduces to 16.4. Additionally, under the name of "Reform", there existed the material cork stone, which was impregnated with grain to reduce moisture ingress. Through the example of cork stone, it was also discussed that the thermal insulation capacity of natural cork stone is lower (~30, at 0 °C) than the thermal insulation capacity of the expanded version (~33-42, at 0 °C), even though in case of a cold store "Linde" in Cologne they returned to the natural cork stone (in thicker layers) because it was more durable against moisture penetration (Möller, 1929-1930).

At the end of the 20th century and the beginning of the 21th century, insulation requirements were tightened (Directive 2002/91/EC; Directive 2010/31/EU; 20/2014. (III. 7.) BM regulation); consequently, this theme drew the attention of an increasing number of researchers. Graphs of the moisture dependent thermal conductivity factor have been produced all over the world (for example: Fraunhofer Institut Stuttgart, University of Technology Vienna, Austria, Generic North America Database, MASEA Database, NTNU Norwegian University of Science and Technology (Künzel, 1995). The factor can also be expressed as a percentage ratio (TRR: thermal resistance ratio, (Powell and Matthews, 1987)); it creates a connection between the moist heat transfer resistance and the dry heat transfer resistance. In addition to this, several articles have also been published in this field in Hungary and abroad; the most important parameters of some international publications are presented (Table 3) as examples.

3 The application of laboratory measurements in Hungarian building structure design

Regarding the work of Károly Möller, the author has already hinted on the practical application; in this article the author deals in more detail with the question of flat roofs, due to the increased moisture exposure of this type of structure (Fülöp, 2007).

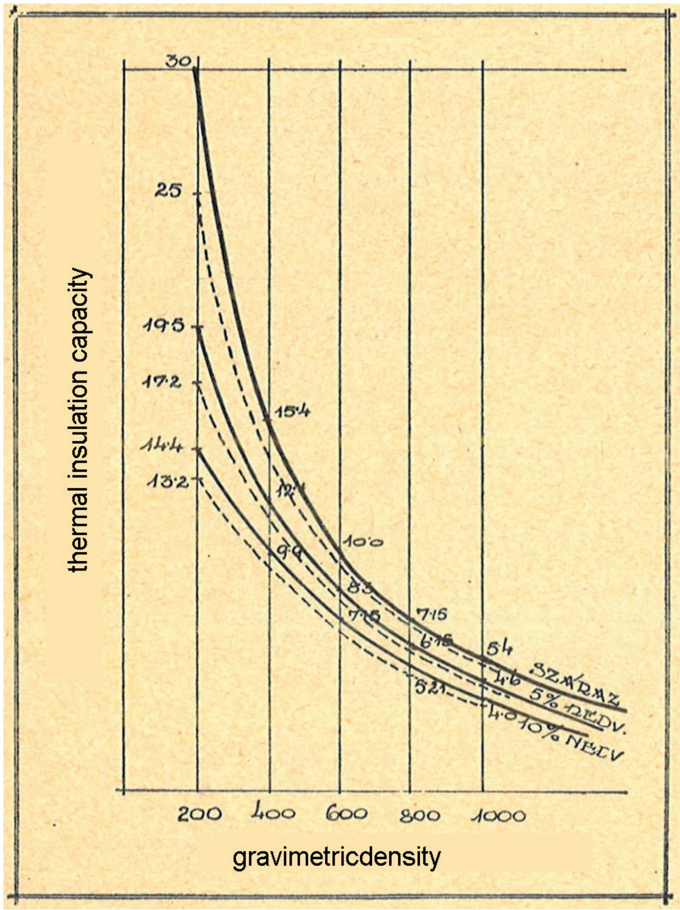

Fig. 3 The thermal insulation capacity of cellular concrete as a function of density and moisture according to Swedish data. The solid line refers to the sand-free version, the dashed line refers to the sand mixed version. (Möller, 1929-1930:p.10)

Gyula Sándy (1868-1953), who worked as a teacher at Budapest University of Technology and Economics, in his book (Sándy, 1930) written in the 1930s, introduces this structure in the chapter titled Flat roofs (XXXVIII. card). The protection of thermal insulation against moisture comes up on two levels: protection against precipitation (the material for this can be copper cladding, or bituminous felt) and protection against moisture caused by layers coming after the layer thermal insulation. He describes the protection against precipitation as follows:

"The waterproofing layer must also be taken out to the outer edge of the wall, formation of drenching is not allowed, the thermal insulation layer should not become damp, because in that case it would lose its thermal insulation capacity." (Sándy, 1930:p.27)

For the protection of the additional layers, Gyula Sándy gives a recommendation in the bold line of Table 4. This solution applies to slabs being insulated from above (Fig. 4).

Gyula Sándy suggests the following in the case of slabs being insulated from below (Fig. 5).

Table 3 The most important parameters of some recently published articles.

Reference, Location, Year	The examined "modifying effect"	Type of the insulation material	Degree of the difference
[24] Crescent, Singapore	**moisture** ○ wetting: rising vapor	**fiber glass** (34, 54-55-56kg/m³ – 62.0-77.6mm; 7 test run)	• At a volumefraction of 0.25 in an insulation of dry thremal conductivity 0.035 W/mK, the 'bead' model (water is distributed uniformly as small beads throughout the insulant) gived a thermal conductivity of 0.063 W/mK, while the corresponding value of the 'series' model (water is distributed in layers perpendicular to the direction of heat flow) was 0.046 W/mK
[22] Espoo, Finland; Saskatoon, Canada 1994	**moisture** (air relative humidity: 0 to 97 %) **temperature** (-21, -5, +5 °C, air: 22 °C)	**fiber glass** (73.1 kg/m³)	• At relative humidity of 97 % and a second cold plate tempera-ture of -5°C the heat flux is 4.9 times greater than the dry case; • the average thermal conductivity of the insulation has increased by only 3.5 % • the local thermal conductivity has increased by as much as 75 %
[15] Fla. 1995	**moisture** (dry air, 5 % moisture by weight added to it) ○ wetting: spray-applied (reweighed to check the percentage of moisture)	**bagasse** (47, 53, 54, 61, 67, 72, 77 80, 88, 99, 110 kg/m³ – 52 mm)	• The biggest values: for the 5 % moisture specimen 0.0056 W/mK – 110 kg/m³, dry 0.0348 W/mK – 11 kg/m³
[23] Canada 2006	**temperature** (soil) **moisture** (climate - rain)	**spray polyurethane foam** (medium density – 76 mm)	• The difference wasn't considerable (the insulation was found to be stable through the heating season, majorn rain and thaw periods do not appear to significantly affect the thermal performance of the specimens during these episodes).
[14] Thessaloniki, Greece 2008	**temperature** (25, 50, 75, 100, 250, 500, 1000 °C) **moisture** (EN 1609, EN 12087 + drying 7 days long in natural conditions)	**stone wool** (50 kg/m³ – 50 mm, 75 kg/m³ – 80 mm, 100 kg/m³ – 80 mm, 175 kg/m³ – 50 mm)	• In case of temperature λ began to grow radically above 250 °C • after absportion λ grew averagely by 22.91, 21,74 % (maximal values: 37.11, 26.26 %), but the material regained its former quality after drying.
[19] Stuttgart, Germany 2008	**moisture** (between 0 and the free satruration water content) **temperature** (between 20 °C and 80 °C)	**expanded glass granules** (140, 180, 190 kg/m³), **expanded clay** (300, 325, 330 kg/m³), **expanded perlite** (90 kg/m³), **foam glass** (150, 170, 195 kg/m³),	• Above about 50 kg/m³ (5 vol.%) an exponential increase was assessed.
[2] Falun, Sweden 2009	**moisture** (warm side: 20 ± 1 °C, 55 % RH ± 3; cold side: °C, well sealed test walls) ○ wetting: - test with open walls (the thermal insulation material was without any capping and exposed to the climate chamber atmosphere (20 °C, RH 55 %) - test capped walls (cassettes capped with sheet metal also on the warm side)	**glass wool** (20 kg/m³), **melamine foam** (10 kg/m³), **moniflex** (13 kg/m³),	• melamine: 0.038 – 0.062 W/m °C • glass wool: 0.045 – 0.057 W/m °C • moniflex: 0.058 – 0.062 W/m °C
[4] Barcelona, Spain 2010	in-situ measurement in Lleida, Spain	**polyurethane** (35 kg/m³ – 50 mm), **mineral wool** (100 kg/m³ – 50 mm), **polystyrene** (48 kg/m³ – 50 mm),	• The biggest was in case of reference (without insulation): 26 ill. 30 %; • average value: 12-14 %.
[12] Prague, Czech Republic 2012	**moisture** (20 %, saturation) ○ wetting: immersed, cup method	**hydrophobic mineral wool MW-HB** (100 kg/m³), **expanded polystyrene** (16.5 kg/m³), **thermal insulation board AAC Ytong Multipo**r (125 kg/m³), **hydrophilic** mineral wool (170, 70 kg/m³),	• mineral wools: λ = 0.041 W/mK (170 kg/m³), λ = 0.036 W/mK (100 kg/m³), λ = 0.037 W/mK (70 kg/m³) – dry λ = 0.10 - 0.14 W/mK – w = 5-20 %, λ = 0.7 - 0.9 W/mK – sat; • AAC: λ = 0.047 W/mK – dry, λ = 0.2 W/mK – w = 20 %, • EPS: λ = 0.037 W/mK – dry, λ = 0.051 W/mK – sat
[3] Dharhan, Saudi Arabia 2013	**temperature** (14, 24, 34 °C), **moisture** (dry, 8, 8.1, 13.6, 16.6, 29 %)	**fiber glass** (*27*, *47*, 65-66, *70*, *84* kg/m³ – 50 mm);	The dreegree of difference is max. 0.04 W/m °C: • from dry state to 29 % at 34 °C.

"If this coating (- thermal insulation coating -) is placed before making the reinforced concrete structure, the coating must be soaked into asphalt and it must be coated with asphalt once more on the surface that will be in contact with the concrete, or the coating must be covered with asphalt plate in order to prevent the absorption of water from the concrete." (Sándy, 1930:p.28)

Table 4 Layers of a building surrounded from above by reinforced concrete plate between iron beams. (Sándy, 1930:p.27)

	copper cladding
26 mm	wooden board covering
2 cm	air gap
6 cm	concrete – impregnated sleepers embedded in it **it can be painted with bitumen, mastikol against the moisture of additional layers**
5 cm	thermal insulation: fossil farina, cellular concrete, cork stone, heraklith, celotex
6-15 cm	concrete in slope dry sand or slag filling equalizing layer reinforced concrete slab between iron holders

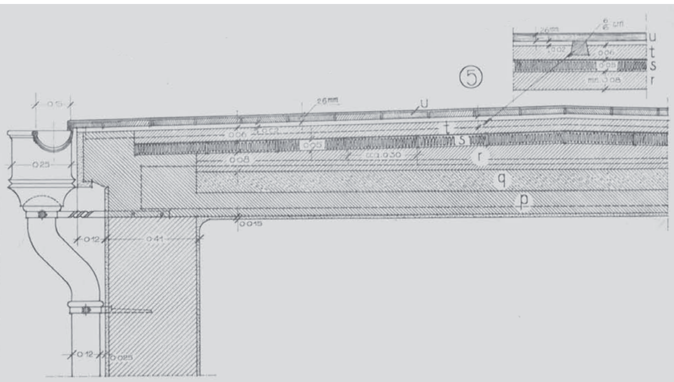

Fig. 4 Building surrounded from above by reinforced concrete plate between iron beams. (Sándy, 1930)

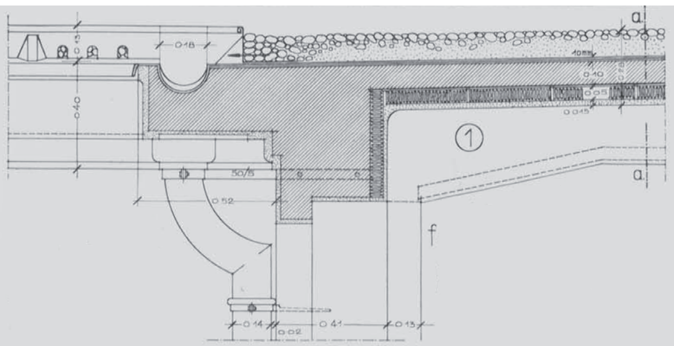

Fig. 5 Slab being insulated from below. (Sándy, 1930)

László Gábor (1910-1981), who also worked as a lecturer at Budapest University of Technology and Economics, devoted a separate chapter to flat roofs in his still available book series (Gábor, 1964). He examined the possible wetting of the thermal insulation layer in terms of precipitation, additional layers, condensation coming from inside and wetting during the building phase. With all layers, the thermal insulation layer is placed under the waterproofing layer (bituminous sheets). He suggests a separate bituminous layer against the building moisture from the concrete, being the layer that follows the thermal insulation. He treats the ventilated roof as a simpler task, because the internal condensation and the building moisture can leave more readily, and in addition to this - solid thermal insulation material is not directly necessary in this case. He analyses the different "warm" roof layers in terms of the danger of condensation by using the Glaser-method (end of the 1950s). Accordingly, the best solution is the case shown in Fig. 6, where

"the thermal insulation protects the load-bearing structure, the vapour barrier layer protects the thermal insulation, and the "vapour-ventilation" layer increases the safety of vapour closing,". (Gábor, 1964:p.233)

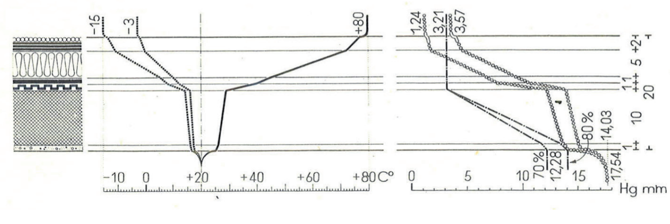

Fig. 6 The theoretical layers of a flat roof. (Gábor, 1964:p.230)

Regarding the "combined" structures, the danger of wetting during the building phase emerges. László Gábor introduces a "Roland-Isoca" covering ("vapour-ventilation" layer – for example ribbed plate + the lower sheet of the bituminous waterproofing layer) and a "Roland-Trisoca" plate ("vapour-ventilation" layer – for example ribbed plate + vapour barrier – for example fibreglass bituminous sheet + thermal insulation – for example cork). With the application of these "combined" structures, the building time can be reduced, but the thermal insulation layer does not receive additional protection against possible moisture effects from above because of its topmost position. A supplemented version of the structure is the type made with a bituminous sheet covering fixed on the top surface of the thermal insulation, which also gives protection against the building moisture from the concrete (Gábor, 1964).

Later, in 1986, László Kakasy in his technical doctoral dissertation (Kakasy, 1986) described his measurements regarding water absorption and the compression of stone wool, reviewing the mechanical and moisture effects on different external partition structures (walls and slabs) (Fig. 7). He also analysed the application conditions of stone wool products available in Hungary in those days. He came to the conclusion with respect to flat roofs and moisture that

"According to theoretical and practical considerations, I do not suggest the use of current stone wool products (being prone

to high water absorption)… as thermal insulation on viable or weight loaded "warm" roofs. Ventilated, shaded structures (walls and slabs) can be insulated with this material and then closed from moisture; protected thermal insulation can be used with maximum security, it effectively utilizes the properties of stone wool." (Kakasy, 1986:pp.83-84)

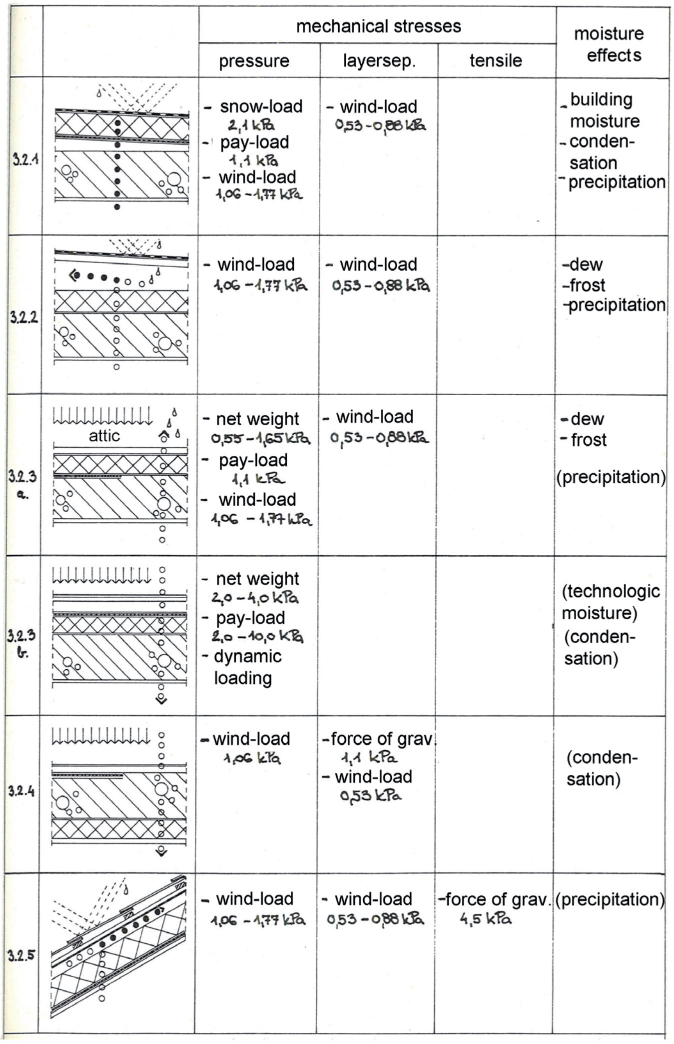

Fig. 7 Mechanical and moisture effects on the thermal insulation of external partition slab structures. (Kakasy, 1986:p.32)

Currently, 2+1 flat roof layer combinations can be typically differentiated in terms of the thermal insulation's exposure to precipitation and other moisture effects: the "normal" layers (slab + thermal insulation + waterproofing layer), the "inverted" layers (slab + waterproofing layer + thermal insulation) and the "DUO" layers (slab + thermal insulation + waterproofing layer + thermal insulation). (The question of vapour vents is not addressed in this article.) The "inverted" layers (where the waterproofing layer is in a more protected position and the thermal insulation is exposed to precipitation) became possible when closed celled (being not prone to water absorption) materials (for example extruded polystyrene foam, "foamed" expanded polystyrene foam) appeared on the market.

The spread of "inverted" layers did not start without problems in Hungary. For example, in the 1980s, during the thermal insulation of the housing estate at Káposztásmegyer, expanded polystyrene foam was originally applied; however, it became wet due to precipitation and lost its thermal insulation capacity. In the topmost flats, condensation occurred. Despite this, there are several well-functioning examples of "inverted" layer flat roofs (with extruded polystyrene). Two of these are part III of the office building of the Metropolitan gas works (1998) and the flat roof of MOM Park shopping centre (1999). The structural plans are linked with the name of Dr Zsuzsanna Fülöp.

There is also a current question regarding the placement of extruded polystyrene foam in two layers on flat roofs. Extruded polystyrene foam can be produced to a maximum 20cm thickness, but this is not enough to meet the ever-tightening requirements for thermal transmittance (20/2014. (III. 7.) BM regulation). As a consequence of this, manufacturers began to deal with the possibility of placing the material in two layers (Styrofoam Lösungen, 2011), although in this case, the water film that could develop between the two layers, may cause problems, it may work as a vapour closing layer for the lower positioned thermal insulation layer. The catalogue (Styrofoam Lösungen, 2011) gives two recommendations in order to prevent this: the lower positioned thermal insulation plate should be thicker (the humidity disperses within a larger volume) and a vapour-tight drainage layer instead of geotextile should be used on the top of the extruded polystyrene foam plates (most of the precipitation could be drained at this level). This layer-type is also recommended by manufacturers in Hungary, although, currently it is not common, and there is limited data for its long-term operation. A more detailed summary of this problem can be found in (Horváthné Pintér and Laczkovits, 2015).

In addition to the design of new buildings, the design of building structures of restorations is receiving increasing attention; this task is necessary because of damage and changes in requirements. If the aim is to reach a lower thermal transmittance factor, the DUO roof is typical; in this case, additional thermal insulation layer (that is not prone to water absorption) is placed on the existing "normal" layers. If the restoration cannot be avoided because of damage, the main purpose is to repair the mistake and the resulting damage, although, in this case, demolition is generally also unavoidable. In addition, the original structure typically does not meet the thermal demands, so besides the necessary repairs, the reduction of the thermal transmittance factor may be a requirement. The building structures design work of Dr Zsuzsanna Fülöp serves as a concrete example in this case. Serious wetting and the resulting damage were found on the terrace of building CH BME, built according to the plans of Győző Czigler in 1904. The original plans were not available; consequently, the existing layers could be determined only by exploration (Table 5, Fig. 8a). A separate thermal insulation layer was not included, "the mass" of the structure ensured the thermal protection, consequently, among others the whole structure should have been protected against moisture in favour of maintaining the thermal properties. In this example, the new layers were developed according to Table 6 (Fig. 8b). Liapor lightweight concrete (thickness ~10-12cm) was set in place of sub concrete. The additional thermal insulation layer (Liapor – it also ensured the necessary slope for the waterproofing layer) was fixed in place and protected from precipitation ("normal layers"). The danger of condensation is not a typical feature of historic buildings, which can be attributed to materials with a significant ability for vapour uptake (plaster, brick, filling) and a typically large headroom. In this case, the function of the room did not involve a high humidity-load (Fülöp, 2012). Because of the restoration, the thermal transmittance factor was lowered from 1.928W/m^{2}K to 0.694W/m^{2}K.

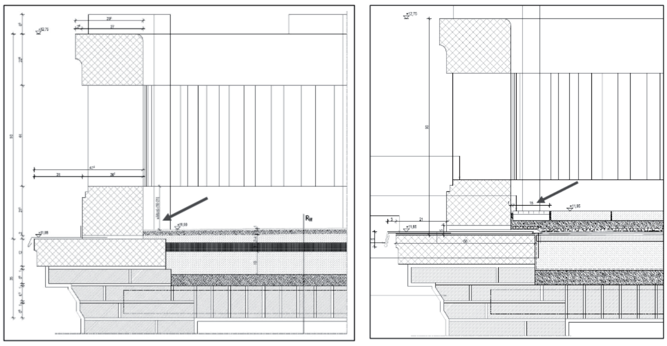

Fig. 8 Layers of the terrace of building CH BME before and after restoration. (design of Dr Zsuzsanna Fülöp)

Table 5 The original layers of the terrace of building CH BME. (Fülöp, 2012:p.45)

7 mm	"mettlachi" tiles
2-3 cm	cement mortar
2-3 cm	protective concrete
3 cm	bituminous felt
10 cm	sub concrete
5-7 cm	sand
12 cm	solid burned clay ceramic vaults supported by steel beams

Table 6 The layers of the restored terrace of building CH BME. (Fülöp, 2012:p.45)

4 cm	stone tiles in crashed rock bedding
5 cm	sand
1 ly	plastic geotextile protection layer 140 g/m^2
2 ly	modified bitumen membranes fixed by torching
1 cm	plastic mortar equalizing layer
10-12 cm	lightweight concrete screed in slope (Liapor)
1 ly	plastic geotextile separation layer 310 g/m^2
3-5 cm	sand
12 cm	solid burned clay ceramic vaults supported by steel beams

4 Summary

The article provides a historical overview of laboratory measurements and the application of these results in the design of Hungarian building structures.

The author intended to support the actuality of the theme "moisture-dependent insulation capability" with the presentation and interpretation of the historical and recent data, laboratory measurements, and their integration into the design of building structures. With the analysis of historical and recently accomplished examples, the article looks at the relevance of the knowledge of the coherencies and the experiences of historical patterns and at the actuality of the theme.

It is interesting to note that the results from laboratory measurements have long been taken into consideration in Hungarian building structures design. Through the example of the typically more exposed flat roof, it can be seen that these concepts were introduced in building texts written in the 1930s, and there were already recommendations on the issue of protecting the thermal insulation layer against different moisture effects. Since then, these principles can be traced continuously through professional texts.

Finally, the author's (through the example of her supervisor's work) draws attention to the situation where, in the case of the restoration of damaged building structures, the improvement of thermal protection may arise. In that case, the thermal insulation material must be placed into existing layers with the observance of the fixed parameters (Fülöp, 2012).

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