Revisiting the analogies of physical processes and connection between thermal and acoustic indexes of roll flooring materials

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Abstract. This issue shows the close correlation between thermophysical and acoustic properties of roll flooring materials, such as linoleum, rubber linoleum and carpet covering. The thermophysical properties are characterized by the heat absorption index, S, and the main acoustic feature is the index of impact noise insulation improvement, ΔL_{nw}. The analyses of equations for boundary conditions, as the smooth transition of temperature and heat flow through the interface of two media, allowed revealing the mathematical similarity between acoustic and thermal wave transmission processes, in particular, between the thermal and acoustic impedances. This similarity provided the basis for correlation research between the heat absorption specific coefficient and the index of impact noise insulation improvement values. Therefore, the correlation formula for different types of roll flooring materials was obtained.

1 Introduction

The civil buildings floors constructions, also including the load-bearing ceilings, should comply with wide range of requirements. Among them there are strength, abrasive resistance, manufacturability, heat transmission resistance, sound insulation, waterproofing, ecological safety (it should not be emissions of dust, dangerous gases, harmful compounds and smells). Within this framework, the floor constructions for different civil buildings premises can have a lot of varieties of main functional layers, fig. 1. The floor structure with the use of roll floor covering materials is one of the most popular variants for the upper floor layer.

Nowadays, practice at building and construction design of civil buildings shows wide appliance of roll materials in floor covering. The linoleum, the rubber linoleum and the carpet covering are among them.

Together with mechanical objectives, such as resistibility, elasticity and low abradability, these covering materials should have thermophysical and acoustical features.

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2 Materials and Methods

Each of the floor layers, which are depicted at figure 1, should have the specified properties for making a smart project design.

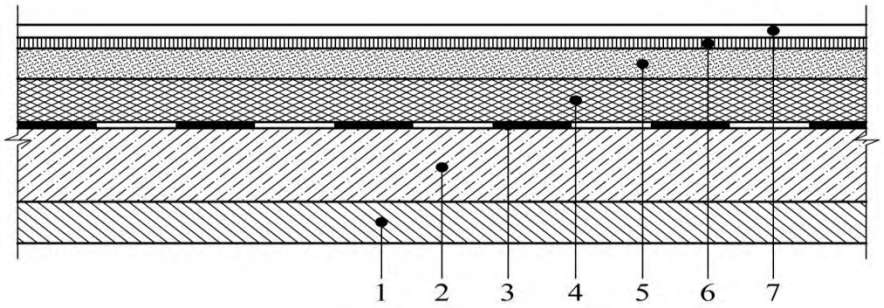

Fig. 1. The main construction layers of a floor construction: 1 - underlay; 2 - sub-floor; 3 - waterproofing; 4 - heat and sound insulation; 5 - topping; 6 - interlaminar layer; 7 – covering.

The sub-floor is a basic layer in floor construction, because of its occurrence in bearing construction design of the building. In case of basement or first storey, the sub-floor can be fulfilled from the ground, which should be previously compacted. As a rule, a floor panel works as a sub-floor at other levels.

There is a need in underlay, when the ground under the building is unreliable. The uniform distribution and transmittance of the load to the soil is the main underlay object. The reinforced concrete bed can be used as an underlay, but, sometimes, in low loads situations the sand, gravel, keramzit gravel and the other fill materials.

Waterproofing is necessary for moisture ingress prevention from the ground under the floor, due the possibility of high subterranean water level. Also, the waterproofing layer is required for wet conditions premises, for instance, for bathroom: in this case this layer can stop the leakages to the underlying storey. The different materials, like tar paper, asphalt mastics, latex mastics and roll insulation.

Mortar topping is provided for the floor surface screeding. Thus, topping allows obtaining sufficient incline for water removal, if floors are disposed in sanitary conveniences and wet engineering spaces. Topping can be prepared by the use of cement mortar or precast slabs, like wood chipboard, oriented structural board, wood fiber board, gypsum fiber sheet or plywood. The choice of topping variant is determined by the sort of floor finish.

Interlaminar layer is the stratum for whole floor construction conjunction with the covering. There are two possible types of the interlaminar layer in relation to applied covering. They are "adhesive" and "distributing" types. For example, the glue between tiles and the topping can work in the capacity of adhesive layer, and the distributing layer can be completed with linoleum or laminate sub-base, that the vertical load to be evenly spread.

Covering is the finishing floor layer. There are different types of floor finishes, but this issue concentrates on roll floor coverings, such as linoleum, rubber linoleum and carpet.

The roll floor coverings are the adequately efficient materials in terms of functional requirements for floor structure. Linoleum, accordingly with its varieties, as well as the carpet, are capable to fulfill the functions of three layers simultaneously: the layers 4, 5, and 6 at the figure 1; particularly, when the special sub-base is using. The combining of thermal and acoustical properties of the roll flooring materials has a primary importance in the scope of this article.

Linoleum is the waterproofing floor coating, it is flexible, polymeric, with the natural materials imitated textures. Linoleums are divided on three categories by their exploitation:

household, semi-commercial and commercial linoleum grades. There are a very few main linoleum species by their basic structural materials.

PVC (polyvinyl chloride) -linoleum is a full chemical product. It is fabricated in two variants: on the textile or on the heat-insulating base. This type of linoleum can be single or multilayered. The deficiency of PVC-linoleum is its shrinkage, that means the decrease of sheets length, width and height and that results to splayed joints. The advantages of such material are its low cost and absolutely safety.

Natural linoleum is fabricated from natural components, like wood meal, conifer resin, broken lime, linseed oil, and colourants. The mentioned compounds form so called "linoleum mass". The natural material is obtained by the result of some technological operations, such as aging, pressing, and drying. The benefits of the natural linoleum application are: ecological properties, household chemical resistance, fire safety, dimensional stability, long durability, antistaticity.

Alkyd floor covering has the base for covering from jute fabric, which is coated by the alkyd resin, modified with plant oil and different fillers (like wood and cork powder). The physical and mechanical features of this covering are more perfect than PVC flooring, however, this type is used only for floors at transport or at utility premises. The appearance of brittleness and friability increase with the course of time, that can be referred to disadvantages. The advantages include reasonably good thermal and sound insulation properties.

Colloxylin (nitro-linoleum) linoleum is a one-layered covering without a base, with the chemical binder from nitrocellulose. Lots of mineral extenders are fed into the linoleum structure for increasing the materials high temperature resistance. Its positive aspects are: high elasticity, humidity resistance, flexibility, and low temperature resistance. The negative impacts are: the lack of color scale (the material has only red and brown gradations), settling qualities, low resistibility to terminal difference and chemical agents affecting.

Marmoleum is a contemporary know-how in the range of roll flooring materials. It contains cork, jute, and resin. This is ecological safety material, which has the next worth: antistaticity, hygienics, heat insulating properties, fire safety, decorativeness, and low cost. Its limitations are: relative frailty (predominantly along the edges), heavy weight, the hardening of the covering in time.

Unsupported rubber linoleum is a special type and it includes two layers. One of them (face layer) is made from colored rubber, and other (lower layer) is manufactured from compound, that is the mix from previously used rubber, bitumen, and synthetic caoutchouc. The lower layer can have the porous structure. Key benefits are: the resistibility to high humidity, chemical reagents, and ultraviolet light, hygienics, reliability, abrasive resistance, durability. Negative side involves minimal color palette, which is represented only by blue, gray and red species, and also the high cost.

Carpet flooring is a variety of carpets, that is fixed to the floor toping. Carpet floorings well keeps heat and absorbs excessive noises. The carpet covering can be divided into the three main types by the way of its manufacturing. They are: woven, tufting (with the cloth base, which is stitched by pile yarns), and needle-punched (when pile yarns are punched by needles in the carpet base).

The woven carpet covering is the most strength, but the priciest, because of its operation process, which is the same one with the customary carpets. This is the natural jute supported roll floor carpet covering, and its support (base) looks like a network.

When tufting carpet covering is fabricated, the yarn is punched in the base and fixed by the mixed glue. Prevalence of this technology is caused by the diversity of this floor carpet floor coverings variants, such as loop covering (with loops on top surface), shaggy covering

(with pile upper side), and their varieties. The loop carpet covering has a rather hard base and upper surface. Due to the loops, their abrasion resistance level is rather high too.

The previously hued yarns are used for manufacturing of loop carpet coverings, and they allow creating solid, tranquil colors. Except the one level loop coverings, there are also the multilevel loop. The multilevel loops height differs, that makes the surface drawings volumetric. The pile carpet coverings are classified by the short-piled (with the pile length of 2-3 mm), middle-piled (3-5 mm), high-piled (more than 5 mm).

Needle-punched carpet floor coverings have a higher abrasive resistance, than the tufting and the woven coverings. The threads are laid down on the primary base, than they are punched into the base, and after this, the secondary base are attached (it is usually made from rubber). The needle-punched carpet surface has not pile and looks like a felt. It can be painted by the different ways. The first way is the manufacturing from the synthetic colored mass threads; the second way is the fabrication from already painted thread; the third way is the printing of drawings with the stencils on already prepared carpet cloth, but these drawings are less durable, and rapidly burns down or fades.

The carpet and linoleum roll coverings often have the sub-base for sound and heating insulation increasing, especially for the floor concrete bases. There are few types of sub-base for roll floor materials.

The jute-supported linoleum has the sub-base from the jute fibers. The jutes fibers have been applied only for coarse cloths (gunny sacking type), cables, and ropes until recently. However, nowadays, the jute fibers show the wide acceptance in different branches, including the construction materials with high ecological safety level. The profit of jute-supported linoleum use lays in capacity of taking in humidity, and gradually removing it with time in inner environment. The jute base (support) is especially elaborated by the appropriate agent that it can resist fire, parasitic insects, and fungus. The only negative characteristic is the high cost.

The cork sub-base is produced from ground bark. This natural, prefabricated without any synthetic, material has actually high thermal and sound insulation indexes. Its poor qualities are high cost and soft structure, which can be damaged by the heavy furniture and equipment.

The linen sub-base provides sufficient natural ventilation, that is the guaranty of hydrophilous fungi colonies and sluggish air absence. As this product is natural, it needs to be worked by special compounds against insects, putrefaction and ignition.

The combined sub-face constitutes from linen, wool, and jute composition. Such mix gives it high abrasive resistance and required hardness.

The foamed sub-base is fabricated from expanded polyethylene and has a low price. It gets out of shape very soon, when being used under the linoleum covering.

Heat absorption specific coefficient (index)S is the basic thermophysical factor in case of flooring materials [1, 2, 3]. This factor characterizes the building material capacity to take up temperature fluctuations of thermal wave on the material's surface with large or low degree of intensity. This oscillating process goes with energy transmission. Taking into consideration hygienic requirements to the floor covering in premises with long-duration habitability and normal temperature, it is essential that the heat quantity absorbed by the flooring surface, to be less than the heat quantity, provided by human body (flowing through the bottom of the foot), or at least, to be equal to this quantity. The magnitude of material's heat absorption specific coefficient is a function of its thermophysical properties and of thermal wave oscillation period. If the period of thermal action conventionally is taking into account with 6.28 hour duration (that approximately corresponds with a length of a working-day), heat absorption specific coefficient, S, will be equal in its absolute value to the coefficient of thermal effusivity (activity) S_a, termed also as "b" in the Western world (formula 1):

$$S_a = \sqrt{\lambda \cdot \rho \cdot c_p}, \text{ W/m}^2\cdot\text{°C}; \quad (1)$$

where λ - coefficient of thermal conductivity, W/m^2·°C;

ρ - density of material, kg/m^3;

c_p - thermal capacitance at constant pressure, J/(kg·K).

Therefore, the coefficient of thermal effusivity S_a, is the main thermophysical index for the heat material absorption capacity.

The impact noise insulation is an acoustical object for flooring structures. The flooring covering insulation capacity is evaluated by the ΔL_{nw} magnitude (in dB). This is the index of impact noise insulation improvement (or the index of normalized impact noise level lowering) [4, 5, 6]. Impact force provokes elastic (acoustic) waves in flooring slab material. The ΔL_{nw} and S_a for some types of linoleum sub-bases are represented in table 1.

Table 1. The features of roll floor coverings and their sub-bases.

N	Sub-base type	Thickness, mm			Index of impact noise insulation improvement, ΔL_{nw}, dB	Heat absorption specific coefficient, S_a W/m^2·°C
		total	base	sub-base		
1.	B	4	1.4	2.6	17	11.4
2.	RS	4	1.4	2.6	23	9.6
3.	RS	3.7	1.2	2.5	25	9.2
4.	C	4	1.2	2.8	20	11.2
5.	RS	5	1.2	3.8	20	10
6.	RS	3.6	1.2	2.4	22	10.1
7.	J	3.7	1.2	2.5	23	9.3
8.	C	3.8	1.2	2.6	22	8.5
9.	RS	4.6	1.2	3.4	17	11.4
10.	RS	5.5	1.5	4	21	9.2
11.	J	3.95	1.35	2.6	17	10.8
12.	RS	4.5	1.2	3.3	19	9.6
13.	RS	4.35	1.2	3.15	20	9.3
14.	J	3.85	1.25	2.6	17	11

Notes. The sub-base type: J – jute fiber with antisaptization; B – bast fiber with antisaptization; RS – mixed of recycled and synthetic fibers; C – chemical fiber.

In this case, the origin of thermal waves is the heat, produced by the human body, and the legged movement along with the different kinds of impact force is the source of acoustic (elastic) waves in flooring covering.

It is common knowledge, that the thermal waves have the same relationships of transmission, as the acoustic waves [7]. The thermal wave incidence on the interface of two media (air - material of flooring covering) shows the fractional reflection, same with the incidence of acoustic waves [8]. The temperature field is determining through the equation (2):

$$\theta_1 = A_1 \cdot e^{j\gamma_1 x} + A_2 \cdot e^{-j\gamma_1 x}, \quad (2)$$

where x - point coordinate;

A_1, A_2 - amplitudes of travelling and exponentially decaying waves;

γ_1 - complex wave number for air.

This equation (formula 2) describes the decaying travelling wave.

The formula for a thermal transmitted wave is:

$$\theta_2 = \bar{A}_1 \cdot e^{j\gamma_2 x}, \quad (3)$$

where γ_2 - complex wave number for material;

$\bar{A}_1$ - complex amplitude of transmitted wave.

The boundary conditions are the smooth transition of temperature and the heat flow through the interface of two media (air - layer of material), (formula 4).

$$(\theta)_{x=0} = A_1 + A_2 = \bar{A}_1 \tag{4}$$

$$\left(\lambda\frac{\partial\theta}{\partial x}\right)_{x=0} = j \cdot \lambda_1 \cdot \gamma_1(A_1 - A_2) = j \cdot \lambda_2 \cdot \gamma_2 \cdot \chi_2,$$

where λ_1, λ_2 - coefficients of thermal conductivity for air and material;

χ_2 - structure factor of material.

The equation (4) is different from the same one for acoustic waves only by the substitution of specified acoustic impedance (resistance) for material surface,ξ_a,(formula 5),with the impedance, by formula (6).

$$\xi_a = \frac{\rho_2 \cdot c_2}{\rho_1 \cdot c_1}, \tag{5}$$

where ρ_1, ρ_2 - the density of air and material;

c_1, c_2 - the sound wave speed in air and material.

$$\xi_{th} = \frac{\lambda_1 \cdot \beta_1}{\lambda_2 \cdot \beta_2} = \sqrt{\frac{\lambda_1 \cdot \rho_1 \cdot c_{p1}}{\lambda_2 \cdot \rho_2 \cdot c_{p2}}} = \sqrt{\frac{S_1}{S_2}}, \tag{6}$$

where β_1, β_2 - decay coefficient of temperature wave for air and material;

c_{p1}, c_{p2} - thermal capacitance at constant pressure for air and material;

S_1, S_2 - heat absorption specific coefficient for air and material.

By analogy with acoustic waves transmittance, the entrance coefficient in case of temperature waves transmittance, can be represented as (formula 7):

$$\alpha_{th} = 1 - \sqrt{\frac{S_1/S_2 - 1}{S_1/S_2 + 1}}. \tag{7}$$

Roll flooring materials, such as linoleum, rubber linoleum and carpet covering fall into the category of elastoviscous materials. The decaying mechanism and the energy losses over the course of oscillating processes in their depth are caused generally by thermal conductivity and viscosity mechanism.

3 Results

The physical and mathematical analyses of analogies (similarities) between heat and elastic (acoustic) waves transmittance processes in elastoviscous materials, which includes roll floor coverings, allowed carrying out the complex experimental researches of correlation between S and ΔL_{nw} indexes, (formula 8), figure 2 [9, 10]. These researches have a profound practical interest.

$$\Delta L_{nw} = 79{,}09 - 10{,}01S + 0{,}389S^2 \tag{8}$$

The measurements of heat absorption specific coefficient, S, and the index of impact noise insulation improvement, ΔL_{nw}, for roll flooring material samples were taken in thermal physics laboratory and acoustic chambers of NIISF RAASN (Research Institute of Building Physics of the Gosstroy in the Russian Federation).

There were observed four types of thermal- and sound isolation linoleums with decorative and protective cover-up from polyvinylchloride. Among them there were linoleums with sub-base from: bast and jute fiber; synthetic (chemical) fiber; textile raw

material reworking and wool fiber; foamed polyethylene. The thickness of samples was varied from 1.4 to 4.9 mm.

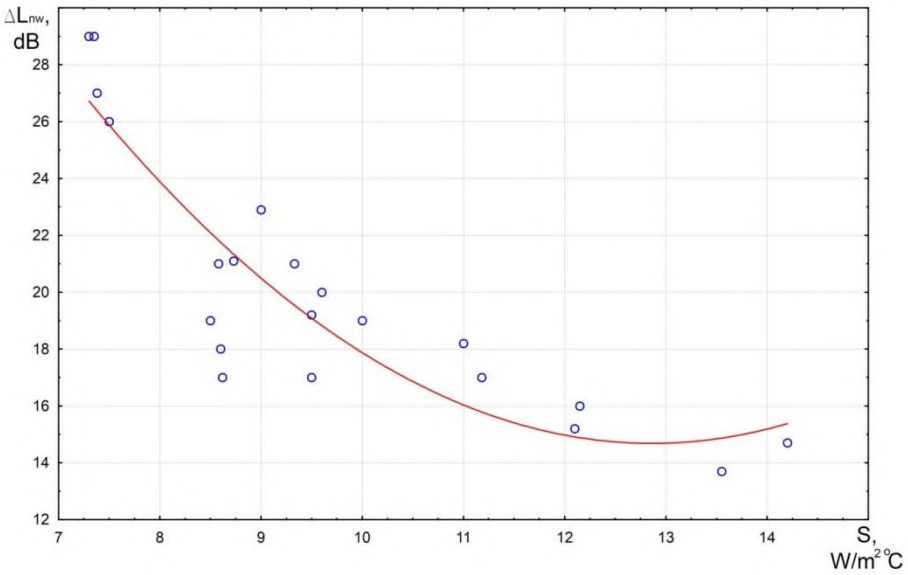

Fig. 2. The graph of correlation between heat absorption specific coefficient, *S*, and index of impact noise insulation improvement, ΔL_{nw} for observed types of roll flooring materials.

There were investigated the properties of the following carpet coverings: with low pile and in 4.4 mm thickness; with nap of "boucle" type in 6.2 mm thickness; with medium pile in 8 mm thickness; with high pile in 12 mm. Also, these kinds of floor carpet coverings had a sub-base from: jute, steeped in acrylic; synthetic fibers, steeped in acrylic; isobutene polymer; rubber with 950÷2000 kg/m^3 density (ρ). The material samples were manufactured in Russia, Finland, Belgium, France and Germany.

The measurements of heat absorption index, *S*, and the index of impact noise insulation improvement, ΔL_{nw}, were performed in compliance with Russian standards.

4 Conclusions

1. Roll floor coverings combine the functions of defense from impact noise and heat loss, that makes them very attractive from the point of view on comfortable internal environment creation in case of residential and public buildings.

2. There are the physical and the mathematical analogies in processes of sound waves and thermal waves transmission in floor surface layer with roll floor coverings. The solutions for equations of continuity on the interface of two media for sound and thermal waves transmission have the very similar form. The impedances and transmission coefficients both for the sounds and thermal waves follows the near physical view formulas.

3. The mentioned above prerequisites give grounds for assuming of the mathematical correlation relationship between the values of heat absorption specific coefficient and index of impact noise insulation improvement for the roll floor covering materials. The obtained correlation formula (1), allows evaluating the value of the one flooring material parameter trough the value of other, that is very important in floor roll covering designing practice.

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