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RESEARCH OF ACOUSTIC PROPERTIES OF MATERIALS FOR FOUNDATIONS UNDER THE FLOOR

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Abstract. The most important components of comfortable conditions for people on the premises of residential and public buildings are thermal (temperature) and acoustic comfort. By the regulatory documents of Ukraine, high requirements are imposed on the thermal and sound insulation qualities of external and internal building envelopes, especially on interfloor floors. While the problem of insufficient thermal protection primarily concerns floors over cold basements and passageways, poor sound insulation of floors is a problem for all apartments in high-rise buildings. This article analyzes the causes of acoustic discomfort in buildings. A person indoors is exposed to three types of noise: airborne, impact, and structural. The most difficult problem to solve is an impact noise through the floors. It is emphasized that despite the different noise sources, the mechanisms of propagation of structural and impact noise are similar – through the structural elements of the building. Therefore, measures to reduce impact noise can simultaneously reduce the level of structural noise. The most common methods of reducing sound transmission through floors are analyzed. It is proposed to replace the conventional screed in the floor structure with a heat and sound-insulating screed based on a gypsum-cement-pozzolana binder. This paper considers only an acoustic aspect of the problem. According to the theory of acoustic dissipation, it is assumed that the effect of sound energy dissipation is enhanced by the introduction of aggregates into the mixture, which increases the number of structural heterogeneities and interfaces. The aggregates used in the mixture are expanded polystyrene granules, cork chips, and granular waste from the production of foam glass. In order to experimentally verify this assumption, laboratory methods and devices were developed for a comparative assessment of the soundproofing properties of the developed compositions. Based on the results of measuring the acoustic properties of the prototypes, experimental and statistical (ES) models were constructed, and the best combinations of mixture components were determined in terms of sound insulation. ES models of noise properties were used in the multi-criteria optimization of the composition of the composite mixture.

Keywords: interfloor floors, floors, acoustics, impact sound, sound insulation, acoustic measurements, planed experiment, modeling.

Introduction. An important task of civil engineering is to provide comfortable conditions for people to stay in buildings. The main components of a comfortable stay of people in residential and public buildings are thermal (temperature) and acoustic comfort. In accordance with the regulatory documents of Ukraine [1-3], rather high requirements are imposed on the thermal and sound insulation qualities of external and internal building envelopes, especially on interfloor floors. Insufficient thermal insulation of floors leads to increased heat loss and higher heating costs. If insufficient thermal protection is manifested primarily in rooms with floors over cold basements or passageways, then acoustic discomfort as a result of poor sound insulation of interfloor floors in residential buildings, especially from impact noise, is a problem for all apartments in high-rise buildings [4].

Despite the differences in the physical phenomena of heat and sound transmission through building structures, a significant improvement in the thermal and sound insulation of floors can be achieved by using special materials with a set of specified properties as floor substrates. The requirements for such materials for some properties are multidirectional, for example, improving sound insulation characteristics by increasing density is accompanied by a deterioration in thermal protection properties. While meeting the requirements of standards for a number of other important properties such as strength, moisture resistance, shrinkage, and fire safety, these materials must also be environmentally friendly and inexpensive.

These requirements are met by water-resistant gypsum-based composite materials, a distinctive feature of which is the consideration of the physical and chemical capabilities of each of the components of building mixtures, their interaction with each other and their predominant influence on certain operational and technological characteristics. Synthesis of a suitable material under many non-coincident conditions is a non-trivial but important task of construction materials science. Thus, the development of a composition of multicomponent gypsum-containing materials for floor substrates with an optimal set of operational and technological properties is an urgent task. This paper considers one of the aspects of creating comfortable indoor conditions – providing acoustic protection against the penetration of airborne noise and, especially, impact noise through the floors.

Analysis of recent research and publications. The problem of heat and sound insulation of not only interfloor floors, but also other building envelopes, both external and internal – walls, partitions, windows and doors – arose with the beginning of mass construction of panel and block buildings using large-sized precast concrete products, in particular, floor slabs [5]. The first Soviet projects of that time included gypsum slabs, and sometimes panels the size of an entire room, which were laid on the floor under a screed. They served as soundproofing and, partially, thermal insulation of the floors, and they did their job quite well. The disadvantage of such gypsum bases was their low water resistance. Plumbing accidents and flooding of the premises with water during firefighting led to soaking of the gypsum bases, loss of strength, cracking, and loss of sound insulation properties. During the renovation, these slabs were dismantled to increase the height of the room, and the sound insulation was completely eliminated. Another solution to the problem of soundproofing the floors was the installation of floors with elastic gaskets. As a material for elastic pads, products made of silicate fibers (glass, mineral) were used, which were intended mainly for thermal insulation purposes. The main disadvantage of all these products as elastic gaskets is their high compressibility during operation [6]. The problem of sound insulation of premises became especially acute with the advent of frame-monolithic buildings, where, in an effort to reduce the weight of structures, the thickness of floors and partitions was reduced to the minimum permissible strength. This has led to a decrease in the soundproofing properties of the enclosures and a sharp increase in complaints from residents about increased noise in their apartments.

There are three types of acoustic impact on humans indoors: airborne noise, impact noise, and structural noise. Airborne noise is noise that spreads through the air, such as loud conversation, media devices, traffic noise, and the operation of machinery under the window. Impact noise is any impact that is perceived by a building structure element and propagates through the premises over a wide area – the sound of heels on a tiled floor, a nail being driven into a wall, a hammer drill, etc. Structural noise is caused by the vibration of communications in the building – the "growling" of the water supply system, the noise of water running down, the operation of elevator equipment, knocks in ventilation shafts, etc. It should be noted that, despite the different noise sources, the mechanism of structural noise propagation is similar to the mechanism of impact noise propagation (Fig. 1) – through the structural elements of the building [7]. Therefore, measures to reduce impact noise can simultaneously reduce the level of structural noise.

The sound insulation of the floor is mainly affected by the value of the total mass of 1 m^2 of the interfloor ceiling with the floor, and if it is greater than 350 kg/m^2, the required sound insulation of airborne noise is generally provided [8]. For impact noise insulation, the mass of the floor is also important, but to meet the standards, it must be several times greater than for airborne noise standards, which is neither technically nor economically feasible. In this case, it is more efficient to use special floor structures [9].

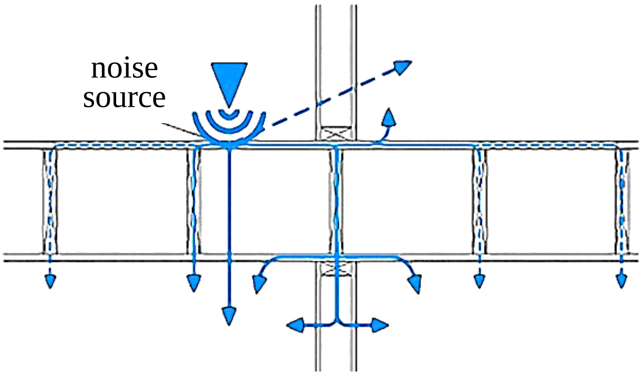

Fig. 1. Scheme of impact noise transmission

Typically, a common floor structure for panel buildings includes the following elements (Fig. 2): coating, screed, and a reinforced concrete slab base.

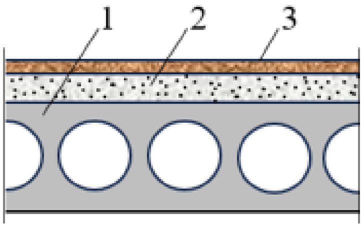

Fig. 2. Elements of the floor structure:
1 – reinforced concrete slab; 2 – screed (underlying layer); 3 – coating

Let us take a closer look at layer 2 – the screed as an element of the floor structure, which is most appropriate to use as a soundproofing base. A screed is a layer that levels the floor surface and also serves to create a flat surface for the coating. Depending on the materials used, screeds are divided into solid (monolithic) and prefabricated.

The composition of solid screeds includes: cement-sand mortars, concrete, expanded clay concrete, gypsum concrete, and cement fiber. Almost all of these types of screeds can be used as self-leveling screeds. A self-leveling screed is a ready-mix that, after pouring, self-distributes and levels without the need for additional leveling or adjustment, making the installation process faster and easier. In flooring technologies with prefabricated screeds, the following materials are mainly used: fiberboard, chipboard, gypsum fiber sheets and plywood.

The list of screeds used shows that their functions do not include the formation of thermal and acoustic protection of the floor.

Existing solutions for soundproofing floors are mainly constructive in nature. To increase the sound insulation of building envelopes, multilayer structures are used - floating floors, suspended ceilings, with the use of elastic roll materials [10]. Obviously, the most effective is the sound insulation of structures from the side of the noise source. However, it is practically impossible to implement sound insulation measures in existing buildings in operation, since they are of no interest to the occupants of the "noisy" upper floors. Therefore, measures for acoustic protection of premises should be provided for at the design stage and implemented during construction, or reconstruction and overhaul.

It is possible to provide both heat and sound insulation properties of floor substrates using special materials and technologies.

In particular, materials with low thermal conductivity, such as extruded polystyrene foam (XPS), extruded polyurethane foam (XPU) or mineral wool, can be used for thermal protection. These materials can be laid under the screed.

For soundproofing, materials such as acoustic mineral wool boards, gypsum board, or rubber mats can be used, which can be placed either under the screed or under the floor covering. However, the above recommendations imply the use of leveling screeds in any case.

In view of the above, it may be considered productive to replace a conventional screed, such as a cement-sand screed, with a heat and sound insulating base for the final coating. It is proposed to use environmentally friendly and energy-efficient building gypsum as the main binder, but not in its pure form, but to increase water resistance, in the form of a gypsum-cement-pozzolan mixture with the addition of ash as a pozzolanic additive. To impart heat and sound insulating properties, expanded polystyrene granules, cork chips, and granular waste from the production of foam glass were introduced into the mixture [11]. It is technologically and economically feasible to make such screeds from self-leveling mixtures, adjusting the setting time over time by means of additives.

The assumption that the introduction of aggregates with soundproofing properties into the mixture should improve the acoustic characteristics of the flooring is based on the theory of acoustic dissipation, which explains the attenuation of sound waves in the propagation medium by the conversion of sound energy into heat energy as a result of molecular friction during the process of scattering on small inhomogeneities [12]. This process occurs in all environments, but its intensity depends on the properties of the environment and the frequency of sound waves. For example, air has a low capacity for acoustic dissipation, so sound energy in air is not actively converted into heat. However, in denser environments, such as concrete, acoustic dissipation is more pronounced, leading to a more intense conversion of sound energy into heat. It can be assumed that the introduction of aggregates into the mixture increases the number of structural inhomogeneities and interfaces, which, according to the theory of acoustic dissipation, enhances the effect of sound energy dissipation and, consequently, its absorption by the material.

Purpose and objectives. The aim of the study is to substantiate the choice of methods for determining the acoustic properties of materials developed as heat and sound insulating floor bases and to analyze the effect of various aggregates on sound insulation properties.

It should be noted that standard methods for measuring airborne and impact noise are designed to study real structures with regulation of the size of the rooms separated by these structures and a certain standard set of equipment [13].

Thus, it can be concluded that there is currently no standardized, generally accepted methodology for determining the soundproofing properties of materials in the form of samples of the compositions being developed. Consequently, there is a need to develop a methodology and laboratory equipment for determining the acoustic properties of samples of relatively small sizes made in large quantities, for example, during planned experiments [14]. Obviously, the results obtained in this way will not correspond to standard sound insulation indicators. However, these results may well be used for a comparative assessment of the sound insulation properties of an array of prototypes of experimental compositions and the selection of the best ones according to the specified quality criteria.

Research methods and materials. The following methods and experimental setups were used to determine the characteristics of airborne and impact noise.

Airborne noise. During laboratory measurements, the soundproofing ability of the material of the samples against airborne noise is taken as the sound transmission, which is the ratio of the power of sound energy that passed through the sample to the power of energy incident on it.

The experimental setup for measuring sound transmission (Fig. 3) is a chamber with wooden walls, separated by a partition with a slot for installing the sample. To eliminate the indirect transmission of sound through the walls of the chamber, its interior is filled with soundproofing material, and the outer walls of the chamber are also covered with it from the outside.

To study the sound processes, we used the Spectralab program, which allows us to measure the spectral power of sound, both at individual frequencies and integral. The sound power corresponding to the voltage of the alternating component at the sound card input in millivolts was determined without the sample $Efal$ and with the sample $Etrans$. The sound transmission coefficient was defined as $Kair\ noise = Efal/Etrans$.

The determination was performed at different frequencies – from 100 to 2000 Hz. Each experiment was performed three times with the sample reinstalled, and the results were then averaged.

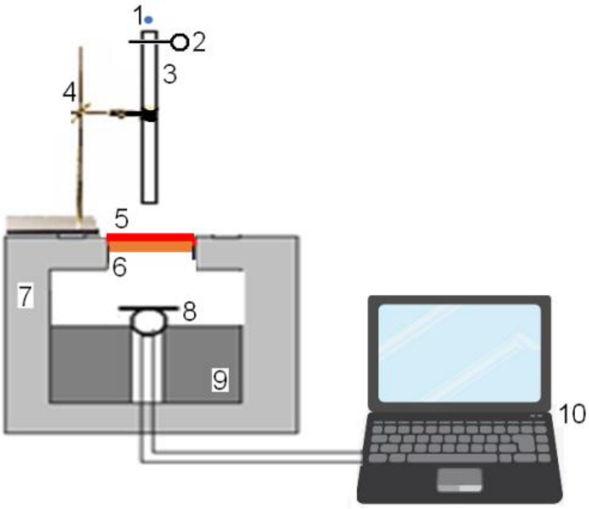

Fig. 3. Device for measuring the sound transmission coefficient:
1 – sound generator; 2 – sound chamber; 3 – sound emitter (speaker); 4 – dynamic microphone; 5 – test sample; 6 – computer with sound card

Impact noise. The proposed method for determining the soundproofing ability of a material uses the effect of converting the kinetic energy of a metal ball falling vertically from a constant height onto an impact surface that contacts the test sample and simulates a finish coating into an electrical signal measured by a computer. A diagram of the test setup is shown in Fig. 4.

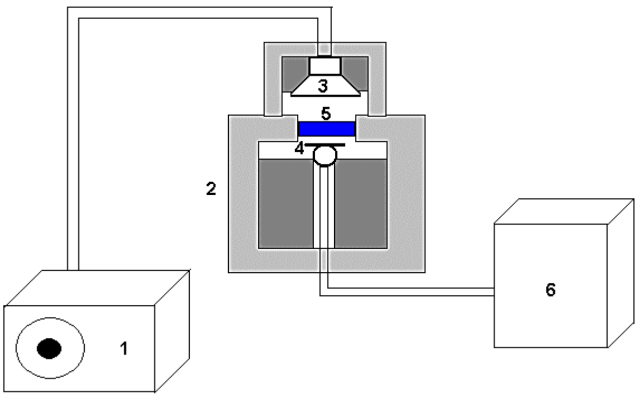

Fig. 4. Device for measuring impact sound:
1 – metal ball; 2 – shutter mechanism; 3 – guide tube; 4 – laboratory tripod; 5 – impact surface; 6 – test sample; 7 – sound chamber; 8 – dynamic microphone; 9 – soundproofing filling; 10 – laptop with sound input (sound card)

In this case, the measured parameter is the amplitude of the electrical signal proportional to the sound energy that has passed through the sample. The best materials are those with the lowest signal amplitude, i.e., the highest sound absorption. As mentioned earlier, this measured parameter does not directly correspond to standard sound insulation characteristics, such as the impact noise insulation index, although such a transition is possible using the material of structures that have passed standard tests. However, this study did not set such a task. For the development of compositions with improved acoustic properties, a relative measurement method is sufficient, in which the actual characteristic of the sound insulation ability to impact noise is proportional (with a certain constant proportionality factor) to those measured by various types of sound analyzers. The relative method makes it possible to correctly perform the most important task of the study – to optimize the composition and technological factors of the material.

Production of prototypes. For the production of prototypes, a comprehensive experiment plan with three dependent (aggregates) and one independent (fly ash/cement ratio) factors was adopted, the so-called "Triangles on a linear segment" plan (Fig. 5). The amount of binding components – gypsum and cement – was fixed, and the ash-cement ratio varied from 30 to 40%. The content of mixed components – polystyrene foam, cork and foam glass – varied at three levels, the gold-cement ratio at two levels: 1.11 (level -1) and 1.65 (level +1). Since the plan is mixed, without technological factors, we consider it possible to denote all factors by X: the amount of expanded polystyrene is X_1, the amount of cork is X_2, the amount of foam glass is X_3, and the amount of ash is X_4. The factors and their levels of variation are shown in Table 1.

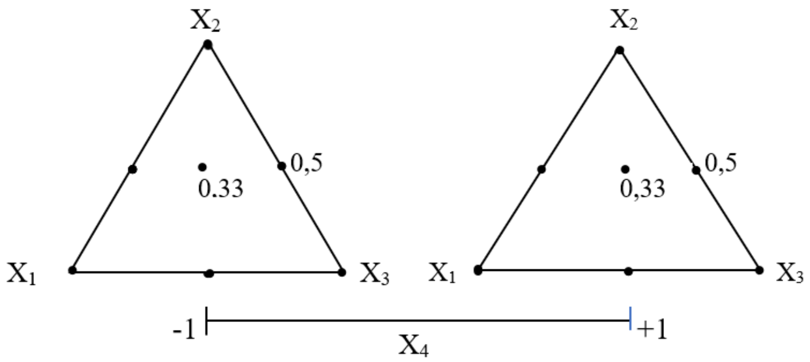

Fig. 5. Scheme of the research plan (levels of variation for X_2 are indicated, for X_1 and X_3 they are symmetrical)

Table 1 – Factors and levels of their variation

Factors	Levels of variation at:								
	X_4 = -1					X_4 = +1			
X_1, X_2, X_3	Coded	0	0.33	0.5	1	0	0.33	0.5	1
	Natural, g	0	61.9	92.9	185.8	0	59.1	88.65	177.3

In accordance with the adopted experimental plan, samples of fourteen formulations were made in the form of standard beams for measuring mechanical and thermophysical properties, as well as in the form of plates measuring 205×100×20 mm for acoustic tests.

Research results and their interpretation. According to the results of measurements of acoustic characteristics, graphs of dependence of the sound permeability coefficient (Fig. 6, a) and impact sound amplitude (Fig. 6, b) on the average density of the material are plotted. The analysis of these graphs shows that density is not the main factor that determines the ability of a material to resist airborne noise, let alone impact sound.

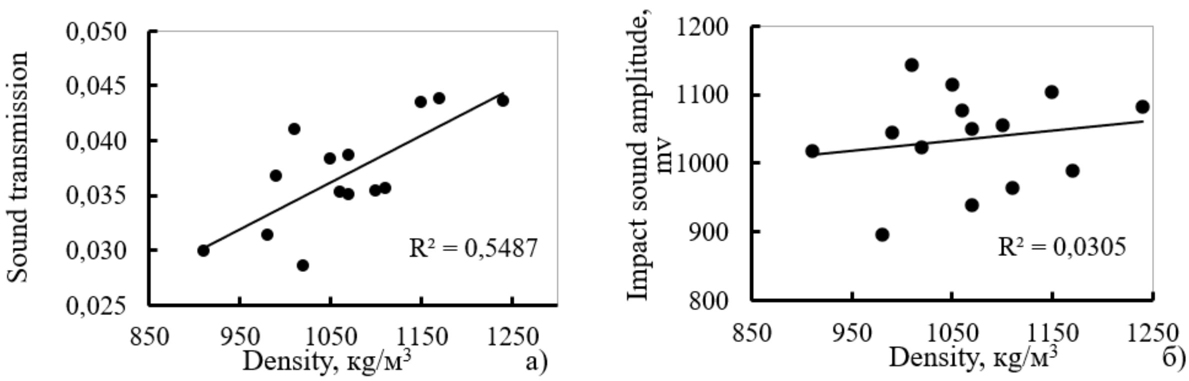

Fig. 6. Dependence of sound transmission (a) and impact sound amplitude (b) on density

The results of the measurements of acoustic properties were used to build experimental and statistical models (ES-models) of sound transmission and impact sound amplitude.

ES model of sound transmission for airborne sound after exclusion of insignificant coefficients:

$$K_{air\,noise} = +0.0924 \cdot X_1 + 0.0404 \cdot X_2 + 0.0392 \cdot X_3 + 0.0048 \cdot X_2 \cdot X_4 + 0.0046 \cdot X_3 \cdot X_4 \quad (1)$$

The final ES model of the impact sound amplitude A blow noise, normalized to the largest value, in relative units:

$$A_{blownoise} = +0.910 \cdot X_1 + 0.0931 \cdot X_2 + 0.938 \cdot X_3 - 0.906 \cdot X_1 \cdot X_2 \quad (2)$$

As an example, the ES model of the impact sound is graphically displayed on a triangle (Fig. 7), the vertices of which correspond to the maximum content of the respective aggregate (the amount of ash – X_4 is fixed at the minimum level).

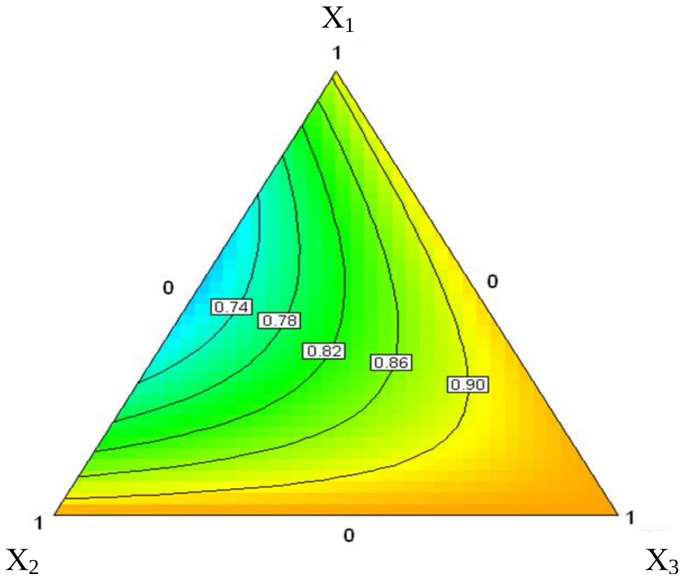

Fig. 7. Dependence of the normalized impact sound amplitude in relative units on the number of aggregates: X_1 – expanded polystyrene, X_2 – cork, X_3 – foam glass

Conclusions and prospects for further research. The analysis of model (1) allows us to conclude that all the introduced components worsen the soundproofing properties of the material, but to varying degrees. Expanded polystyrene has a relatively significant impact, which confirms the information on the deterioration of the sound insulation ability against airborne noise of walls insulated with expanded polystyrene.

The ES model of impact sound (2) shows that the introduction of the accepted components into the mixture separately also slightly increases the sound transmission of the material. The minimum signal value, i.e., the highest sound insulation against impact noise, corresponds to the composition that includes a combination of expanded polystyrene and cork. This can be attributed to two effects: a decrease in the thickness of the matrix material partitions, through which impact noise mainly propagates, and the dissipation of strain energy on elastic inclusions and its conversion into heat at the interfaces in the material. The amount of ash in the studied factor space does not affect the sound transmission from impact sound.

However, it should be understood that the study of acoustic characteristics is a rather limited task of creating materials for floor substrates that must meet a wide range of requirements for thermal conductivity, water resistance, strength, etc. The obtained experimental and statistical models for airborne and impact noise are used for further multicriteria compromise optimization of the gypsum composition by a set of properties.

Further research involves a comprehensive selection of plasticizing and retarding additives to ensure the required mobility of the mixture, as well as the regulation of setting times.

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ДОСЛІДЖЕННЯ АКУСТИЧНИХ ВЛАСТИВОСТЕЙ МАТЕРІАЛІВ ДЛЯ ОСНОВ ПІД ПІДЛОГИ

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Анотація. Найважливішими складовими комфортних умов перебування людей у приміщеннях житлових і громадських будівель є тепловий (температурний) і акустичний комфорт. Відповідно до нормативних документів України, до теплоізоляційних і звукоізоляційних якостей зовнішніх і внутрішніх огороджувальних конструкцій будівель висуваються високі вимоги, особливо щодо міжповерхових перекриттів. Якщо проблема недостатнього теплового захисту стосується насамперед підлог на перекриттях над холодними підвалами і проїздами, то погана звукоізоляція перекриттів – це проблема всіх квартир у багатоповерхових будинках. У цій статті аналізуються причини акустичного дискомфорту в будівлях. Людина в приміщенні піддається впливу трьох різновидів шуму – повітряного, ударного і структурного. Показано, що найбільш складно розв'язуваною проблемою є зниження ударного шуму через перекриття. Акцентовано на тому, що незважаючи на різні джерела шуму, механізми поширення структурного та ударного шуму є аналогічними – по конструктивних елементах будівлі. Тому заходи щодо зниження ударного шуму одночасно дають змогу знизити рівень структурного шуму. Проаналізовано найпоширеніші методи зниження звукопередачі через перекриття. Запропоновано замінити звичайну стяжку в конструкції підлоги на тепло-звукоізолюючу на основі гіпсоцементно-пуцоланового в'яжучого з відповідними заповнювачами. У цій роботі розглядається тільки акустичний аспект проблеми. Згідно з теорією акустичної дисипації, зроблено припущення про посилення ефекту розсіювання звукової енергії за рахунок введення заповнювачів у суміш, що збільшує кількість структурних неоднорідностей і поверхонь розділу. Як заповнювачі до суміші взято гранули пінополістиролу, коркову крихту і гранульовані відходи виробництва піноскла. З метою експериментальної перевірки цього припущення було розроблено лабораторні методики і пристрої для порівняльної оцінки звукоізолюючих властивостей розроблюваних складів. За результатами вимірювання акустичних властивостей дослідних зразків побудовано експериментально-статистичні (ЕС) моделі і визначено найкращі поєднання компонентів суміші з точки зору звукоізоляції. Шумові ЕС моделі використано при багатокритеріальної оптимізації складу композитної суміші.

Ключові слова: міжповерхові перекриття, підлоги, акустика, ударний звук, звукоізоляція, акустичні вимірювання, планований експеримент, моделювання.

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