PERFORMANCE CHARACTERISTICS OF A MODIFIED COMPOSITE MATERIAL CONTAINING INORGANIC LIGHTWEIGHT AGGREGATES

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ABSTRACT

A modified thermal and sound insulation composite material, potentially applicable in the field of modern construction, has been developed. Experimental samples based on foam glass aggregate (made from recycled waste glass), perlite (with fraction size up to 3 mm) and hydraulic binders were obtained. The acoustic and mechanical characteristics and the thermal conductivity coefficient of the prepared series of composite samples were studied. Values for R_w in the range from 38 to 46 dB and for λ from 0.04 to 0.15 W m^{-1} K^{-1} were established. The influence of the different components of the composition on the values of the studied performance indicators and the structure of the composite was analysed.

Keywords: lightweight aggregates, thermal conductivity coefficient, weighted sound reduction index.

INTRODUCTION

The existence of a variety of waste materials of industrial, commercial and domestic origin raises several environmental, sanitary, infrastructural and organisational problems related to their efficient collection, periodic transportation and safe disposal [1]. A significant hazard is posed by waste products practically indegradable for prolonged periods in the natural environment [2]. To overcome some of the existing problems, there has been a trend in recent decades to recover waste products as production raw materials [3 - 5]. Recycling the available quantities of waste glass materials is an appropriate technological and environmental approach due to their suitable physicochemical characteristics, durability and stability in natural environment [6, 7]. Industrial methods have been developed to recover waste glass and produce an assortment of foam glass products, applicable for thermal insulation of buildings and facilities and other purposes [6 - 8]. The use of durable, non-flammable thermal insulation materials (obtained based on foam glass) in the construction of buildings minimizes the need for periodic reconstruction of the thermal insulation system throughout the service life of the facility [8].

At the same time, an innovative acoustic and thermal insulating composite material was developed involving granulated foam glass (obtained from household glass waste), inorganic hydraulic binders and zeolite [9 - 12]. The resulting composite is a potential alternative to several traditional and standard materials applicable in construction.

In relation to building codes and standards for energy efficiency, sound insulation and fire safety, the development of innovative materials with adequate performance characteristics is of significant interest [13].

In this aspect, further modification of the composite, by introducing additional sound and heat insulation component (perlite with fraction size up to 3 mm and others) and partial modification of the technological regime in the preparation of the samples is considered as promising. An additional possibility for the development of the material is the preparation of products with specialized functionality, such as composite elements applicable for the insulation of areas around doors and windows for different types of buildings. As a guideline for the complex planning of the present study, a variety of experimental data from different research fields have been analysed [14 - 18].

The aim of this work is the study of the performance characteristics of a modified composite material based on inorganic lightweight porous fillers and hydraulic binders. The research carried out is related to the implementation of a research and application project providing for the development of non-combustible long-lasting thermal and acoustic insulating composite materials, tailored to the existing technological capabilities of a specific industrial enterprise (beneficiary).

EXPERIMENTAL

The necessary raw materials, reagents, process additives and laboratory equipment were used in the preparation of the sample bodies: a KERN PCV 200 - 2 precision balance, a scale up to 10 kg, a porcelain ball mill with a capacity of 50 L (rotation speed 260 rpm), a set of sieves, an Astel dryer, a pelletising unit, an LM - 312.11 programmable muffle furnace, waste glass, foaming agent ($C_3H_8O_3$), sodium silicate (module 3.0), Portland cement (CEM I 52.5 R and white CEM I 52.5 N), expanded perlite (fraction size up to 3 mm), etc.

For the preparation of the experimental samples, different fractions of foamed glass granules (from 5 to 20 mm in size) with a cellular structure were used, which were obtained under laboratory conditions using the following methodology: grinding of waste glass to a powdery state, preparation of batches of powdered glass, foaming agent and sodium silicate, preparation of primary raw granulate and thermal foaming at temperatures at 850°C for 15 min.

Obtained are specimens with composite structure by preparing compositions with different hydraulic binders (Portland cement - CEM I 52.5 R or white CEM I 52.5 N) with proportion of components - cement : granules : perlite (1:2:1) and water - cement ratio w/c = 0.5. Unlike previous modifications of the composite, zeolite was not present in the compositions of the experimental specimens [9].

A technological regime of several stages has been developed: preparation of cement solutions, introduction of perlite and foam granules into the composition, homogenization of the mixture, pouring of the resulting mass into the formwork moulds, technological standstill (up to 48 h at 16 - 30°C), removal of the specimens, etc. Experimental specimens with dimensions 250/250/35÷110 mm was obtained for the planned laboratory studies.

The two chamber method according to the requirements of EN ISO 717 - 1 and EN ISO 10140 - 2 is applied to determine the sound insulation capacity of the developed materials [19 - 22]. Specifically for the developed composite plates, miniaturized chambers (rooms) were constructed, one of which is reverberatory and the other a receiving chamber (an anechoic type). Fig. 1 shows a block diagram of the installation used for the sound insulation study.

The reverberation chamber is constructed from outside to inside of plasterboard, chipboard, mineral wool and glass panels. The glass walls on the inside form a five-walled box with no parallel walls. In this chamber two wideband loudspeakers with a frequency range from 20 Hz to 20000 Hz are installed. The reception chamber is constructed of chipboard, mineral wool and two insulating layers of foam and sound absorbing foam, pyramid type. Between the two chambers there is a frame with an opening for mounting the specimens to be examined. The measuring microphones have a frequency range from 20 Hz to 20000 Hz and are installed in both chambers. White noise in the frequency range from 20 Hz to 20000 Hz is used as the noise source. The level of the emitted sound signal is 100 dB. The sound pressure differences of the sound waves in the sound source chamber and the receiver chamber are recorded by a two - channel Real Time Acoustic Analyzer, a Sound Level Meter, a two-channel sound card and a dedicated control and measurement software MultiInstrument 3.9 Proffessional. The sound transmission outside the experimental setup is minimized.

The determination of the sound insulation coefficient of the partitions consists of making measurements of

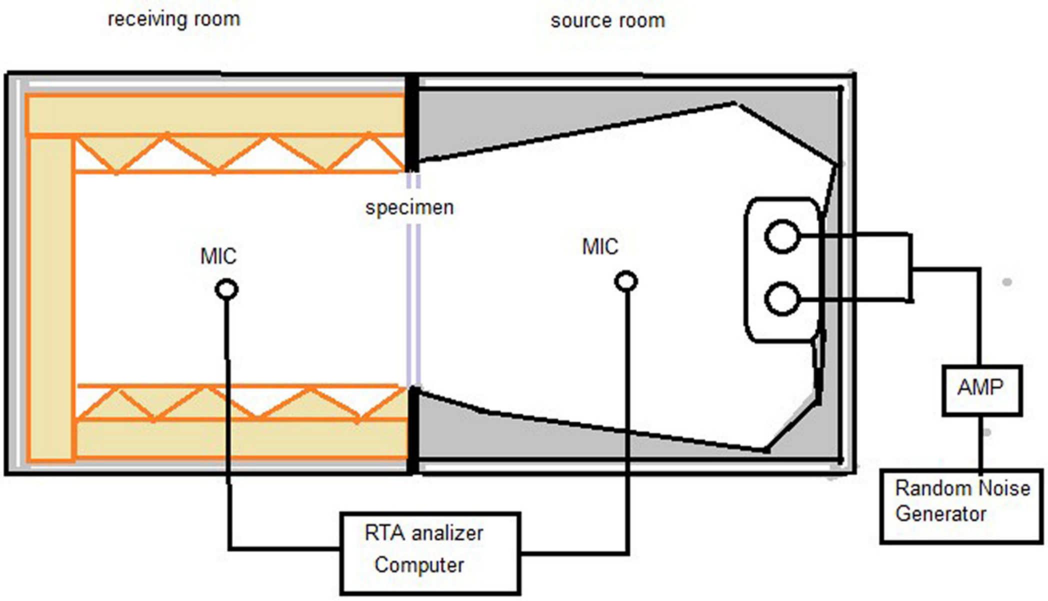


Fig. 1. Block diagram of the installation for measuring the sound insulation coefficient.

the sound pressure levels in the source chamber and in the receiving chamber, followed by a calculation of the difference between the two values.

An upgraded Amsler load testing machine was used for mechanical testing. The specimens were tested between hardened tool steel tips with a hardness of 64 HRC at loading rates from 0.2 to 0.8 mm s^{-1}. Special test bodies (for compressive strength testing, cubes of 100/100/100 mm and for tensile strength testing, prisms of 100/100/400 mm) were prepared to perform the mechanical tests. Gypsum moulds with silicone inserts, facilitating the removal of the samples, were used for the moulding of the sample bodies.

The study of the thermal insulation properties of the developed composite materials is realized by the Guarded hot plate method using a reference material plate ("heat flow plate") with a known value of the thermal conductivity coefficient [23]. For the purpose of the study, a calorimetric chamber was constructed, and its interior was insulated with mineral wool and aluminium foil.

The method is based on the passage of heat through parallel walls and consists in measuring the temperature difference between the two opposite sides of the composite plate under test. A reference specimen of the same area as the test object is placed on the composite plate. A heater is placed in the heat chamber on the underside so that the heat flux through the composite plate is equal to the heat flux through the reference plate. The thermal conductivity coefficient is determined by the following relation [24]:

$$\lambda_x = \lambda_R \frac{\Delta T_{23}}{\Delta T_{12}} \frac{d_x}{d_R} \tag{1}$$

where $\Delta T_{12} = T_1 - T_2$ and $T_{23} = T_2 - T_3$ are the temperature differences; T_1 is the temperature of the test material near the heater, T_2 is the temperature of the inner surface of the reference plate and T_3 is the temperature of the outer surface of the reference plate.

The diagram of the experimental setup is presented in Fig. 2, where the arrangement of the thermocouples in the calorimetric chamber is shown. Four Type K (chromel-alumel) thermocouples and a channel digital thermometer were used for temperature measurements. Two of the thermocouples were placed on the underside of the plate to be investigated (T_1), towards the inside of the calorimetric chamber (heated side); thermocouple T_2 is placed in the middle, between the two plates, and the thermocouple T_3 is placed on the reference plate.

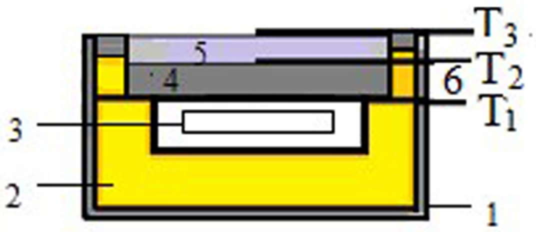


Fig. 2. Diagram of the experimental setup: 1 - calorimetric chamber; 2 - thermal insulation of mineral wool; 3 - heater; 4 - specimen to be tested; 5 - reference plate; 6 - thermocouples.

RESULTS AND DISCUSSION

The specimens produced are composites based on Portland cement, perlite and granulated foam glass (in the role of a non-standard lightweight additive material) and can be considered as an alternative to some types of thermal insulation lightweight concretes obtained solely by using traditional porous fillers. When analysing the laboratory cross-sections (Fig. 3 and 4) of the prepared test bodies, distinct zones of concentration of foamed granules (mainly without direct contact between the individual aggregates) were found to predominate.

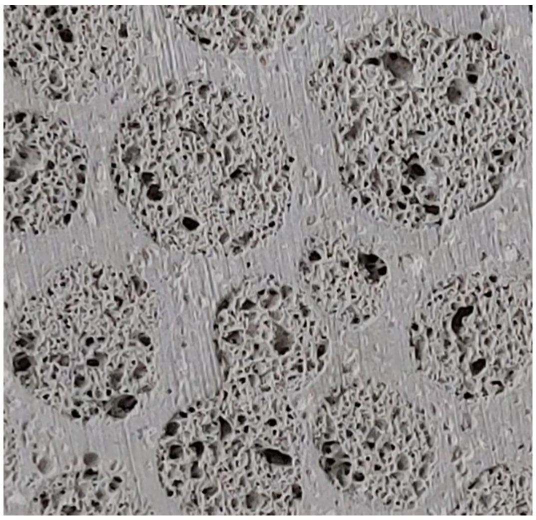
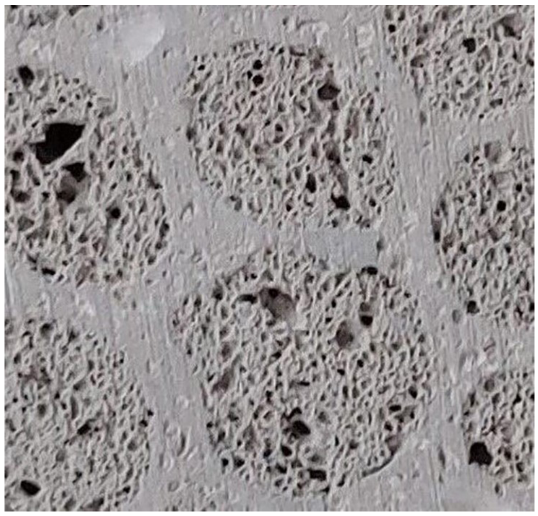
a)  b) 

Fig. 3. Cross-section (a, b) of an experimental specimen, obtained based on Portland cement (CEM I 52.5 R), foam glass granules and perlite.

Fig. 4. Cross-section of an experimental specimen obtained based on Portland cement (white CEM I 52.5 N), foam glass granules and perlite.

At the same time, in some cases, limited local zones formed predominantly of cement phase and perlite were found.

Bulk densities ranging from 847 to 898 kg m^{-3} were found for the test prepared specimens. The laboratory tests of the investigated mechanical parameters (after 28 days) recorded compressive strength values in the range from 4.38 to 4.62 MPa and flexural tensile strengths from 1.43 to 1.67 MPa. When comparing the performance of composite specimens from previous studies (without the presence of perlite), it was found that the fraction of perlite introduced into the compositions in the present specimens lowered the mechanical performance [9].

White noise was used in the laboratory acoustic tests. In the frequency range up to 20 kHz, sound pressure measurements of the incident sound wave in the first chamber and of the one passing through the specimen were performed. The received signals and their frequency characteristics were monitored using an oscilloscope, and the analysis was performed in triple octave frequencies.

The determination of the sound insulation coefficient of the "partitions" (experimental samples) consists of making measurements of the sound pressure levels in the source chamber and in the receiving chamber, followed by a calculation of the difference between the two values. The sound insulation coefficient *R* is calculated using the relationship:

$$R = L_{p1} - L_{p2} + 10(S/A), [dB] \quad (2)$$

where L_{p1} is the average sound pressure level in the source chamber, L_{p2} is the average sound pressure level in the receiving chamber, S is the area of the test specimen and A is the sound absorption of the receiving chamber.

The results of the measurements carried out for the composite plates tested are averaged and shown in Fig. 5.

For the 35 mm thick specimen with a density of 847 kg m^{-3} in the frequency range from 500 Hz to 10 kHz, an average sound insulation coefficient of 43 dB was obtained, and for the 110 mm thick slab with a density of 898 kg m^{-3} the average sound insulation coefficient was 50 dB. The difference in values is due to the different composition of the samples.

According to EN ISO 717, a weighted sound reduction index, denoted R_w, is defined, which for airborne noise is represented by the expression [21]:

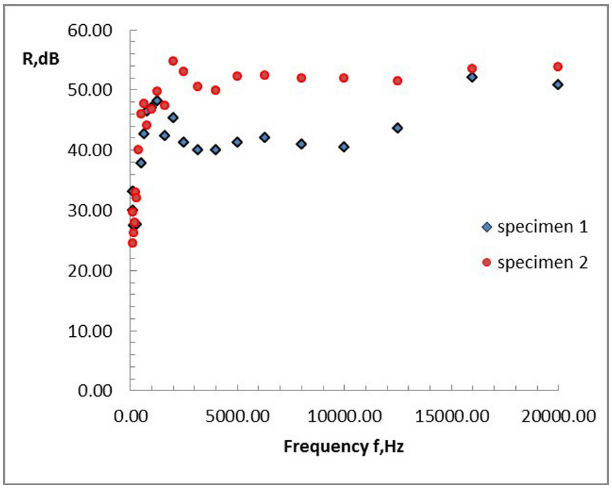


Fig. 5. Sound insulation coefficients of the studied composite plates in the frequency range up to 10 kHz; specimen 1 - composite plate with a thickness of 35 mm and a density of 847 kg m^{-3}; specimen 2 - composite plate with a thickness of 110 mm and a density of 898 kg m^{-3}.

$$R_w = 52 + \Delta L, [dB] \quad (3)$$

where ΔL denotes the correction (in dB) obtained by comparing the measured frequency response of the partition and the normative response for building materials according to EN ISO 717 - 1. According to the applied methodology, the reference standard curve is shifted by steps of 1 dB and compared with the experimentally obtained curve. The value of ΔL is obtained by determining the deviations below the normative reference curve for 1/3 octave middle frequences. The shifting of the reference curve is continued until the sum of the unfavourable deviations becomes as large as possible, but not more than 32 dB at airborne noise for 1/3 octave bands [19]. The weighted sound reduction index R_w is determined by the value of the shifted reference curve at a frequency of 500 Hz.

Fig. 6 and Fig. 7 show the weighted sound reduction index values for airborne noise (with red solid lines) at a frequency of 500 Hz recorded in the laboratory. The determined weighted sound reduction indices for specimens 1 and 2 are $R_w = 38$ and $R_w = 46$ dB, respectively.

For residential buildings, hotels, schools and other sites, the weighted sound reduction index for external walls is standardised in the range from 38 to 48 dB depending on the equivalent external noise level LAeq. (51 - 75 dB during the day). Meanwhile, for offices the permissible normative values for R_w range from 33 to 43 dB [25].

According to the results of laboratory tests of building materials presented in for dense bricks with a thickness of 120 mm R_w = 48 dB, for hollow bricks with the same thickness R_w = 46 dB and for aerated concrete (class D500) R_w = 37 dB [21]. The weighted sound reduction index results obtained by investigating the developed composite panels show good sound insulation properties according to the requirements of Ordinance No. 4 of December 27, 2006, with amendments from 2016 on limiting harmful noise by soundproofing buildings during their design and on the rules and norms in the execution of constructions regarding noise emitted during construction and at smaller panel thickness [25].

To determine the thermal conductivity coefficient of the developed composite plates, the Guarded hot plate method was applied. Mineral wool, the thermal conductivity coefficient of which is l_R = 0.04 W m^{-1} K^{-1}, was used as a reference material. The prepared square plates of the test and reference material were placed in the calorimetric chamber in a horizontal position, one on top of the other, tightly and without clearances. After switching on the heat source, temperature values were monitored until steady state was established. For test plate No 1, 60 min of heating to steady state was applied, and for test plate No 2 (110 mm thick), the test lasted up to 2 h. Based on the recorded temperature differences (Table 1) and applying formula (1), the values of the thermal conductivity coefficients given in table 1 were calculated.

In the tests carried out for the obtained sample bodies, values of the thermal conductivity coefficient l in the range from 0.04 W m^{-1} K^{-1} (sample No 2) to 0.15 W m^{-1} K^{-1} (sample No 1) were determined.

The obtained different values for l, R_w, mechanical indicators and density are considered as a consequence of the characteristics of the cement brands used, the varying degree of foaming of the foam glass granules and the individual distribution (in the volume of the specific samples) of the introduced fractions of foam glass and perlite aggregates.

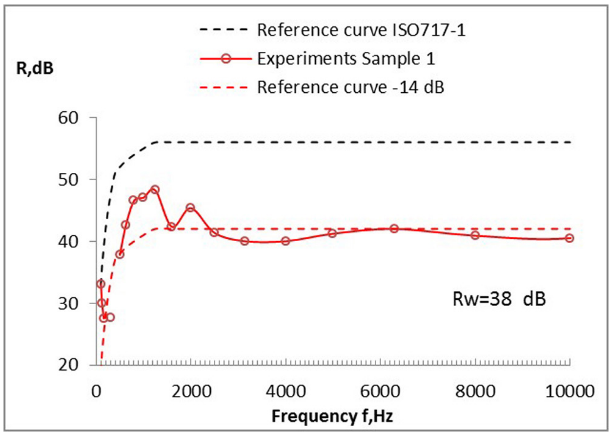


Fig. 6. Weighted sound reduction index for sample 1.

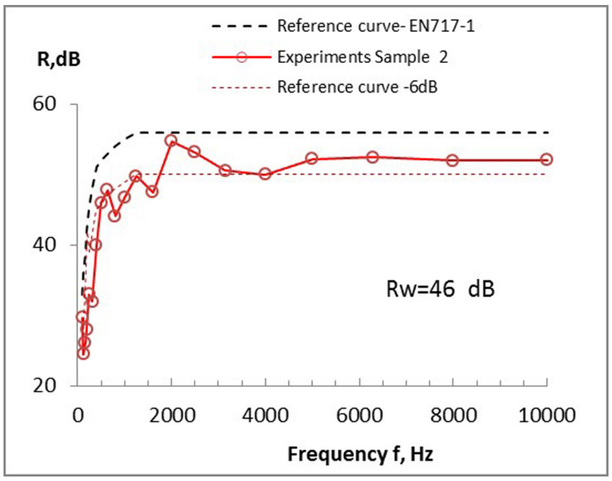


Fig. 7. Weighted sound reduction index for sample 2.

Table 1. Results for the thermal insulation properties of composite materials.

No	T_1, K	T_2, K	T_3, K	$\Delta T_{12} = T_1 - T_2$, K	$\Delta T_{23} = T_2 - T_3$, K	λ_x, W m^{-1} K^{-1}
1	378	351	310	28.7	41.3	0.15
2	363	312	302	51.2	9.8	0.04

CONCLUSIONS

Experimental specimens of a modified composite material based on granulated foam glass (recycled waste glass), hydraulic binders (Portland cement - CEM I 52.5 R or white CEM I 52.5 N) with the introduction of an additional acoustic and thermal insulating component (expanded perlite) were prepared under partial modification of the technological regime.

The experimental specimens obtained in laboratory conditions, showed values for the weighted sound reduction index R_w in the range from 38 to 46 dB and for the thermal conductivity coefficient l in the range from 0.04 to 0.15 W m^{-1} K^{-1} and can find practical application.

The resulting composite combines the main characteristics of the individual components and is potentially applicable for the preparation of various long-lasting, non-flammable thermal and acoustic insulation non-load-bearing products (boards, panels, plates, blocks, profiles, etc.). The exploitation properties of the composite materials obtained by the presented method is determined by a number of factors: concentration of the components in the compositions, degree of foaming of the foam glass granules, used fractions of granular foam glass, cement brand used, value of the water-cement (w/c) ratio, parameters of the cement mortar, the distribution (in the volume of the samples) of the introduced fractions of foam glass and perlite aggregates, thickness of the final specimens and others.

The use in construction of long-lasting and non-flammable thermal insulation materials (based on foam glass, cement, etc.) lowers the risk of maintanence of the building and minimizes the need for further reconstruction of the thermal insulation system.

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