Indoor Acoustic Comfort Provided by an Innovative Preconstructed Wall Module: Sound Insulation Performance Analysis

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Abstract: The complicated nature of indoor environmental quality (IEQ) (thermal, visual, acoustic comfort, etc.) dictates a multi-fold approach for desirable IEQ levels to be achieved. The improvement of building shells’ thermal performance, imposed by the constantly revised buildings’ energy performance regulations, does not necessarily guarantee the upgrade of all IEQ-related aspects, such as the construction’s acoustic quality, as most of the commonly used insulation materials are characterized by their low acoustic performance properties. From this perspective the SUSTainable PRerconstructed Innovative Module (SU.PR.I.M.) research project investigates a new, innovative preconstructed building module with advanced characteristics, which can, among other features, provide a high quality of acoustic performance in the indoor space. The module consists of two reinforced concrete vertical panels, between which the load bearing steel profiles are positioned. In the cavity and at the exterior surface of the panel there is a layer of thermal insulation. For the scope of the analysis, different external finishing surfaces are considered, including cladding with slate and brick, and different cavity insulation materials are examined. The addition of Phase Change Materials (PCM) in different mix proportions in the interior concrete panel is also examined. For the calculation of the sound insulation performance of the building module the INSUL 9.0 software is used. The results were validated through an experimental measurement in the laboratory in order to test the consistency of the values obtained. The results indicate that the examined preconstructed module can cover the sound insulation national regulation’s performance limits, but the implementation of such panels in building constructions should be carefully considered in case of lower frequency noise environments.

Keywords: sound insulation; acoustic performance; indoor environment; preconstructed module

1. Introduction

The building sector is a major contributor to the human-induced environmental degradation [1–5]. Due to this fact, the implementation of sustainability principles into the built environment has become a focal point of the global efforts to restrain environmental burdening. In this context, the functional unit of the built environment, i.e., the building, is of fundamental importance. Given the perplex nature of the building itself (multi-fold requirements to meet, different materials and components of varying life durations, function under dynamically changing conditions) and the (at-least) three main pillars of sustainability (environmental, economic and social axes), the assessment and improvement of the buildings’ environmental performance cannot but be implemented via a holistic approach. It is not only the energy efficiency of buildings, but also parameters related to every aspect of their construction, operation and end-of life (environmental
impacts, materials used, indoor environmental quality (IEQ), location, waste, water use, etc.) that must be taken into consideration for a truly sustainable result to be achieved.

The quality of the indoor environment is an issue of fundamental importance for the health and the well-being of the buildings’ occupants. It is no coincidence that IEQ consists one of the major assessment areas in the structure of the buildings’ environmental performance assessment systems, with each one of its main axes (visual, thermal, acoustic comfort and indoor air quality) being analytically evaluated with the use of specific criteria and indicators [6]. With noise levels having a severe impact on the health of the buildings’ occupants [7], acoustic comfort should be an indispensable part of any study aiming at the assessment and the improvement of IEQ. As a result, the sound insulation capacity of the building elements that enclose spaces with specific indoor noise level requirements is a feature of great significance.

In this context of the holistic approach previously described, efforts towards the development and the integration of new elements (structural, mechanical or others), adapted to the need for upgraded building performance, should be accompanied by the consideration of all the aspects of their lifecycles and function. This is the case for the preconstructed building element of advanced performance, which is developed under the research project Sustainable PReconstructed Innovative Module (SU.PR.I.M.) [8]. More specifically, SU.PR.I.M. focuses on the development of an innovative building module with advanced thermophysical properties, properties related to flow and transfer of energy and mass and mechanical properties that will act as a load bearing element and/or as an interior partition wall in preconstructed residential buildings. The innovativeness lies on the formation of the building element; elements of innovation can be detected in the design of the connections between its layers, the design of the connections between the preconstructed components and the main load bearing elements of the building, as well as in its layout and configuration. In fact, with regard to the component’s configuration, the examined alternatives include the addition of Phase Change Materials (PCMs) in one of the layers. In the context of this building module’s development effort, the preconstruction process requirements, such as the feasibility and ease of assembly and prefabrication, and all the aspects of the component’s performance are taken into consideration. Specifically, the objective of the design is to create an element that will address all requirements of modern constructions, in terms of structural, hygrothermal, energy, fire, acoustic and environmental performance. Within this context, the assessment of the element’s sound insulation performance defines its capacity to provide acoustic comfort.

The assessment of acoustic comfort in indoor spaces involves the consideration of several parameters such as reverberation times and indoor noise levels, with the sound insulation capacity of the building elements enclosing them holding a determining role. In fact, the related regulatory contexts, where existent, include extended references to this capacity; for example, this becomes obvious in the review presented in [9] regarding the related requirements for housing in Europe. In Greece, the regulatory requirements related to the acoustic indoor environment and comfort include maximum values for noise levels generated in a property’s boundary [10], sound insulation from noises of different origin [11], and standards regarding measurements and calculations [12].

In this study, the main objective is the assessment and the determination of the sound insulation levels provided by the examined preconstructed element and the analysis of various alternatives for its configuration. This component’s basic structure consists of two lightly reinforced concrete plates that are positioned on either side of vertical steel profiles, with the cavity being filled with a thermal insulation material. As a result, its behavior regarding the transmission of sound was not expected to be the same as the one of a single layered building element [13]. The sound transmission via double layered structures is a complex phenomenon depending on several parameters such as the surface mass of the connected panels, the type of connection between them, the cavity insulation material and the size of the cavity. Therefore, its prediction is not straightforward. Several efforts dealing with the prediction and the assessment of the sound insulation capacity of such partitions have been reported in the literature, regarding either the approaches—numerical or otherwise—generally employed or studies of specific types of
construction [14–20]. Other researchers have also investigated the sound insulation performance of double leaf walls incorporating both acoustic and structural transmission paths and have tried to determine their performance in low and high frequencies [20]. Researchers have examined the effect of structural connections, such as steel profiles in the sound insulation capacity of double leaf walls in order to take into account the effect of structural connections, such as steel profiles or ties [21], while others focus mostly on the cavity material’s properties [22].

In general, most studies on double leaf walls concern lightweight walls, but there have also recently been some studies on more massive construction walls [23] which can be load bearing façade elements and provide thermal mass in the construction as well.

For the assessment of the sound insulation performance of building elements, both numerical and experimental approaches are used (often at the same time in order to compare and validate the results). Well-established calculation models can be found in the literature for the estimation of the protection provided by building elements. The models vary from simpler to more complicated (depending on the assumptions and simplifications adopted). Numerical approaches have been formulated for single-, double- and multilayered components, with other parameters also considered (such as types of connections or cavity insulation materials). Since manual calculations might be time consuming due to the complexity of the algorithms, the computational processes are often materialized via computer software (ACOUBAT Sound [24], INSUL [25]), into which these algorithms are integrated. For the experimental measurements, certified labs should be used in order to acquire valid results and to obtain a valid sound insulation certificate.

**Basic Objective of the Study and Research Questions/Contribution**

The basic objective of this study is the assessment of the sound-insulation performance of an innovative, double-layered preconstructed building module, which is described in detail in Section 2. The preconstructed module is a double-layered component and can be categorized as a heavy-weight panel, as it is designed as a structural element that complements the load-bearing structure. The design of the preconstructed module can be expected to combine the advantages of the higher sound insulation performance of double panels while limiting their main disadvantage, which is their inability to provide high sound insulation performance in lower frequencies. This is because the examined building module has a structure of a double layered panel but it also includes two heavyweight layers of concrete, which are intended to provide the necessary mass in order to improve the sound insulation performance of the module in lower frequencies. Different types of exterior cladding layers are also examined to define even better levels of sound insulation due to the heavier construction.

Moreover, one of the alternative configurations studied involves the addition of PCM in the mix for the preparation of the interior concrete panel. Phase change materials have often been used recently as a thermal mass increase method, in order to improve the thermal performance of building shells [26]. However, their effect on the sound insulation capacity has not yet been examined extensively, with relatively few studies dealing with the subject [27,28].

The main goal, therefore, is to determine the sound insulation performance of the preconstructed building module and to assess its ability to meet the requirements of the Greek legal framework for the sound insulation of buildings, as well as to explore possible solutions for sound insulation improvement. A special focal point of the study is also the investigation of the effect of the addition of phase change materials on the mass of concrete in the sound insulation performance of the building module.

**2. Materials and Methods**

**2.1. Description of the Preconstructed Module and of the Analyzed Cases**

The preconstructed module is mainly intended to be used in residential single-family buildings, mostly detached or semi-detached constructed in low-rise, low density residential areas of permanent or holiday use. This means that low outdoor noise levels are expected, which is mostly
the case in the city suburbs in at the semi-rural or rural areas, where holiday houses are mostly situated. However, it is important to define the limit of outdoor noise levels up to which the preconstructed module can be applied without further measures of improvement. Therefore, not only low but also higher outdoor noise levels are considered in this study. The main structure of the building element is described as follows:

Two lightly reinforced concrete panels (5 cm thick each) are positioned as planes parallel to each other and on the two opposite sides of steel profiles (square hollow structural sections—HSS, 5 cm × 5 cm). The steel profiles are mainly vertical, with the distance between them being around 0.70 m–1.30 m depending on the wall’s geometry, dimensions and the existence and positioning of openings on the building’s facade. The preconstructed elements are interconnected and connected to the main load bearing structure with anchors that are designed specifically for this construction. The 5 cm cavity between the concrete panels is filled with a thermal insulation material. Beyond the main structure previously described, the component’s configuration, as a ready-to-use module, is complemented by other layers as well:

1. layers composing the exterior coating/cladding
2. exterior insulation layer
3. interior coating.

As already mentioned, as part of the research, the sound insulation performance of the preconstructed module is examined for varied alternative configurations of some of the layers it consists of. Specifically, the layers for which alternatives are examined are the following:

1. layers composing the exterior coating or cladding (three alternatives);
2. cavity thermal insulation material (two alternatives);
3. interior concrete layer alternatives (according to the addition of PCM to the composition of the interior concrete panel); different proportion mixes are considered (five alternatives).

The scenarios studied regarding these varying parameters are presented in Table 1.

| Interior Coating   | Lime Plaster Coating                  |
|--------------------|---------------------------------------|
|                    | Concrete 0% PCM $^1$                  |
|                    | Concrete 10% PCM $^{(28)}$ $^2$       |
| Interior concrete layer | Concrete 10% PCM $^{(28 + 24)}$ $^3$ |
|                    | Concrete 20% PCM $^{(28)}$ $^2$       |
|                    | Concrete 20% PCM $^{(28 + 24)}$ $^3$  |
| Cavity insulation  | Expanded polystyrene (EPS)            |
|                    | Rockwool (rigid board)                |
| Exterior insulation layer | Graphite expanded polystyrene (EPS) |
|                    | Type 1: Lime plaster coating          |
|                    | Type 2: Solid decorative bricks       |
|                    | Type 3: Decorative slate tiles        |

$^1$ PCM: Phase Change Materials. $^2$ Aggregation melting point at 28 °C. $^3$ 50% aggregation melting point at 28 °C and 50% aggregation melting point at 24 °C.

More specifically, three basic types of configurations are examined, depending on the external coating (Type 1, Type 2 and Type 3). It should be noted that Type 2 and Type 3 refer to exterior cladding with slate or brick, respectively, which is fixed with mortar (and not with a mechanical fixing and/or an air gap).

The alternative configurations are produced by all the possible combinations of the aforementioned scenarios; a total of 30 different cases were examined.

In all the examined scenarios, the exterior thermal insulation material is graphite expanded polystyrene, while the interior surface of the module is covered by lime plaster coating. The research flow is presented in Figure 1.
The properties of the materials, which are presented in detail in Table 2, were determined based on the following:

- The materials’ density (except for concrete) was determined based on the values obtained from national relevant databases [29].
- Density and modulus of elasticity of concrete were determined experimentally as part of the research program; for all other properties of concrete, values found in the software database were used.
- The rest of the materials’ properties were determined with the help of the software library. As the software manual suggests, the flow resistivity should not be less than 500 Rayls/m or more than 60,000 Rayls/m. The air flow resistivity value used for rockwool (40,000 Rayls/m) was defined according to INSUL’s material library for absorptive materials according to its density. For the expanded polystyrene (EPS), an assumption was made for the flow resistivity value.
taking into account the smaller permitted value the software suggests and the material’s density, as INSUL only includes open-cell and sound absorptive material options in its material library.

Table 2. Properties of materials used in the analysis.

| Position of the Layer          | Material                                                | Thickness (mm) | Density (kg/m³) | Young’s Modulus (Gpa) | Damping |
|-------------------------------|---------------------------------------------------------|----------------|-----------------|----------------------|---------|
| Exterior                      | Organic coating with fiberglass reinforcement            | 7              | 1800            | 36.60                | 0.04    |
|                               | Decorative slate tiles                                   | 10             | 2800            | 68.16                | 0.01    |
|                               | Decorative solid ceramic bricks                         | 60             | 1700            | 8.96                 | 0.00    |
|                               | Graphite EPS                                            | 100            | 20              | 0.005                | 0.20    |
| Cavity                        | EPS                                                     | 50             | 20              | 0.005                | 0.01    |
|                               | Rigid rockwool boards                                   | 50             | 100             | 0.025                | 0.20    |
| Interior/exterior concrete panel | Lightly reinforced concrete 0% PCM                     | 50             | 2300            | 51.29                | 0.20    |
| Interior concrete panel       | Lightly reinforced concrete 10% PCM (28)                | 50             | 2340            | 41.72                | 0.01    |
|                               | Lightly reinforced concrete 10% PCM (28 + 24)           | 50             | 2305            | 45.17                | 0.01    |
|                               | Lightly reinforced concrete 20% PCM (28)                | 50             | 2215            | 39.40                | 0.01    |
|                               | Lightly reinforced concrete 20% PCM (28 + 24)           | 50             | 2210            | 36.28                | 0.01    |
| Interior                      | Lime plaster coating                                    | 20             | 1800            | 36.60                | 0.01    |

Based on the values presented in Table 2, it is deduced that the preconstructed module for Type 1 has a total thickness of 27.7 cm, for Type 2, 29.0 cm and for Type 3, 34.0 cm.

For the calculation of the sound insulation performance of the preconstructed module several assumptions were necessarily made for its dimensions and for the distance between the steel profiles. In order to represent a typical wall unit positioned between the main structural vertical elements of a building, the preconstructed module’s typical size was shown to be 3.0 m × 2.7 m. The vertical steel profiles (50 mm × 50 mm) were assumed to be distributed per 1 m and a rigid connection was considered between the steel profiles and the concrete panels. Regarding other information required as input for the simulations, the room’s volume was defined as 50 m³ and a typical value for the reverberation time of 0.5 s was considered.

2.2. Sound Insulation Performance Criteria

The minimum requirements for the sound insulation of new buildings are defined in article 12 of the Greek Building Regulation [11]. Sound insulation criteria are the limit values of the acoustic comfort parameters set by the regulation for each type of sound protection and each class of acoustic comfort. Three classes of acoustic comfort are defined in the regulation:

- Class A: High acoustic comfort
- Class B: Normal acoustic comfort
- Class C: Low acoustic comfort

In order to classify a building into a class of acoustic comfort, it is necessary to cover all the criteria of this class.

In the regulation, the following five criteria are defined for the vertical building partitions (criteria of performance against airborne sound transmission):
1. For the sound insulation from an adjacent space of main or auxiliary use and from the communal spaces of the building (e.g., between two apartments of the same building), the sound insulation criterion for airborne noise should fulfill a minimum of the limit value of the weighted apparent sound reduction index \( R'_w \) (dB).

2. For the sound insulation of an apartment from another space of the building with a different main use (e.g., between an apartment and an office), the sound insulation criterion for airborne noise should fulfill a minimum of the limit values of the weighted apparent sound reduction index \( R'_w \) (dB).

3. The sound insulation criterion for external noise (environmental, traffic or urban noise) should fulfill a maximum of the limit values of the A-weighted sound level \( L_{Aeq,h} \) in the interior space.

4. For the sound protection from mechanical installations, the sound insulation criterion should fulfill a maximum of the limit values of the A-weighted sound level \( L_{pA} \) in all interior spaces of main use.

5. For the sound insulation between the spaces of the same residence, the sound insulation criterion for airborne sound insulation should fulfill a minimum of the limit value of the single number quantity of the weighted apparent sound reduction index \( R'_w \) (dB).

Among the five above mentioned criteria, number 1 and 3 were considered according to the intended use of the considered building element.

The above-mentioned criteria refer to all building uses, however different limit values are applied according to the use. It should be noted that the regulation also has criteria for impact noise which are apply only to horizontal building elements.

The study of the preconstructed module’s sound insulation performance takes into account the limit values of Class B according to article 12 of the Building Regulation [11], in order to test the sound insulation capacity of the building module, since, as is mentioned in the regulation texts, this is the Class to which all new buildings should belong. Table 3 presents the values for residential building use that are considered in the study as performance limits.

| Sound insulation from adjacent space of main or auxiliary use. | Sound protection from external noise (expressed as maximum permissible indoor noise level) |
|---------------------------------------------------------------|----------------------------------------------------------------------------------|
| Sound insulation from communal spaces (expressed as sound reduction index of the partition) |                                                                                  |
| Weighted apparent sound reduction index \( R'_w \), dB | A-weighted sound level \( L_{Aeq,h} \) dB (A) |
| \( \geq 50 \)                                                 | \( \leq 35 \)                                                                        |

According to ISO 12354-3/2017: “the sound insulation… of a façade or other external surface of a building is based on the sound reduction index of the different elements from which the façade is constructed and it includes direct and flanking transmission” [30]. This means that flanking noise should also be considered in the above-mentioned limits. As mentioned in the regulatory texts, the relation between the weighted apparent sound reduction index and the weighted sound reduction index can be correlated according to the values described in article 12 [11], as presented in Table 4. In order to take into account the noise flanking paths during the construction process, appropriate measures should be applied in order that the differences between \( R_w \) and \( R'_w \) do not exceed the differences presented in Table 4.
Table 4. Relation between the weighted apparent sound reduction index $R'_w$ and the weighted sound reduction index $R_w$ according to the Greek Regulation for the sound insulation of buildings, article 12 [11].

| $R'_w$ (dB) | $R_w = R'_w + d$ |
|-------------|------------------|
| up to 42    | $R'_w + 0$       |
| from 43 to 48 | $R'_w + 2$      |
| from 49 to 52 | $R'_w + 3$      |
| from 53 to 55 | $R'_w + 4$      |
| from 56 to 60 | $R'_w + 6$      |

2.3. Methodology Used for the Calculation of the Sound Reduction Index for the Building Module and Validation through Experimental Measurement

The sound insulation capacity of the examined module is determined both with analytical methods and laboratory measurements. More specifically, the INSUL 9.0.1 software of Marshall Day Acoustics software was used for calculating the sound reduction index of one case scenario, while the results were validated through an experimental measurement in the laboratory, for the same case, in order to test the consistency of the values obtained. The experimental measurement and validation results are analytically described in Section 3.1.

Then, the sound insulation capacity of all the alternative solutions of the preconstructed module was calculated with INSUL software. The calculated results were compared to the regulatory limits in order to assess them in terms of their ability to cover the required values. Given that the Building Regulation’s requirements for vertical building elements are limited to controls related to their sound protection against airborne sound transmission, the analyzed cases are as described below.

1. Assessment of the sound insulation performance of the preconstructed module against sound transmission for diffuse sound was performed by calculating the sound reduction index $R$ for the frequency range 100–3150 Hz and the weighted sound reduction index $R_w$ corresponding to the above-mentioned range.

2. Calculation of the sound insulation capacity of the preconstructed module against environmental noise was performed by calculating the $A$-weighted sound level $L_{Aeq,h}$ inside the building.

Furthermore, the results derived for the studied alternative configurations were compared, so that the impact of the examined parameters’ variations could be assessed. The results and the outcomes are presented and discussed in the following sections.

2.4. Description of the Software Applied and of the Experimental Facility Used

As mentioned in the previous sections, the numerical approach to the estimation of the developed building module’s sound insulation capacity was conducted via the application of the software INSUL 9.0.1. INSUL is a computational tool for the prediction of the sound insulation performance of building components (walls, floors, ceilings and windows). In general, as deduced from several sources [31–34], the software is based on models proposed by Sharp, Cremer and others; it can provide predictions for single-, double- and multilayered components. Regarding double panels systems, different types of connections between the two layers can be taken into consideration. For double panel elements, the transmission loss is calculated for 4 frequency regions, which are identified within the frequencies spectrum based on the prevailing mechanisms determining the transmission phenomenon through double layered components in each region (mass law, coupled or decoupled layers, etc.) [34]. The transmission loss in each region is governed
by different mechanisms and, therefore, varies in size per octave. For example, in the low frequencies area (below the mass–air–mass resonance frequency) it is the mass law that primarily determines the transmission loss (i.e., dependence on the surface mass of each panel) [34].

For the experimental measurement, the SU.PR.I.M. wall was installed in the premises of the certified Laboratory of Architectural Technology, School of Architecture, Aristotle University of Thessaloniki, in order to measure the sound reduction index.

The structure of the tested module consisted of two vertical steel profiles and two layers of lightweight concrete, without PCM aggregation, on both sides. The exterior surface consisted of a layer of graphite expanded polystyrene (EPS) insulation board and the cavity insulation material of expanded polystyrene (EPS). Both the interior and the exterior surface remained exposed (without coating). The dimensions of the tested module were (1.23 × 1.48) m. This size was chosen because of the weight of the building element (the specific size weighs up to 400 kg). As it was not possible to build the building element in the lab due to constructional reasons, a larger size would make its transfer and installation in the laboratory room impossible.

The test took place under laboratory conditions according to ISO 10140-2:2010, Acoustics—Laboratory measurement of sound insulation of building elements—Part 2: Measurement of airborne sound insulation [35]. In order to estimate the sound reduction index, $R$ (dB) Equation (1) was used:

$$ R = L_1 - L_2 + 10 \log \frac{S}{A} $$

(1)

where:

- $L_1$: the average sound pressure level in the source room in dB;
- $L_2$: the average sound pressure level in the receiving room in dB;
- $S$: the total surface of the tested module in m$^2$;
- $A$: the equivalent sound absorption area in the receiving room given by Equation (2):

$$ A = \frac{0.163V}{T} $$

(2)

where:

- $V$: the volume of the receiving room in m$^3$;
- $T$: the reverberation time of the receiving room in s.

For the calculation of the reverberation time, 6 measurements in six different microphone positions were performed. No background noise correction was required. A dodecahedron loudspeaker (Lab-1217, Roister) was used. The source room volume was 55.5 m$^3$ and the receiving room volume was 50.6 m$^3$.

The test results in 1/3 octave bands from 100 to 3150 Hz were used to calculate the weighted sound reduction index of the building module according to ISO 717-1: 2013 [36].

3. Results

3.1. Experimental Results and Software Validation

As already mentioned, a laboratory measurement was performed. After the test, the sound reduction index of a module with the same properties and dimensions was calculated with the help of the INSUL software in order to test the compliance of the results.

According to the experiment’s derived values, the weighted sound reduction index is: $R_w$ (C; $C_{100-3150}$) = 44 (–2; –5) dB. The weighted sound reduction index of the same configuration and the same dimensions (as in the experiment) of the module was calculated with the help of the INSUL software. The calculated value in this case is $R_w$ (C; $C_{100-3150}$) = 48 dB (–3; –9). Concerning the weighted sound reduction index it can be seen that there is a 4 dB difference, while, for spectrum adaptation terms difference, can be seen that there is a 1 dB difference for C and a 4 dB difference for $C_{100-3150}$. The difference of 4 dB in the weighted sound reduction index between the measured and
the calculated values can be considered as reasonable since the examined building element is a four layered module, which includes also a steel profile frame and, as mentioned in the software’s user’s guide [25], the accuracy of its calculations seems to decrease as a function of the number of elements involved in the construction. The difference could also be related to the software’s calculation assumption about the rigid connection of the profiles with the concrete panels. Moreover, other researchers [37] have also concluded that the INSUL software tends to overestimate the weighted sound reduction index $R_w$ values against experimental results especially when multilayered configurations are examined. Moreover, the software developer gives an error margin (generally) of $\pm 3$ dB. Based on the limited difference (below 10%) between the measured and the estimated values, it is deducted that the model is validated, and it is reliable to be used for further simulations. Concerning spectrum adaptation terms the results of both the experiment and the calculations imply that the module’s performance against traffic noise might be lower from 5 to 9 dB than expected when considering the weighted sound reduction index.

### 3.2. Sound Insulation Performance of the Preconstructed Module Results and Assessment

The sound reduction index $R$, the weighted sound reduction index $R_w$ and the A-weighted sound level $L_{Aeq}$ for the examined scenarios mentioned in Section 2.1 were calculated with the use of the INSUL software.

The preconstructed module for these calculations was considered with all the necessary layers, including its final coatings. It was found that the weighted sound reduction index for all examined cases ranges from 53 dB to 58 dB (Table 5). As expected, the cases with decorative slate and solid brick exterior cladding present higher values of the sound reduction index, when compared to the cases with simple exterior organic render finishing. This obviously means that the heavier cladding affects the sound insulation capacity of the preconstructed module positively.

The cases with rockwool as a cavity insulation material present a slightly higher sound insulation capacity by 1 dB when compared to the corresponding cases with EPS. This result must be interpreted together with the high density of rockwool rigid boards and the limitation of the software in simulating non sound absorptive materials such as EPS. Concerning the effect of PCM in the sound insulation performance of the preconstructed module, it can be found that the sound insulation capacity is not significantly affected, as all corresponding values of the weighted sound reduction index before and after taking into account the PCM presence in the mixture of the interior concrete layer remain unchanged for all examined alternatives. Furthermore, a similar research [27] on a dry wall lightweight building element has also pointed out that the PCM do not provide a significant contribution in the sound reduction index of wall elements.

### Table 5. Weighted sound reduction index values ($R_w$) for all the examined cases.

| Exterior Surface Material | Type 1: Organic Coating | Type 2: Decorative Slate Tiles | Type 3: Decorative Bricks |
|---------------------------|-------------------------|--------------------------------|--------------------------|
| % PCM at the Interior Concrete Layer | External Thermal Insulation | Core Thermal Insulation | $R_w$ | $R_w$ | $R_w$ |
| A (0%)                   | EPS (graphite)          | A1 EPS                        | 53       | 54       | 56       |
| B                        | EPS                    | B1 EPS                        | 53       | 54       | 56       |
3.2.1. Examination of the Sound Insulation Performance of the Preconstructed Module When Installed as a Partition

In order to define the capacity of the examined preconstructed module to cover the requirements of the sound insulation regulation’s Class B (normal acoustic comfort), the weighted apparent sound reduction index ($R'_w$) was calculated. As already mentioned, $R'_w$ is calculated according to the approximation methods described in the national regulation [11] according to Table 4. The weighted apparent sound reduction index values for all the cases are presented in Table 6. The weighted apparent sound reduction index values range from 50 dB to 54 dB, which means that all examined cases can cover the requirements of the regulation (50 dB). For the modules with an external finish of Type 1 (plaster), rockwool appears to be more favorable as a cavity insulation material for the sound insulation of the wall. The same applies for most of the examined elements. Regarding the impact of the type of the exterior cladding, Type 3 presents the most favorable behavior, with Type 1 being characterized by the lowest $R'_w$ values (however, still higher than the regulation’s limits). This could be explained by the surface mass contribution of each type of external covering.

Values of the weighted sound reduction index, for all the examined cases range between 53 and 58 dB. According to calculations, the $R_e$ of a conventional double brick masonry wall with an insulated cavity ranges between 54 and 59 dB. This means that the SUPRIM wall has a similar sound insulation performance to a conventional double brick masonry wall.

| Exterior Surface Material | Type 1: Organic Coating | Type 2: Decorative Slate Tiles | Type 3: Decorative Bricks | Weighted Apparent Sound Reduction Index |
|---------------------------|-------------------------|-------------------------------|--------------------------|----------------------------------------|
| % PCM at the Interior Concrete Layer | Thermal Insulation Material | Exterior Thermal Insulation | Cavity Insulation | $R'_w$ | $R'_w$ | $R'_w$ |
| A [0%] | EPS (graphite) | A1 | EPS | 50 | 51 | 53 |
| B [10% PCM (28)] | EPS (graphite) | B1 | EPS | 50 | 51 | 53 |
| C [10% PCM (28+24)] | EPS (graphite) | C1 | EPS | 50 | 51 | 53 |
| D [20% PCM (28)] | EPS (graphite) | D1 | EPS | 50 | 51 | 53 |
| E [20% PCM (28+24)] | EPS (graphite) | E1 | EPS | 50 | 51 | 53 |
3.2.2. Examination of the PCM Aggregation Calculation Results

The calculations of the weighted sound reduction index show that the change in the composition of the interior concrete panel with the addition of phase change materials does not influence the sound insulation capacity of the preconstructed module. However, except for the comparison of the weighted sound reduction index, it is very important to also examine the sound reduction index per frequency in order to draw conclusions on the capacity of the preconstructed module to provide a satisfactory sound reduction in all frequencies. In fact, reduced performance (transmission loss decrease) in some frequencies can be an issue, as, under specific conditions, the resulting effects can severely affect the quality of the acoustic environment (e.g., in the case of low frequencies [38]).

From the comparison of the values of the sound reduction index per frequency for the alternatives A.1 and B.1 when Type 1 exterior coating is used, there is no difference in the capacity of the preconstructed module. The resonance frequency also remains common in both cases at 125 Hz (Figure 2).

Similar conclusions are drawn from the comparison of the values of the sound reduction index per frequency for the alternatives A.1 and D.1 of Type 1 (Figure 3). The same conclusion applies, regardless of the quantity of PCM mixture in concrete, to all Type 1 alternatives. Diagrams comparing C.1 and E.1 are not presented as the results are similar to B.1 and D.1, respectively.

In any case, the preconstructed module presents significantly lower values in lower frequencies than in higher frequencies. This is an expected condition as the lower sound insulation performance in lower frequencies is a common weakness in all steel profile-based double leaf walls when compared to simple panels.

However, despite the examined preconstructed module’s lower performance in lower frequencies, it still performs better, even in these frequencies, than the lightweight panels with similar air cavity widths [39].

It should be noted that, in the context of this paper, the term “lower frequencies”, is used in a comparative sense and does not indicate low frequencies such as 20, 60, or 80 Hz. Specifically, the study focuses on the range of 100-3150 Hz; although some conclusions can be drawn for the module’s performance for frequencies lower than 100 Hz, the analysis focuses on frequencies above this limit.

![Figure 2. Sound reduction index R, calculated for A.1 (0%PCM) and B.1 (20%PCM (24 + 28)) configuration alternatives.](image_url)
3.2.3. Examination of the Exterior Coating Calculation Results

Figure 4, Figure 5 and Figure 6 show the comparative analysis of the three types, regarding the external coating or cladding, of the preconstructed module (Type 1, Type 2 and Type 3) in order to determine whether the exterior coating, (lime plaster, slate or solid bricks, respectively) can significantly affect sound reduction index at all frequencies. As already mentioned, the quality of sound insulation is not only a function of the weighted sound reduction index, it also depends on the values of the sound reduction index at different frequencies. At lower frequencies, especially in double layered building elements where the drop in the sound reduction index is more intense, it is important to study the frequency variation of the sound reduction index in order to define the quality of acoustic comfort provided to the building’s occupants.

Figure 3. Sound reduction index $R$, calculated for A.1 (0%PCM) and D.1 (20%PCM (28)) configuration alternatives.

Figure 4. Comparison of the sound reduction index of the three types regarding the external finishing material (Type 1, Type 2 and Type 3) for the case A.1 (exterior insulation layer Graphite EPS, cavity insulation layer EPS, 0% PCM).
As already mentioned, Type 3 (exterior cladding with solid bricks) has higher sound insulation capacity than Type 1 and Type 2, which is obviously due to the higher mass of the exterior cladding material. However, it is noted that the resonance frequency area, both in the case of Type 2 (exterior cladding with slates) and in the case of Type 3, occurs at a lower frequency (100 Hz) than in the Type 1 (125 Hz). The values of the sound reduction index at this frequency (22 dB) in both Type 2 and Type 3 are higher than in Type 1 (21 dB) but the sharp drop of its value at this frequency range is still large. This means that the preconstructed module has a weaker sound insulation performance at low frequencies and interventions to improve its sound insulation capacity in low frequencies (near the resonance frequency) should be examined.

3.2.4. Examination of the Sound Insulation Performance of the Preconstructed Module against Environmental Noise

Indoor noise levels were calculated with INSUL’s indoor to outdoor calculator in order to assess the capacity of the examined preconstructed module to fulfill the regulatory requirement for exterior
walls ($L_{Aeq} \leq 35$ dB). All three types of the preconstructed module were examined (with EPS in the cavity between the concrete panels)

According to the Greek regulation (Government Gazette 1367/B’/27.04.2012) “Road, rail and airborne noise limits”, the environmental noise should not exceed the following values:

- For the $L_{den}$ indicator (24 h): 70 dB.
- For the $L_{night}$ indicator (8 h—night): 60 dB.

The maximum permitted noise level at properties’ boundaries in residential areas is 50 dB [10].

For the calculations three different levels of traffic noise (65, 70 and 75 dB) were considered and a flat geometry of the façade was assumed. The traffic noise levels in the 1/3 octave bands were also calculated with the help of INSUL software which uses ISO 717-1:2013 for the calculations. Despite the fact that the panel is to be used in environments with low or moderate noise levels, a 5 dB higher value (than the maximum permitted value) for the calculations was considered as in many cases the regulatory requirements for traffic noise are exceeded.

All alternatives considering PCM mixture in the interior concrete panel were considered. As shown in the histogram of Figure 7, in all cases the increase in external noise by 5 dB results in an increase in the A-weighted sound level of the indoor space by 18%. For 65 and 70 dB exterior noise levels; the preconstructed module can meet the requirement of the regulation ($L_{Aeq} \leq 35$ dB). However, at 75 dB none of the three types of the building module can meet the regulatory requirements, as the value of the A-weighted sound level slightly exceeds the limit value of 35 dB.

![Figure 7. Indoor sound level of the examined building module under different traffic noise levels (65, 70, 75 dB) for a flat geometry of the façade and for Type 1, Type 2 and Type 3 in the case of cavity insulation material with EPS and for all PCM aggregation alternatives.](image)

3.3. Suggestions for the Improvement of the Module’s Acoustic performance

The improvement of the sound reduction index of a building element can be achieved with various interventions. The greater the improvement required in each case, the more radical the interventions that should be made.

In general, the sound insulation capacity of the examined building element is considered satisfactory, especially in cases where rockwool is used as a cavity insulation material and in cases where the exterior finish is realized with decorative slates or solid bricks. The only case where measures may be required to improve the sound insulation capacity of the preconstructed module is
for the conventional finish with plaster (Type 1) and only in case the environmental noise level is higher than 70 dB. Of course, it should be noted that this case requires the existence of an extremely noisy environment beyond the legal limits. However, in case the preconstructed module is required to be improved in terms of its sound insulation capacity, the cavity width and the cavity insulation material’s thickness can either be increased, or resilient bars and a metal bracket incorporating a rubber or neoprene isolation element can be placed between the steel profiles and its connection to the inner concrete panel in order to provide a more elastic connection.

In order to support these suggestions, further calculations were made. For the first case (increase in the cavity and cavity insulation thickness) the improvement of the A-weighted sound level of the indoor space is relatively small. However, for both cavity insulation materials it is possible to achieve the desired sound insulation performance. The calculation of the sound reduction index for different thicknesses of the cavity insulation material and the improvement of the A-weighted indoor sound level for the increase in thickness of the cavity insulation material is presented in Table 7.

### Table 7. Weighted sound reduction index and A-weighted sound level change for different thickness of the cavity of the wall and of the cavity insulation material.

| Thickness of the Cavity and Insulation Material (mm) | EPS | Rockwool |
|-----------------------------------------------------|-----|----------|
|                                                     | $R_w$ (dB) | $L_{Aeq}$ (dB) | $R_w$ (dB) | $L_{Aeq}$ (dB) |
| 50                                                  | 53  | 36.6     | 54  | 35.2     |
| 100                                                 | 57  | 35.0     | 58  | 32.5     |

In the second case (resilient bars and rubber isolation clips connection), the improvement of the sound insulation capacity of the structural element is much greater, as it was calculated that the sound reduction index is 74 dB for both cavity insulation material alternatives. In this solution the value of the sound reduction index is improved at all frequencies, as shown in Figure 8. In fact, in the case of elastic connection, not only is the value of the weighted sound reduction index improved but also the quality of the sound protection of the indoor space, as the fluctuations of the sound reduction index per frequency decrease significantly, especially in the lower frequency area (around 100 Hz - 125 Hz), where the examined preconstructed module in its original form shows weakness in its sound-insulating behavior due to the sharp dip of the curve in 125 Hz.

![Figure 8](image.png)

**Figure 8.** Comparative values of the calculated sound reduction index $R$ between the standard SUSTainable PReconstructed Innovative Module (SU.PR.I.M.) wall and the improved isolated frame SU.PR.I.M. wall.

However, in this solution two parameters must be considered. The first has to do with the load bearing capacity of the preconstructed module, which should be re-examined with the new
connection to ensure that it can meet the static and structural requirements, and the second has to do with the possible increase in the thickness of the structural element in order to include the necessary distance required for the installation of the rubber insulation connections and the horizontal resilient bars, leading to extra construction costs.

4. Discussion

The outcomes of the calculations showed that the examined configurations of the preconstructed module can meet the requirements of acoustic comfort for Class B, with an exception of the case of high traffic sound loading (noise level 75 dB). Specifically, regarding the calculations of the A-weighted sound level of the indoor space for traffic noise for when EPS is used as cavity, it was found that the examined building element can meet the requirements of the regulation \( (L_{Aeq} \leq 35 \text{ dB}) \) for environmental noise [11], in case the noise level is up to 70 dB.

Based on the comparative analysis of the examined alternatives’ performance, the main observations derived were the following:

- In all cases, the use of rockwool board in the cavity between the concrete panels led to higher (in very few cases to unaltered) performance compared to EPS.
- The addition of PCM to the interior concrete panel does not affect the sound insulation of the examined module against airborne noise. Other researchers have concluded that a 1.4 dB improvement might be observed on a lightweight dry wall due to the existence of a 5 mm PCM panel [27]. In our research, the difference is non-remarkable as the weighted sound reduction index remains unchanged, which can be explained by the fact that the PCMs do not form a separate layer but are incorporated in the concrete mixture and their quantity is obviously smaller and by the fact that the wall is characterized by a high mass construction due to the two concrete panels.
- The type of exterior cladding was proven to affect the sound insulation performance of the examined module, with the exterior organic coating (Type 1) having the lowest contribution.
- The preconstructed module’s weighted apparent sound reduction index \( R'_{w} \) was calculated to be above the limit of the building regulation \( (R'_{w} \geq 50 \text{ dB}) \), which means that the examined module could be used in all alternative configurations as an internal partition between spaces of main or auxiliary use and as partition adjacent to communal spaces as well.

However, the above-mentioned conclusions are based on the calculation results and further analysis is necessary. The present work is a feasibility study, which represents the first approach to the estimation of the examined building module’s sound insulation capacity. As such, the analysis is characterized by limitations that extend to some of its aspects. Specifically, additional experimental data would be useful as INSUL uses corrections based on empirical data of more common materials; measurements for various potential configurations of the element (considering not only the use of “unconventional” materials but also different sizes of the specimen) would enhance the depiction of its acoustic performance.

Another limitation of the research is that flanking sound was approximated according to the Greek Building Regulation, which means that, in real buildings, flanking may vary significantly and there may be cases where the regulation limits may not be complied with, due to weak flanking elements and construction errors. At this point further research is necessary including field measurements which would provide data on the components’ sound insulation performance under real-life conditions, as part of an actual building. The results presented in this pre-study provide systematic information for the sound insulation performance of the examined module, but limitations regarding the assessment of its behavior in the context of the actual working conditions exist. Field measurements on an actual building, constructed with the use of this element, have been planned in the next stage of the research.
5. Conclusions

The high quality demand at all levels of construction is nowadays an important target and, in the study of new innovative ways to improve the quality of life in buildings, indoor acoustic quality should be provided through appropriate materials, methods and construction practices. The present research, carried out in the framework of the research program SU.PR.I.M., examined the capacity of an innovative building module—designed for advanced performance in terms of structural thermal and environmental performance—not only to comply with the regulatory indoor sound level requirements but also to provide a high acoustic quality for the inhabitants.

The sound insulation performances of a variety of alternative configurations (different coating/cladding types, different cavity insulation materials, and addition of PCM in the interior concrete panel) were calculated and conclusions related to whether regulatory limits are met were drawn.

Specifically, the sound insulation capacity of the preconstructed module was calculated based on the weighted sound reduction index for all the alternative configurations and all the three types of exterior coating/cladding analyzed (Type 1, Type 2, Type 3). In addition, the A-weighted sound level of the indoor space for traffic noise for Type 1, which was calculated to be the weaker alternative in terms of the Rw calculated values, was examined.

The results of the research showed that the definition of the overall quality of the construction demands the thorough study of all design parameters as the high thermal insulation or structural quality of building elements does not necessarily lead to a high acoustic quality. The examined preconstructed module may be able to meet the regulatory requirements, but, as further step, in order to be able to provide also a high indoor acoustic quality for lower frequency noises several measures could be examined. In fact, two scenarios for improving the sound insulation capacity of Type 1 modules were examined—which, however, demand further considerations (thickness of the element, structural issues)—and it was found that the structural element can be significantly improved covering the sound insulation requirements of the regulation.

In addition, further research is needed concerning the connections of the prefabricated module to the perimeter and to the side panels, as they can significantly affect the sound insulation performance of the construction. Moreover, the current research analyzed a specific configuration of the preconstructed module concerning the distance between the steel profiles. However, in real buildings the varying distances that might be applied according to the architectural and geometry constraints might significantly alter the indoor sound levels. Therefore, in a further and more detailed analysis, the effect of the distance between profiles on the sound insulation performance of the preconstructed module would be useful.

Another aspect that arose in the context of this study regarding future research is the need for data regarding novel technologies such as components incorporating PCM; the absence of such information may represent a limitation for calculation methods that are based on conventional materials.

Of course, the weaker sound insulation capacity in low frequencies is an inherent weakness of double leaf building elements in comparison to single panels and not only of the examined building element. Therefore, in similar constructions, the specific environmental noise conditions of the building should be considered in order to ensure that all building elements will be able to meet the sound insulation requirements. In general, special care should be taken in the case of composite wall surfaces (with openings), for which, in addition to the opaque structural element, a careful selection of the sound insulation capacity of the openings should be made, in order to balance the low performance of the composite structural element at low frequencies.

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References

1. United Nations Environment Programme—Sustainable Buildings & Climate Initiative. Buildings and Climate Change: Summary for Decision Makers; UNEP DTIE Sustainable Consumption & Production Branch: Paris, France, 2009.
2. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (recast). Off. J. Eur. Union L, 2010, 53, 13–35.
3. European Environment Agency. Final Energy Consumption by Sector and Fuel in Europe; European Environment Agency: Copenhagen, Denmark, 2020.
4. Kanters, J. Circular Building Design: An Analysis of Barriers and Drivers for a Circular Building Sector. Buildings 2020, 10, 77, doi:10.3390/buildings10040077.
5. UN Environment and International Energy Agency. Towards a Zero-Emission, Efficient, and Resilient Buildings and Construction Sector. Global Status Report 2017. Available online: https://www.worldgbc.org/sites/default/files/UNEP%20188_GABC_en%20%28web%29.pdf (accessed on 2 August 2020).
6. Giarma, C.; Tsikaloudaki, K.; Aravantinos, D. Daylighting and Visual Comfort in Buildings’ Environmental Performance Assessment Tools: A Critical Review. Procedia Environ. Sci. 2017, 38, 522–529, doi:10.1016/j.proenv.2017.03.116.
7. World Health Organization, Regional Office for Europe. Burden of Disease from Environmental Noise: Quantification of Healthy Life Years Lost in Europe; World Health Organization, Regional Office for Europe: Copenhagen, Denmark, 2011.
8. Research Project SU.P.R.I.M.—SUsustainable PRerconstructed Innovative Module. Available online: Suprim.gr (accessed on 8 August 2020).
9. Rasmussen, B.; Machimbarrena, M. Existing sound insulation performance requirements and classification schemes for housing across Europe. In COST Action TU0901—Building Acoustics throughout Europe, 2014, Volume 1: Towards a Common Framework in Building Acoustics throughout Europe (ISBN (Electronic) 978-84-697-0158-4); Rasmussen, B., Machimbarrena, M., Eds.; DiScript Preimpresion, S.L.: Madrid, Spain, 2014; pp. 31–54. Available online: http://www.costtu0901.eu/tu0901-e-books/volume-1/separated-chapters.html (accessed on 24 September 2020).
10. Presidential Decree 1180/1981. On the regulation of issues referring to the establishment and operation of industries, crafts industry, all kinds of mechanical installations and warehouses, and to the respective environmental safety in general. In Government Gazette 293/A’6.10.1981; Ministry of Environment, Energy and Climate Change: Athens, Greece, 1981. (In Greek)
11. Ministerial Decision 3046/304. Building Regulation. In Government Gazette 59/D’3.2.1989; Ministry of Environment, Energy and Climate Change: Athens, Greece, 1989. (In Greek)
12. Hellenic Organization for Standardization (ELOT). Available online: http://www.elot.gr/default_en.aspx (accessed on 5 August 2020).
13. Tadeu, A.; António, J.; Mateus, D.M. Sound insulation provided by single and double panel walls—A comparison of analytical solutions versus experimental results. Appl. Acoust. 2004, 65, 15–29, doi:10.1016/j.apacoust.2003.07.003.
14. Tadeu, A.; Mateus, D.M. Sound transmission through single, double and triple glazing. Experimental evaluation. Appl. Acoust. 2001, 62, 307–325, doi:10.1016/s0003-682x(00)00032-3.
15. Kropp, W.; Rebillard, E. On the air-borne sound insulation of double wall constructions. Acta Acust. United Acust. 1999, 85, 707–720.
16. Tadeu, A.; Pereira, A.; Godinho, L.; António, J. Prediction of airborne sound and impact sound insulation provided by single and multilayer systems using analytical expressions. Appl. Acoust. 2007, 68, 17–42, doi:10.1016/j.apacoust.2006.05.012.
17. Hongisto, V. Sound insulation of double panels-comparison of existing prediction models. Acta Acust. United Acust. 2006, 92, 61–78.
18. Arjunan, A.; Wang, C.; Yahiaoui, K.; Mynors, D.; Morgan, T.; Nguyen, V.; English, M. Development of a 3D finite element acoustic model to predict the sound reduction index of stud based double-leaf walls. J. Sound Vib. 2014, 333, 6140–6155, doi:10.1016/j.jsv.2014.06.032.
19. Arjunan, A.; Wang, C.; Yahiaoui, K.; Mynors, D.; Morgan, T.; English, M. Finite element acoustic analysis of a steel stud based double-leaf wall. Build. Environ. 2013, 67, 202–210, doi:10.1016/j.buildenv.2013.05.021.
20. Craik, R.; Smith, R. Sound transmission through double leaf lightweight partitions part I: Airborne sound. Appl. Acoust. 2000, 61, 223–245, doi:10.1016/s0003-682x(99)00070-5.
21. Vigran, T.E. Sound insulation of double-leaf walls – Allowing for studs of finite stiffness in a transfer matrix scheme. Appl. Acoust. 2010, 71, 616–621.
22. Uris, A.; Llopis, A.; Llinares, J. Effect of the rockwool bulk density on the airborne sound insulation of lightweight double walls. Appl. Acoust. 1999, 58, 327–331, doi:10.1016/s0003-682x(98)00065-6.
23. Calleri, C.; Astolfi, A.; Shtrepi, L.; Prato, A.; Schiavi, A.; Zampini, D.; Volpatti, G. Characterization of the sound insulation properties of a two-layers lightweight concrete innovative façade. Appl. Acoust. 2019, 145, 267–277, doi:10.1016/j.apacoust.2018.10.003.
24. Centre Scientifique et Technique du Bâtiment—France (CSTB). Available online: http://www.cstb.fr/dae/en/nos-produits/logiciels.html (accessed on 8 August 2020).
25. INSUL Software. Available online: http://www.insul.co.nz/ (accessed on 8 August 2020).
26. Berthou, Y.; Biwole, P.H.; Achard, P.; Sallée, H.; Tantot-Neirac, M.; Jay, F. Full scale experimentation on a new translucent passive solar wall combining silica aerogels and phase change materials. Sol. Energy 2015, 115, 733–742, doi:10.1016/j.solener.2015.03.038.
27. Alessandro, S.; Carpinello, S.; Pietraèsa, C.; Valsesia, E.; Griginis, A.; Prato, A.; De Astis, V.; Zito, D.; Cavaleri, A. Acoustical performance of an innovative dry-wall facade system with high thermal properties/Arianna, Astolfi. In Proceedings of the 22nd International Congress on Sound and Vibration, Florence, Italy, 12–16 July 2015; pp. 1–8.
28. Uthaichotirat, P.; Sukontasukkul, P.; Jitsangiam, P.; Suksiripattanapong, C.; Sata, V.; Chindaprasirt, P. Thermal and sound properties of concrete mixed with high porous aggregates from manufacturing waste impregnated with phase change material. J. Build. Eng. 2020, 29, 101111, doi:10.1016/j.jobe.2019.101111.
29. Technical guideline: T.O.T.E.E 20701-2/2017. Thermophysical properties of building materials and thermal insulation capacity of buildings. In Technical Chamber of Greece; Ministry of Environment and Energy, General Secretariat for Energy and Mineral Resources: Athens, Greece, 2017; pp. 56–61.
30. ISO 12354-3:2017(E). Building Acoustics—Estimation of Acoustic Performance of Buildings from the Performance of Elements—Part 3: Airborne Sound Insulation against Outdoor Sound; International Organization for Standardization: Geneva, Switzerland, 2017.
31. Ballagh, K.O. Accuracy of Prediction Methods for Sound Transmission Loss. In Proceedings of the 33rd International Congress and Exposition (INTER-NOISE 2004), Prague, Czech Republic, 22–25 August 2004. Available online: https://www.marshallday.com/media/1341/10_accuracy_of_prediction_methods_for_sound_transmission_loss.pdf (accessed on 2 September 2020).
32. Kurra, S. Comparison of the models predicting sound insulation values of multilayered building elements. Appl. Acoust. 2012, 73, 575–589, doi:10.1016/j.apacoust.2011.11.008.
33. Garg, N.; Kumar, A.; Maji, S. Parametric sensitivity analysis of factors affecting sound insulation of double glazing using Taguchi method. Phys. Appl. Acoust. 2013, 74, 1406–1413, doi:10.1016/j.apacoust.2013.05.008.
34. INSUL Software Website, Technical Information, Available online: http://www.insul.co.nz/tech-info/ (accessed on 2 September 2020).
35. ISO 10140-2:2010. Acoustics—Laboratory Measurement of Sound Insulation of Building Elements Part 2: Measurement of Airborne Sound Insulation; International Organization for Standardization: Geneva, Switzerland, 2010.
36. ISO 717-1:2013(E). Acoustics—Rating of Sound Insulation in Buildings and of Building Elements—Part 1: Airborne Sound Insulation; International Organization for Standardization: Geneva, Switzerland, 2013.

37. Pereira, A.; Santos, P.; Roque, E. Evaluation of the acoustic performance of lightweight steel-framed facade walls. In Proceedings of the 48th Congreso Español de Acústica Encuentro Ibérico de Acústica European Symposium on Underwater Acoustics Applications, European Symposium on Sustainable Building Acoustics, Coruna, Spain, 3-6 October 2017.

38. Baliatsas, C.; Van Kamp, I.; Van Poll, R.; Yzermans, J. Health effects from low-frequency noise and infrasound in the general population: Is it time to listen? A systematic review of observational studies. Sci. Total Environ. 2016, 557, 163–169, doi:10.1016/j.scitotenv.2016.03.065.

39. Roque, E.; Santos, P.; Pereira, A. Thermal and sound insulation of lightweight steel-framed façade walls. Sci. Technol. Built Environ. 2018, 25, 156–176, doi:10.1080/23744731.2018.1506677.

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