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Influence of Freeze/Thaw Cycles on Mechanical and Thermal Properties of Masonry Wall and Masonry Wall Materials

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Received: 7 March 2019; Accepted: 14 April 2019; Published: 17 April 2019

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Abstract: In this study, the influence of freeze/thaw cycles on the mechanical and thermal properties of bricks and mortar as building parts of masonry walls, as well as the influence on the masonry wall itself is investigated. At the material level, the influence of freeze and thaw cycles on the mechanical and thermal properties of masonry components (bricks and mortar) was investigated; at the construction level, the influence of freeze and thaw cycles on the mechanical and thermal properties of a masonry wall was studied. To study the influence of freezing on the energy demand characteristics of masonry buildings, in terms of energy conservation and greenhouse gas emission, a case study was investigated on a typical structure of a historical building located in Croatia, that had undergone a process of energy certification. The applied freeze/thaw regime negatively influenced the compressive strength and the thermal properties of bricks and mortar, as well as the mechanical and thermal properties of the wall. Considering the thermal properties of the material before and after its exposure to freeze/thaw cycles, we concluded that the annual energy consumption, the heating costs, and the CO_2 emission of a family house could increase up to 3.7% after frost action in the studied case.

Keywords: clay brick; mortar; freeze/thaw action; wall properties; energy consumption; emission of CO_2

1. Introduction

The durability of buildings has become one of the most pressing issues in contemporary building construction. Often the basic properties of buildings weaken after only ten years. The numerous causes of building deterioration manifest in terms of the partial or full building destruction, extension and remodeling, repurposing, etc. The most frequent cause of masonry structure deterioration is humidity/moisture. Regardless of the manner, it entered the wall, humidity can cause an entire range of building degradation mechanisms, i.e., chemical processes that alter the masonry unit and the building properties. Therefore, the buildings no longer perform in the manner in which they were designed to, which is indicated by means of wall surface damage, spalling, change in color, crumbling, increased permeability, cracking, swelling, or shrinkage. The most significant building degradation mechanisms caused by moisture include [1,2] mineral alteration, salt crystallization, freezing/thawing damage, and biological colonization. The freezing action in a masonry unit/brick occurs when the temperature drops below 0 °C, at which point the process of water freezing inside the brick is initiated. The expansion of ice results in the increase of stresses within the material. The intensity of the stress caused by freezing depends on the number of pores in the material and on the level of its saturation [3]; a higher proportion of pores causes greater stress, whereas, in the case of a low saturation level, the stress is negligible because the free space in the pores allows the water to expand during freezing. If the generated stress exceeds the brick strength, the brick will be damaged, owing to the repeated freezing and thawing cycles. Apart from affecting the mechanical properties of masonry units, humidity has a negative effect on their thermal properties as well. The thermal conductivity value of porous building materials increases rapidly with the increase in their moisture content; consequently, the insulation capacity decreases and the heat loss increases [4–15]. The increase in the thermal conductivity of a material with the increase in its moisture content is the direct result of the fact that water, which has replaced the air in the pores of the material, has a thermal conductivity value of 0.61 W/(mK) at air temperature [16], which is twenty-four times higher than that of air. Although the conductivity coefficient increases continuously with the increase in the moisture level of the material, it is necessary to stress that the initial increase in the moisture content causes a sharp increase in the conductivity coefficient. The sharper increase in the value of the coefficient at a lower moisture level is explained by the fact that during the wetting of the material, water first fills the finer pores and capillaries, whose effect on the thermal conductivity is more significant than that of the larger pores. The thermal conductivity increases additionally in the case where water freezes within the material because the thermal conductivity value of ice exceeds 2.0 W/(mK) [17], which is approximately four times higher than that of water.

The decreased mechanical properties of wall units owing to the influence of humidity and, consequently, owing to the influence of freeze/thaw cycles, will directly affect the walls, which consist of such units. At present, the estimation of the actual energy performance of buildings has become a priority to achieve energy conservation; therefore, it is important to evaluate the thermal performance of masonry considering all influencing parameters on the energy performance of buildings. Recent research performed conducted Litti et al. [13] on areas that were detected to be wet revealed thermal transmittance values that were more than three times higher than those of the dry areas on the same masonry surface. Considering the aforementioned points, it is extremely important to quantify the actual thermal transmittance of the wall and the influencing factors in order to be able to plan optimal refurbishment interventions.

According to EN 771-1 [18], the freeze/thaw resistance category of a clay masonry unit shall be declared by the manufacturers in reference to its applicability to masonry, or elements subjected to passive, moderate, and severe exposure (F0, F1, and F2, respectively). However, there is also a possibility for manufacturers not to test all the properties of their product. This should be clearly indicated in the Declaration of Performance, marking the non-tested property as NPD (no performance determined). The same procedure is followed for the testing of the brick resistance to freeze/thaw cycles. In this manner, bricks that are not resistant to freeze/thaw cycles can be made available in the market. According to Reference [19], one out of eight brick types available in the market are non-resistant to freeze/thaw cycles. In larger buildings, the designer will prescribe the need for masonry units to be tested in freeze/thaw cycles. For smaller buildings, such as family houses, such a need is omitted; consequently, bricks that are not resistant to freeze/thaw cycles can be inbuilt. Family houses often remain unplastered, which directly allows atmosferills to affect the properties of the materials and the structure.

In this study, the influence of freeze/thaw cycles on the mechanical and thermal properties of bricks and mortar as building parts of masonry walls will be investigated, as well as the influence on a masonry wall itself. To study the influence of freezing on the energy demand characteristics of masonry buildings, in terms of energy conservation and greenhouse gas emission, a case study will be investigated on the typical structure of a historical building located in Croatia that has undergone a process of energy certification.

2. Experimental Part

The experimental part of the paper is divided into three subparts. The experimental part focused on the material level, the construction level, and a case study on the energy demand of masonry buildings as influenced by freeze/thaw cycles. In the part focused on the material level, the influence of the freeze/thaw cycles on the mechanical and thermal properties of masonry components (namely, bricks and mortar) was investigated. The second experimental part focused on the construction level, the influence of the freeze/thaw cycles on the mechanical and thermal properties of the masonry wall itself. In the third part, the impact of the freeze/thaw cycles on the energy efficiency of a real building was investigated.

2.1. Influence of the Freeze/Thaw Cycles on the Properties of Bricks and Mortar

Four types of full bricks available in the market and cement mortar with a cement-to-sand ratio of 1:3 were considered in the present study. Bricks 1 and 2 were hand-molded bricks, whereas bricks 3 and 4 were molded with an extrusion machine. The mortar was prepared with CEM II/B-M (P-S) 32.5R, with a density of 3050 kg/m^3 and a water-to-cement ratio of 0.55. Mortar in its fresh state was tested for consistency according to EN 1015-3 [20], for density according to EN 1015-6 [21], and for the pore content according to EN 1015-7 [22]. The results of the tests on mortar in its fresh state are listed in Table 1.

Table 1. Properties of mortar in its fresh state.

Property	Value
Consistency (cm)	140
Density (g/cm^3)	1.87
Pore content (%)	3.3

The mortar specimens were first stored in a polyethylene bag in the mold for two days, left for five days outside the mold, and finally, they were placed in the chamber under controlled conditions with a 65 ± 5% moisture content until the sample reached an age of 28 days, as prescribed in EN 1015-11 [23].

For assessing the effects of the freeze/thaw cycles on masonry materials, the bricks and mortar were subjected to compressive strength tests before and after their exposure to freeze/thaw cycles. The same properties were used for the estimation of the ratio. In this study, a higher compressive strength ratio means that the resistance of the material to the freeze/thaw action would be greater. Although European standards specify that the resistance of bricks to freezing/thawing cycles should be checked according to CEN/TS 772-22 [24], owing to the insufficient number of bricks for the manufacturing of the test wall, a different method, namely HRN B.D8.011 [25], was employed in the present work. According to HRN B.D8.011, the water-saturated samples were placed in the refrigerator and were exposed to a temperature of −20 ± 2 °C for 4 h. Next, the samples were immersed in water, where they were kept for 4 h at a temperature of 15 to 20 °C. This cycle was repeated 25 times and the condition of the sample was checked after every cycle. The brick was considered to be resistant to freezing/thawing cycles if the signs of damage were not visible on any of the tested samples after 25 cycles of freezing and thawing in water. In the present study, all observed bricks were estimated as resistant to freeze/thaw cycles according to HRN B.D8.011. The mortar specimens subjected to freeze/thaw cycles were treated in the same manner. The compressive strength of the brick specimens was tested according to EN 772-1 [26], whereas the compressive strength of the mortar specimen was tested according to EN 1015-11 [23]. The thermal conductivity and the thermal diffusivity of the mortar and of bricks 1 and 3, prior to and after their exposure to freeze/thaw cycles, were tested according to ISO 22007-2 [27]. Three tests were conducted for each of the observed properties observed in this study.

2.2. Influence of the Freeze/Thaw Cycles on the Properties of a Masonry Wall

The influence of the freeze/thaw cycles on the mechanical properties of masonry walls was studied through the initial shear strength, which was tested using real wall sample. The influence of the freeze/thaw cycles on the thermal properties of a masonry wall was investigated using a computer simulation. The test specimens for the determination of the initial shear strength were manufactured by interconnecting three bricks using mortar, as per EN 1052-3 [28], where the mortar layer had a thickness of 10 mm. Six samples with a 250 mm thickness were prepared for each brick type (Figure 1). Three samples were used for the initial shear-strength testing at room temperature and the remaining three were used for the initial shear-strength testing after exposure to freeze/thaw cycles. The samples exposed to freeze/thaw cycles were subjected to a total of 25 freeze/thaw cycles, similar to the brick and mortar samples. Prior to being subjected to freeze/thaw cycles, the samples were immersed in water for 24 h.

Figure 1. Wall specimens for the initial shear strength.

Based on the results of the laboratory tests before and after freezing the samples, the heat transfer modeling of the wall was made in the COMSOL Multiphysics v5.3a simulation software (COMSOL Multiphysics®v. 5.3a. COMSOL AB, Stockholm, Sweden) [29]. Two models were made, with brick 1 and 3 for two types of environmental conditions, i.e., before and after freezing (Table 2), to study the influence of freezing on the thermal properties of the wall. Brick 1 was chosen as a representative of the hand-molded bricks and brick 3 was chosen as a representative of the extruded brick. The walls were modeled using the tested thermal properties of the brick and mortar obtained from prior and after the samples had been subjected to freeze/thaw cycles.

Table 2. Model definition.

Model	Composition	Environmental Conditions
Model 1	Brick 1 + Mortar	Before freezing
		After freezing
Model 2	Brick 3 +Mortar	Before freezing
		After freezing

In this study, a steady heat transfer through a wall was analyzed, meaning that the internal and external temperatures were constant over time. The convection and radiation from the internal environment to the internal surface of the wall, as well as the convection and radiation from the external surface of the wall to the external environment, were considered in the heat transfer coefficient, i.e., the internal and external thermal resistance. The values of thermal resistance used in the simulation corresponded to typical values provided in the ISO 6946 [30] standard. This means that the values used in the present study for R_{si} and R_{se} were 0.13 and 0.04 $m^2 \cdot K/W$, respectively. The wall was modeled in correspondence to construction technology as a single-layer wall, with a thickness of 250 mm and mortar layer/joint thickness of 10 mm. The adiabatic conditions and the boundary settings of the models are shown in Figure 2.

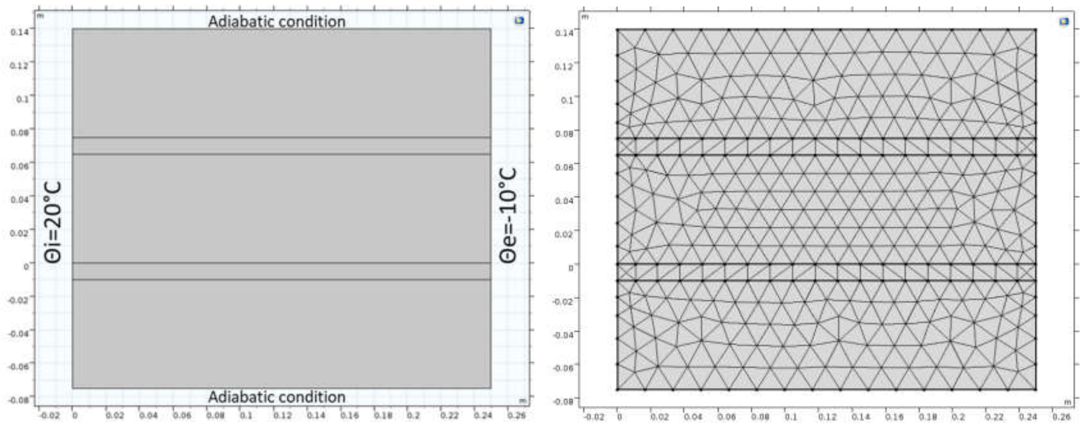


Figure 2. Adiabatic conditions and boundary settings of the models under the steady-state condition.

In addition, the theoretical thermal transmittance value (U-value) is an important factor for the evaluation of the energy performance and the achievement of energy conservation in buildings for all wall models before and after freezing. It was calculated according to the following equation [30]:

$$U = 1/(R_{si} + R_1 + R_{se}), (W/m^2 \cdot K)$$

where R_1 is the design thermal resistance of the layer, and R_{si} and R_{se} are the internal and the external surface resistances, respectively, with values of R_{si} = 0.13 and R_{se} = 0.04 $m^2 \cdot K/W$.

2.3. *Influence of the Freeze/Thaw Action on the Energy Efficiency of an Actual Building*

For this purpose, a case study on a family house was investigated, which had undergone a process of energy certification. The house is in the Osijek-Baranja county, Croatia (some of the major characteristics of the building are listed in Table 3). The building has natural ventilation and a central heating system, in which gas is utilized as an energy source for heating. The building has external walls constructed entirely of clay bricks. For the purpose of this study, the thermal characteristics of the external walls—subjected to freeze/thaw cycles—have been replaced with the thermal characteristics of the bricks investigated in the present study, before and after freezing.

Table 3. Major construction characteristics of the case-study building.

Characteristics	Value
A_K [m^2]	80.33
V [m^3]	172.27
f_0	1.23
Year of construction	1970
Orientation	SE-NW
Wall area [m^2]— external brick wall, thickness of 25 cm	41.75
Wall area [m^2]— external brick wall, thickness of 25 cm	18.67

The ground floor layout and external view of the studied family house are presented in Figure 3.

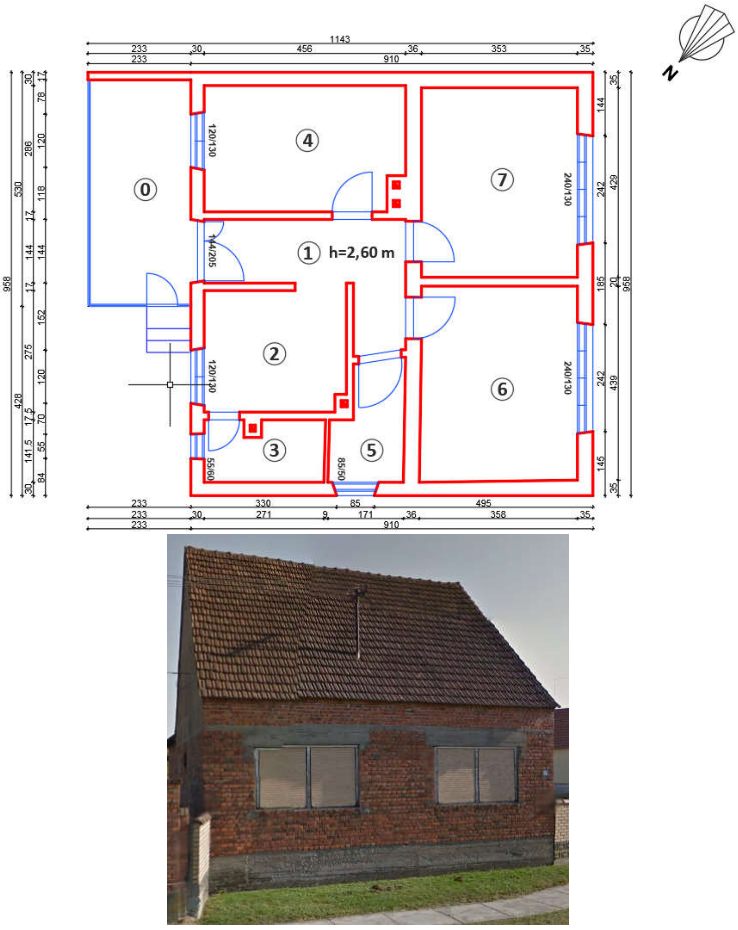


Figure 3. Layout of the ground floor and external view of the analyzed building.

Considering the characteristics of the building listed in Table 3, the annual energy consumption, heating costs, annual CO_2 emissions, and the specific annual heating energy needs for referential climatic data were calculated according to EN ISO 13790 [31] using the values of the thermal properties for brick 1 and brick 3, before and after their exposure to freeze/thaw cycles.

2.4. Results and Discussion

The average values of the compressive strength and the thermal properties of the bricks and the mortar prior and after their exposure to freeze/thaw cycles, as well as the change in each of the aforementioned properties, are listed in Table 4, along with the corresponding standard deviations.

Table 4. Properties of bricks and mortar prior and after their exposure to freeze/thaw cycles.

Property	Brick 1	Brick 2	Brick 3	Brick 4	Mortar
Compressive strength of material before freezing (MPa) / standard deviation	30 /± 1.23	35 /± 2.10	36 /±2.31	56 /± 2.54	30.9 /± 1.34
Compressive strength of material after freezing (MPa) / standard deviation	22 /± 1.04	30 /±1.54	29 /±1.67	43 /± 2.01	23.8 /± 1.03
Change in compressive strength after and before freezing	↓ 27%	↓ 14%	↓ 19%	↓ 23%	↓ 23%

Table 4. *Cont.*

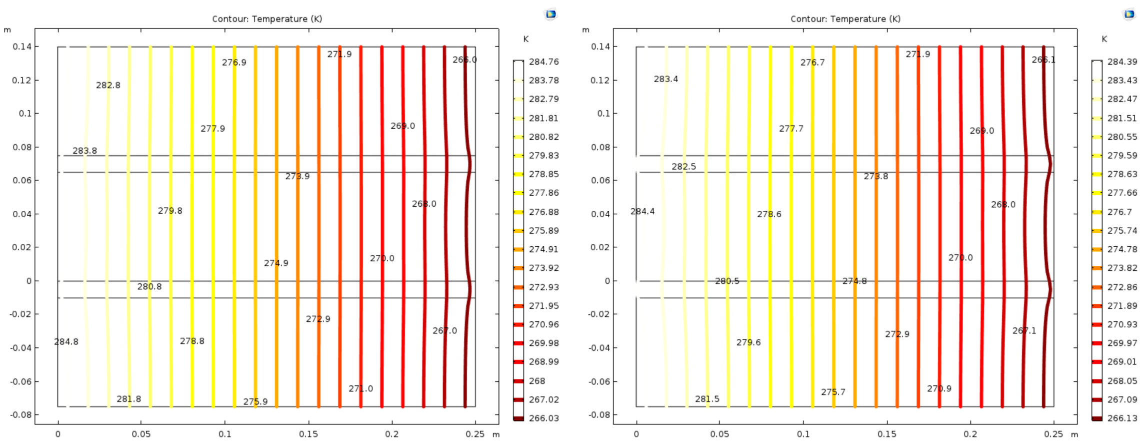
Property	Brick 1	Brick 2	Brick 3	Brick 4	Mortar
Thermal conductivity of material before freezing (W/m^2·K) / standard deviation	0.745 /± 0.003	Not tested	0.818 /± 0.002	Not tested	1.233 /± 0.001
Thermal conductivity of material after freezing (W/m^2·K) / standard deviation	0.793 /± 0.002	Not tested	0.954 /± 0.004	Not tested	1.465 /± 0.003
Change in thermal conductivity after and before freezing	↑ 6%	Not tested	↑ 17%	Not tested	↑ 19%
Thermal diffusivity of material before freezing (mm^2/s) / standard deviation	0.640 /±0.001	Not tested	0.511 /± 0.003	Not tested	0.694 /± 0.005
Thermal diffusivity of material after freezing (mm^2/s) / standard deviation	0.603 /± 0.006	Not tested	0.607 /± 0.004	Not tested	0.716 /± 0.007
Change in thermal diffusivity after and before freezing	↑ 6%	Not tested	↑ 19%	Not tested	↑ 3%

The average values of the initial shear strength of the wall specimens prior and after their exposure to freeze/thaw cycles, as well as the change in the value of each of the properties, are summarized in Table 5, together with the corresponding standard deviations.

Table 5. Initial shear strength of wall samples prior and after their exposure to freeze/thaw cycles.

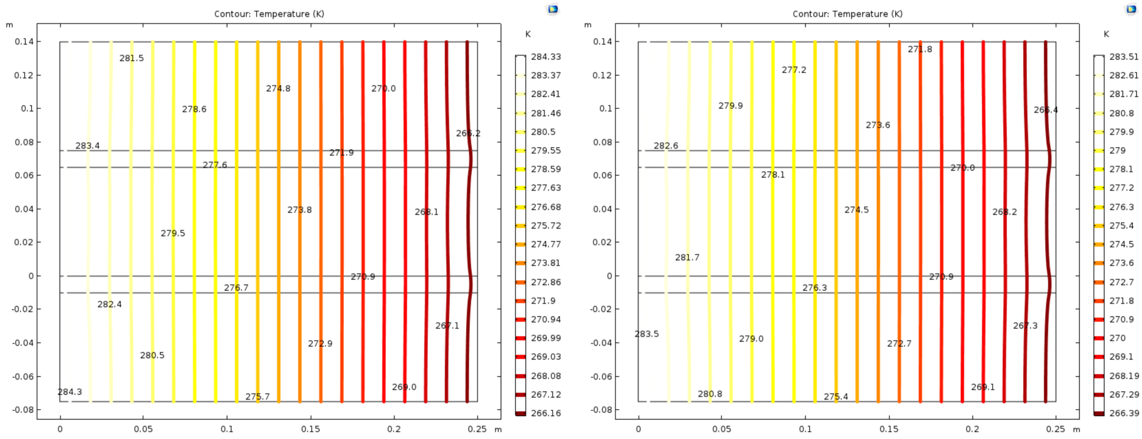
Sample Description	Initial Shear Strength, f_{voi} (N/mm^2)		Change in Initial Shear Strength After and Before Freezing
	Before Freezing	After Freezing	
Brick 1 + Mortar	0.376 /± 0.012	0.345 /± 0.013	↓ 8%
Brick 2 + Mortar	0.386 /± 0.015	0.361 /± 0.016	↓ 6%
Brick 3 + Mortar	0.344 /± 0.008	0.307 /± 0.007	↓ 11%
Brick 4 + Mortar	0.338 /± 0.011	0.300 /± 0.013	↓ 11%

The isothermal contours of the presently studied models are illustrated in Figures 4 and 5. The temperature and the heat flux distribution across the cross section were compared between the models both graphically and numerically, before and after freezing (Table 6).



(**a**) (**b**)

Figure 4. Isothermal contours in model 1: (**a**) Prior exposure to freeze/thaw cycles and (**b**) after exposure to freeze/thaw cycles.



(**a**) (**b**)

Figure 5. Isothermal contours in model 2: (**a**) Prior exposure to freeze/thaw cycles and (**b**) after exposure to freeze/thaw cycles.

Table 6. Percentile difference in the temperature and the heat flux distribution across the cross-section in the x-direction.

Section Observed/Model	**Mean Differences in Temperature Before–After Exposure to Freeze/Thaw Cycles**		**Mean Differences in Heat Flux Before–After Exposure to Freeze/Thaw Cycles**	
	Model 1	**Model 2**	**Model 1**	**Model 2**
At the middle of the brick	–0.05%	–0.11%	3.45%	8.93%
At the middle of the mortar	–0.05%	–0.10%	12.46%	10.37%
On the border between the brick and the mortar	0.05%	–0.10%	12.81%	10.45%

The calculated thermal transmittance values for walls constructed using brick 1 and brick 3 before and after their freezing are listed in Table 7.

Table 7. Calculated U-value of walls.

Wall Model	**Thermal Transmittance, U (m^2·K/W)**		**Change in Thermal Transmittance After And Before Freezing**
	Before Freezing	**After Freezing**	
Brick 1	1.98	2.06	↑ 4%
Brick 3	2.10	2.31	↑ 10%

The annual energy consumption, heating costs, the annual CO_2 emissions, and the specific annual heating energy for referential climatic data for the building that was constructed using brick 1 and brick 3, before and after their exposure to freeze/thaw cycles, are listed in Table 8.

Table 8. Building major annual energy demand characteristics.

Characteristics	Building Made of Brick 1		Change in Characteristics Before And After Exposure To Freeze/Thaw Cycles (%)	Building made of Brick 3		Change in Characteristics Before And After Exposure To Freeze/Thaw Cycles (%)
	Before Freeze/Thaw Cycles	After Freeze/Thaw Cycles		Before Freeze/Thaw Cycles	After Freeze/Thaw Cycles	
Annual energy consumption [kWh]	25,029.29	25,403.33	−1.49	25,591.63	26,544.71	−3.72
Heating costs [€]	994.09	1008.95	−1.49	1016.43	1054.28	−3.72
Annual emissions of CO_2 [kg]	4672.31	4742.14	−1.49	4777.29	4955.20	−3.72

Observing the results in Table 4, it may be seen that the compressive strength of all materials (brick and mortar) decreased after their exposure to freeze/thaw cycles in the range of 14–27%. Moreover, the differences in the compressive strength ratios after and prior to the freeze/thaw actions were more pronounced in hand-made bricks (27% and 14%, respectively) than in extruded bricks (19% and 23%, respectively). This was probably caused by the greater uniformity in the molding of the extruded bricks. Meanwhile, the thermal conductivity and the thermal diffusivity increased in all materials in the range of 6–19% and 3–19%, respectively, after being exposed to freeze/thaw cycles. It should be noted that the changes in the thermal properties were less in the case of the hand-made bricks than in the case of the extruded bricks. The present authors expected that the brick with the highest decrease in compressive strength would achieve a higher increase in thermal properties; however, this was not the case. More specifically, it was shown by Martinez et al. [32] that materials with high open porosity are less durable during weathering. Meanwhile, the thermal properties of the material are more influenced by a closed porosity [33]. It is likely that the bricks with a higher compressive strength ratio after and before freeze/thaw cycles had a higher content of open pores, whereas the bricks with a higher thermal-properties ratio had a higher content of closed pores. By observing Table 5, it was clear that the values of the initial shear strength decreased after freezing for the wall samples; the change in the shear strength before and after the freeze/thaw cycles ranged from 6–11%.

As observed in Figures 4 and 5, the increase in the thermal conductivity after wall exposure to freeze/thaw cycles resulted in a decrease in the temperature gradient and an increase in the heat flux.

As observed in Table 7, the value of the thermal transmittance increased by 10% for the wall made of brick 3 and by 4% for the wall made of brick 1 after their exposure to freeze/thaw cycles. Such results were expected, considering that the thermal properties of brick 3, which were integrated to model 2, underwent a greater change when exposed to freeze/thaw cycles than that of brick 1, which were integrated to model 1 of the wall.

From Table 8, it was observed that when the thermal properties obtained via experimental testing after freezing were applied, the energy consumption, the heating costs, and the CO_2 emission increased by more than 1% on an annual basis in the building made of brick 1, and by more than 3% in the building made of brick 3. Although the percentages may appear negligible, it should be emphasized that the influence of 1% and 3% refers to a single family house with a useful area of only 80.33 m^2 and that the thermal properties were evaluated for only 60.42 m^2 of the walls. If the entire life cycle of the building and the size of the building stock would be considered, the influence would become significantly higher.

3. Conclusions

Encouraged by the fact that clay brick units are often available in the market without a declaration regarding their resistance to freeze/thaw cycles, the authors investigated how freeze/thaw cycles affect such units and the walls in which they are built, in terms of to their exposure to the freeze/thaw action. The influence of the freeze/thaw cycles on the mechanical and thermal properties of masonry materials, as well as the mechanical and thermal properties of the masonry itself, was studied. Based on the results of the research, it may be concluded that by neglecting this property, the brick and the wall suffer from loss of mechanical and thermal properties, which is evident in the consumption of energy for the heating of the buildings, in which such types of bricks are installed. Ignoring the need for testing the freeze/thaw resistance on bricks/masonry units is often a consequence of the high demands of the devices required for testing this property, as well as the test sample massiveness. This points to the need for a new, simpler method—preferably focused on masonry units—that would enable manufacturers to test the brick resistance under freeze/thaw cycles as a part of their factory production control.

Author Contributions: Formal analysis, M.T. and H.K.; investigation, M.V.; methodology, I.N.G.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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