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A comparative analysis on the effects of pumice, tuff and conventional aggregates on energy efficiency performance in new generation composite mortars

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Abstract
It is often stated that there is an energy efficiency gap between optimal energy use and actual energy use in the world. In the construction sector, various building materials are produced to optimize energy efficiency in buildings. Among these construction materials, cement mortars are widely used. Cement mortars are produced from various raw materials and aggregates. The aggregates, which are volcanic and porous property between these aggregates, have high insulation properties due to their porous structures. In this study, two different volcanic porous aggregates with suitable unit weight and pore structure for thermal insulation were used in cement mortar. At the end of the experimental study, the thermal behaviour of the cement mortars produced was investigated. According to the results of the research, it was determined that the cement mortar produced with pure pumice was the most suitable for the heat insulation between the tested aggregates.

Keywords Pumice · Tuff · Aggregate · Composite mortar · Energy efficiency

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Introduction

In recent years, one of the most important challenges the society facing is climate change. One of the biggest causes of climate change is the emission of greenhouse gases released into the environment. Taking the energy consumption to the minimum is an important way to minimize greenhouse gas emissions (Wu et al. 2016). Recently, energy-efficient buildings have started to carry a great importance both economic and environmental factors in the world. Countries increasingly focus on energy-efficient buildings since one-third of the energy consumption spent by buildings (Koksal et al. 2015). The buildings and construction sectors together are responsible for 36% of global energy consumption and almost 40% of total direct and indirect CO_2 emissions. According to studies, the energy consumed by buildings is 39% in the UK, 37% in the European Union (Pérez-Lombard et al. 2008), 40% in the USA (DOE 2012) and 31% in Japan (Juan et al. 2010). Approximately 40% of the energy consumed in Turkey is consumed in buildings and 80% of this for heating (Binici et al. 2015). For all these reasons, the production of energy-efficient buildings becomes an important challenge.

The use of new generation composite mortars has recently gained importance. Composite mortars pose a new challenge in building design and production of building materials. Building design and energy efficiency issues in composite mortar are already extremely important. Within the framework of insulation, a number of technical features such as thermal conductivity, specific heat and heat storage capacity are important parameters. Furthermore, such parameters as resistance to water, resistance to fire and high-temperature environments, vapour diffusing ability and resistance to radiation environments of specially developed species can show values that generate awareness.

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Composite mortars can be seen to have transformed in recent years as a natural component against the energy efficiency property in buildings (Kılınçarslan et al. 2018; Chung et al. 2015). Recently, composite mortars can be produced with so many different aggregate derivatives. These include natural originated materials, half synthetic or artificial aggregate derivatives, providing wall compatibility, reversibility and comfort (Bayraktar et al. 2018; Zhang et al. 2019). The fact that the thermal comfort in today's buildings is ensured under optimum conditions has been put into practice as an inevitable rule in the regulations and standards as well (Bilgin and Arıcı 2017; Kılınçarslan et al. 2018). Furthermore, the overheating and overcooling of the areas where people live have negative effects on human psychology and physiology (Topay 2013; Topay and Parladir 2015; Çetin 2015; Çetin et al. 2018). For this reason, reducing the heat transfer of construction materials in areas where people continue to live will reduce the overwarming or overcooling of the environments and reduce the negative impact on people.

The distribution range of lightweight aggregates used in the production of lightweight structural elements is quite wide and they differ from each other in their origin, appearance, density, classes, surface conditions, porosity, mechanical strength, water absorption and costs. Natural lightweight aggregates are generally industrial raw materials with a porous structure formed as a product of volcanism. Pumice, diatomite, perlite, vermiculite, tuffs and volcanic slag can be considered as aggregate types, which are evaluated in this context. When ecological and durability conditions are taken into consideration, the naturally originated porous aggregates, in particular, have become important in the production of new material. Among the most prominent of these materials are pure pumice and volcanic tuff aggregates (Ceylan and Saraç 2017; Kılınçarslan et al. 2017; Bozkurt and Taşkin 2017). It is observed that there is not enough information about the use of pure pumice and volcanic tuff aggregates in composite mortar production and providing technical advantages for thermal comfort parameters according to mortar properties. The pumice and volcanic tuff aggregates nowadays are generally used in lightweight concrete applications in the construction industries and have wide applications, one of them being used as an additive to sound and thermal insulation purposes for lightweight construction units.

The tuff used in this study is defined as the product of Hasandağı volcanism in the Central Anatolia Region. Tuff series of ignimbrite and tuff formations, which are deposited in the belt extending from Hasandağı volcano to Aksaray City centre, were used. The pumice aggregate used in this experimental study was obtained from the location of the pumice mining quarry in the Nevşehir Region. Pumice is a geological material and has a spongy and porous structure. Therefore, the conductivity of pumice is low and has very high heat and sound insulation. Because of these properties, pumice is widely used as a lightweight aggregate in lightweight concrete designs.

In this paper, technical aspects and performances of pure pumice and volcanic tuffs as different two natural porous aggregates in new generation cementitious composite mortars were evaluated based on the experimental results for the use of especially energy-efficient plaster and mortar specimens in civil engineering applications. Physical, mechanical and thermal comfort properties of the composite mortar specimens will be discussed. The effects of their energy efficiency in the composite mortar will be discussed compared to traditional mortars in detail.

Materials and methods

Two different types of volcanic originated materials are investigated in this study. These are pure pumice and tuff. Basalt crumbs are usually mixed into the pumice. Basalt can be separated from the pumice in various aqueous systems and thus pumice is enriched. This enriched pumice is called pure pumice. CEM I 42.5 Portland cement is used as binder, lime is used as pH stabilizer, a polymer is used to improve fresh properties and glass fibre of 14 μm in diameter and 12 mm in length was used as reinforcement in the mixtures. In the control specimen (M0), sand and limestone are used instead of pure pumice and tuff, in order to understand the technical difference between pure pumice and tuff and traditional aggregates. Table 1 and Table 2 show the physical and chemical properties of the pure pumice and volcanic tuff materials, respectively. In the test mixtures, as the amount of pure pumice decreased, tuff amount was increased by decreasing the amount of pure pumice, and mixtures were prepared. The mixture proportions are given in Table 3.

After the crushing and sieving process, basalt components were separated from pumice, i.e. basaltic fragments, by passing through pool system and purified. In order to make a comparison between products easier, the grain sizes of the aggregates evaluated in mortar combinations were used as 0/2 mm. Also, cement, lime, fibre and polymer ratios in all mixtures were kept constant for a more accurate comparison. It is determined in the initial trial works that the use of more lime, fibre and polymer than the ratios given in the table significantly reduces the mixing and workability properties of the mixtures. For this reason, 5% for lime, 0.3% for fibre and 0.7% for polymer were used as optimum values. However, the W/C ratios of the mixtures differed in order to produce similar consistency (150 ± 5 mm) products due to the difference in water absorption capacity of the aggregates used in the study. As can be easily observed from Table 3, an increase in the tuff ratio resulted in an increase in the amount of water for similar consistencies. In each mixture combination, 12 pieces of 5 × 5 × 5-cm cube specimens were produced and the

Table 1 Physical properties of the pure pumice and volcanic tuff materials

Lightweight aggregate	Hardness (MOHS scale)	Specific gravity (g/cm^3)	Bulk density (kg/m^3)	Water absorption (%)	pH
Pure pumice	6.0	2.33	550–650	25	5.5–6.0
Volcanic tuff	5.5–6.0	2.51	650–750	40	5.5–6.0

compressive strength values were tested on these specimens. Compressive strength tests were conducted according to the ASTM C190 standard. 3 pieces of 20 × 40 × 3-cm rectangular specimens were produced for each mixture combination, in order to determine the thermal properties of the specimens. Thermal properties of the specimens were examined with the hot-box apparatus (ASTM 2011). Also, TS 825 (TS 825 2013), TS EN 998-1 (TS EN 998-1 2011) and TS EN ISO 6946 (TS EN ISO 6946 2017) standards were used for conducting the tests, calculations and evaluation of the results.

Results and findings

Physical, mechanical and thermal comfort properties of the composite mortar specimens were experimentally investigated. The research findings of these properties are given in Tables 4 and 5.

When Table 3 is considered, the addition of pumice and tuff increased the water requirement of the mortar with the increase of porous aggregates. When Table 4 is examined, workability (consistency) of the specimens is decreased with the increase in tuff ratio. In order to eliminate this situation, the consistency was adjusted by adding more mixing water to the mortars together with the increase in the use of volcanic tuff. Using pure pumice and tuff was reduced the hardened density of the mortar specimens to half of the density of the control specimen (498–770 kg/m^3), when compared with control specimen (1383 kg/m^3). The lightest specimen (M1) is produced with only pure pumice aggregate (498 kg/m^3). When evaluated within the scope of TS EN 998-1 standard, all samples from M1 to M6 can be considered as lightweight mortar. Because in this standard, the upper limit of the unit volume weight of lightweight mortars is defined as 1300 kg/m^3. Because the lowest density is reached for the M1 specimen, it is expected to show an improvement in the thermal behaviour of the material. In relation to the low density of the specimens, the compressive strengths were found to be low (1.13–2.18 MPa) compared to the control specimen (4.45 MPa).

Compressive strength values of tested mortars were all analysed in accordance with TS EN 998-1 standard. Compressive strength values of cement-based composite mortar specimens are divided by 4 different groups in TS EN 998-1 standard for 28 days curing time. These are as follows: CS I class (0.4–2.5 N/mm^2), CS II class (1.5–5.0 N/mm^2), CS III class (3.5–7.5 N/mm^2) and CS IV class (≥6 N/mm^2). Figure 1 shows the compressive strength values according to the unit weight of the specimens. According to Fig. 1, it can be easily observed that all specimens have appropriate compressive strength values to meet the required lower limit in TS EN 998-1 standard that is 0.4 MPa. Specimens with a density less than 600 kg/m^3 are in the CS I class (M1–M5) while the denser ones are in the CS II class (M6–M9). Moreover, it is emphasized in this standard that the minimum compressive strength of lightweight mortars intended to be used for thermal insulation should be 0.4 MPa. When evaluated in this respect, the compressive strength values of the produced specimens are quite positive.

Thermal conductivity values of cement-based mortar specimens are divided by two different groups in TS EN 998-1 standard. These are as follows: T1 class (λ ≤ 0.100 W/mK), T2 class (λ ≤ 0.200 W/mK). Figure 2 shows the thermal conductivity values according to the unit weight of the specimens. When Fig. 2 is examined, it is concluded that as a function of low density, the thermal conductivity coefficient of cement mortar produced with only pure pumice (M1) was found to be quite low (0.081 W/mK), when compared with the control specimen's thermal conductivity value (0.462 W/mK). In the previous studies conducted by the researchers, thermal conductivity values of cement mortar/concrete produced using pumice aggregate were determined in the range between 1.694 and 0.321 W/mK (Aydın and Baradan 2007; Kurt et al. 2015; Kurt et al. 2016; Amel et al. 2017; Gündüz 2008; Gündüz and Uğur 2005). Similarly, concretes using tuff aggregates have relatively high thermal conductivity values (0.25–0.85 W/mK) in the literature (Frattolillo et al. 2005; KAN and GÜL 2008). Since high strength is not desired in lightweight mortars as in concrete, lower thermal conductivity values can be obtained with lower strength and lower unit volume weights. Therefore, lower thermal conductivity values could be achieved with lower density cement-bonded composite mortars.

Table 2 Chemical properties of the pure pumice and volcanic tuff materials

Lightweight aggregate	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	TiO_2
Pure pumice	74.10	13.45	1.40	1.17	3.70	4.10	0.35	0.07
Volcanic tuff	72.00	11.78	1.17	1.46	2.34	5.27	0.58	0.20

Table 3 Mixture proportions by weight.

Mixture	OPC (%)	Sand (%)	Limestone powder (%)	Pure pumice (%)	Volcanic tuff (%)	Lime (%)	Synthetic fibre (%)	Polymer (%)	W/C
M0	27.0	26.8	40.2	0.0	0.0	5.0	0.3	0.7	2.15
M1	27.0	0.0	0.0	67.0	0.0	5.0	0.3	0.7	2.89
M2	27.0	0.0	0.0	60.3	6.7	5.0	0.3	0.7	2.93
M3	27.0	0.0	0.0	53.6	13.4	5.0	0.3	0.7	2.93
M4	27.0	0.0	0.0	40.2	26.8	5.0	0.3	0.7	2.96
M5	27.0	0.0	0.0	33.5	33.5	5.0	0.3	0.7	3.00
M6	27.0	0.0	0.0	26.8	40.2	5.0	0.3	0.7	3.00
M7	27.0	0.0	0.0	13.4	53.6	5.0	0.3	0.7	3.04
M8	27.0	0.0	0.0	6.7	60.3	5.0	0.3	0.7	3.04
M9	27.0	0.0	0.0	0.0	67.0	5.0	0.3	0.7	3.04

Similar to the compressive strength results, the value of 600 kg/m^3 can be evaluated as the limit in the thermal conductivity values of the specimens. Because the samples that exhibit a density below this value are classified as T1, the remaining samples are classified as T2 according to TS EN 998-1. The low thermal conductivity coefficient is one of the most important parameters that will affect the energy saving in the area where it will be applied.

The U-value of a wall system, which can be obtained by applying the mortars produced in the study to a wall surface, is calculated by using the model in Fig. 3. This model is used to determine the U-values to be obtained when the lightweight mortar is applied on the 25-cm concrete block element internally and externally.

In this study, produced specimens' specific heat values (790–1033 J/kgK) are higher than control specimen (640 J/kgK). More heat energy is required to increase the temperature of a substance with a high specific heat capacity than one with a low specific heat capacity. This means that from M1 to M9, specimens need to be more heated to make them warm compared with traditional plasters/mortars. Thus, compared to the control specimen, the heat energy in the environment will not be wasted, as these materials will be less heated. In this study, the highest specific heat was determined for the M1 specimens (1033 J/kgK). This is 1.61 times the specific heat of the control specimen. Also, it could be concluded from Table 5 that specimens' heat storage capacity is low (514–609 J/m^{3}K). When a heat source emits heat in the indoor environment, some amount of heat reflects from the wall surface, and it is protected inside the room section and some amount of heat transfers through the wall to the other side; moreover, some amount of heat is absorbed in a wall section and it is stored. To reach a higher insulation performance, this stored heat should be very low inside the wall section. The heat storage capacity varies depending on the specific heat and density of the materials. Although the specific heat values of the samples produced in this study were high, their heat storage characteristics were also low because of their low density. In the experiments, the produced specimens (M1–M9) were stored at the heat of 1.45 to 1.70 times lower than the control/traditional mortar specimen (M0). This means that less heat energy is consumed by insulation mortars (from M1 to M9). Constructing the walls of buildings with materials that store less heat storage capacity contributes to energy saving by

Table 4 Physical and mechanical properties of tested specimens

Mixture	Fresh mortar volume weight (kg/m^3)	Dry unit volume weight (kg/m^3)	Consistency (mm)	28 days compressive strength (N/mm^2)	Thermal conductivity, λ (W/mK)	Specific heat (J/kg K)
M0	2269	1383	150 ± 5	4.45	0.462	640
M1	936	498	150 ± 5	1.13	0.081	1033
M2	980	517	150 ± 5	1.18	0.083	968
M3	1020	537	150 ± 5	1.26	0.088	946
M4	1112	581	150 ± 5	1.33	0.091	927
M5	1170	607	150 ± 5	1.45	0.102	882
M6	1258	643	150 ± 5	1.58	0.118	837
M7	1373	701	150 ± 5	1.79	0.126	828
M8	1435	734	150 ± 5	1.92	0.128	814
M9	1503	770	150 ± 5	2.18	0.163	790

Table 5 Thermal comfort properties of the specimens

Mixture	Heat storage capability (J/m^{3}K)	Heat diffusion coefficient (×10^{-6}) (m^2/s)	Amount of heat required for 1 °C temperature increase in 1 cm thickness application (cal)	Thermal transmittance (U-value) (3-cm mortar thickness + 18.5-cm concrete masonry block "λ = 0,12 W/mK" + 3-cm mortar thickness) (W/m^{2}K)
M0	0.885	0.522	2114	0.409
M1	0.514	0.157	1229	0.339
M2	0.500	0.166	1195	0.342
M3	0.508	0.173	1214	0.348
M4	0.539	0.169	1287	0.353
M5	0.535	0.191	1278	0.362
M6	0.538	0.219	1286	0.368
M7	0.580	0.217	1386	0.370
M8	0.597	0.214	1427	0.371
M9	0.609	0.268	1454	0.379

preventing the heat consumption by the walls, when energy is used to heat the indoor.

The thermal diffusion coefficient is the ratio of thermal conductivity to the specific heat and the density. In this study, it varies from 0.157 × 10^{-6} to 0.268 × 10^{-6} m^2/s for the lightweight composite mortars and 0.522 × 10^{-6} m^2/s for the control specimen. In addition, thermal diffusion coefficient values of lightweight concrete with pumice aggregate in the literature are given in the range between 0.320 × 10^{-6} and 0.480 × 10^{-6} m^2/s (Nguyen et al. 2017). Changes in thermal conductivity, specific heat and density have the same linear trend on the thermal diffusion coefficient. The increases of these properties also increase the thermal diffusion coefficient. Besides, cement mortar specimens with pure pumice and tuff aggregates transport the heat slowly because of their less heat diffusion coefficient. The lower the heat permeability of the mortars produced by the pure pumice and tuff, or the lower the heat storage, the lower the energy required for heating of them. This means that the specimens that come into contact with the heat can get warmer by taking less energy from the heated room. It has been found that mortars produced with highly pure pumice aggregate store less heat and require more energy to be heated, rather than mortars that are traditionally produced with sand and limestone aggregates. Also in this study, the U-values of the specimens are compared and graphically given in Fig. 4 to understand how the specimens can affect energy savings.

Thermal transmittance, also known as U-value, is the rate of transfer of heat through a structure (which can be a single material or a composite), divided by the difference in temperature across that structure. U-values measure how effective material as an insulator. The lower the U-value means more insulating and energy efficiency for the material. When the composite cement mortars produced in this study are applied to both surfaces of a wall element (λ=0.12 W/mK) with a thickness of 3 cm, the U-values of the new wall combination are given in Table 5. If Table 5 and Fig. 4 are examined together, it could be observed that composite mortars with only pure pumice aggregate are much energy efficient (20.5%), when compared with the control specimen. This is

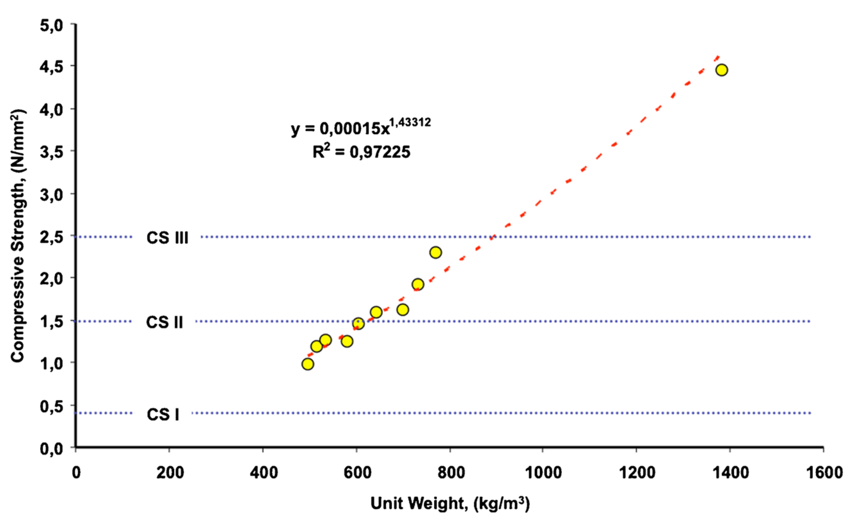

Fig. 1 Compressive strength values versus unit weight of the specimens

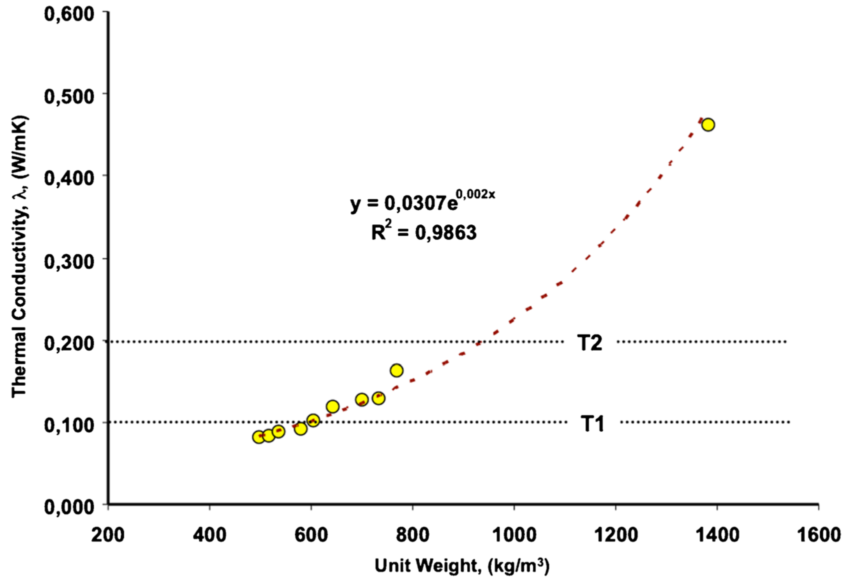

Fig. 2 Thermal conductivity values versus unit weight of the specimens

due to the fact that the pores forming the inner structure of the pure pumice make the heat difficult to transmit. Secondly, the mortars, produced by the pure pumice and tuff aggregates together, appear to be very resistant to heat and effective in energy saving.

Conclusions

In this study, two different volcanic porous aggregate types were compared in terms of thermal performance in the production of cement mortar separately. Nine different mixtures of lightweight composite mortar made of two different natures were tested. The use of aggregates with porous properties in cement mortar has been found to significantly reduce the unit weight of the mortar from 1383 kg/m^3 up to 498 kg/m^3. Accordingly, it has been found that their thermal performance of them is better than conventional/control cement mortar. Lightweight composite mortars have thermal conductivity values varying from 0.0814 to 0.162 W/mK, specific heat varying from 790 to 1033 J/kgK and a thermal diffusion coefficient ranging from 0.157×10^{-6} to 0.268×10^{-6} m^2/s and heat storage capacity ranging from 0.514 to 0.609 J/m^{3}K. In this study, the hardened density value of 600 kg/m^3 can be considered as a limit. This is because, even if the mechanical properties of the specimens below this density value worsen, their thermal properties are improved. In the study, specimens with a density below 600 kg/m^3 could be obtained by using pure pumice more than tuff. Furthermore, it can be said that the specimens with the best thermal properties are the cement mortars produced with pure pumice among these two aggregate types. According to the results of this study, it is highly efficient to use aggregates with volcanic and porous properties to produce heat insulation cement mortars and these porous and lightweight aggregates improve thermal properties and thermal comfort parameters of the insulation mortars.

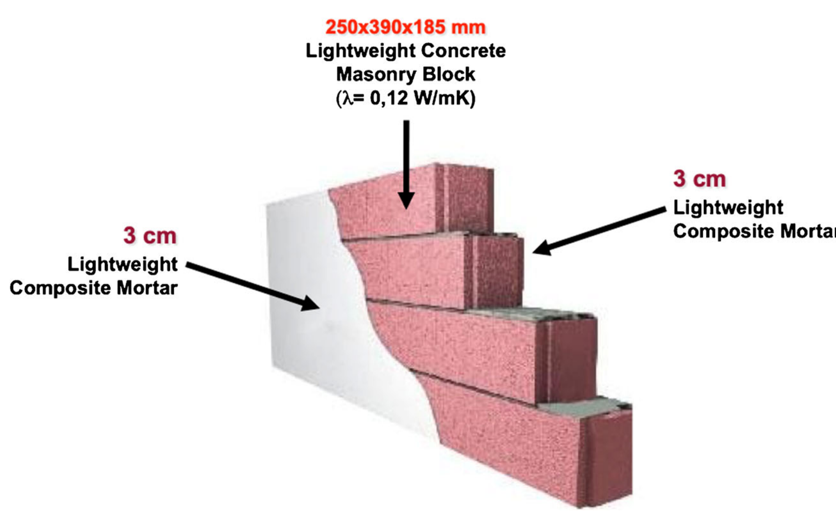

Fig. 3 Model of a simple wall system

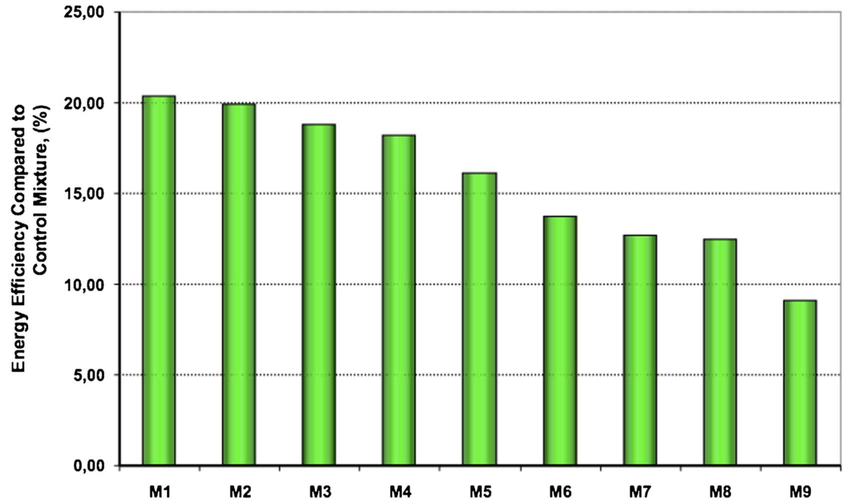

Fig. 4 Energy efficiency compared to control mixture, according to the U-values of the specimens

Furthermore, the application of the produced mortar samples to a wall surface is simulated. U-values of the structure formed by this simulation were determined. It is observed that composite mortars with pure pumice aggregate are much energy efficient up to 20.5%, according to the U-value results, when compared with the control specimen.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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