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ARTICLE

# Thermal Analysis of Concrete Mixtures with Recycled EPS Aggregates

**Aisha Ayoubi[1] Emilio Sassine[1*] Joseph Dgheim[1] Joelle Al Fakhoury[1,2] Yassine Cherif[2] Emmanuel Antczak[2]**

1. Lebanese University, Habitat and Energy Unit, Group of Mechanical, Thermal and Renewable Energies—Laboratory of Applied Physics (LPA-GMTER), Faculty of Sciences, Fanar Campus, Lebanon, 248199, France
2. Univ. Artois, IMT Lille Douai, Junia, Univ. Lille, ULR 4515, Laboratoire de Génie Civil et géo-Environnement (LGCgE), F-62400 Béthune, France

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ABSTRACT

Reusing recycled waste materials in buildings is gaining more and more attention for what it offers economic, environmental, and energy benefits; and many researchers are nowadays working on producing new sustainable construction materials incorporating recycled wastes. In this scope, this work uses an experimental approach aiming at understanding the effect of incorporating Expanded Polystyrene (EPS) beads in concrete and proposing thermally improved concrete mixtures for the production of hollow blocks in Lebanese constructions by substituting fine aggregates with recycled products such as EPS in order to promote their insulating properties. Three different diameters of EPS beads (2 mm ~ 3 mm, 3 mm ~ 4 mm and 4 mm ~ 5 mm) are studied with different volumetric ratios (20%, 40%, 60% and 80%) in order to investigate the effect of EPS on the thermal properties of concrete. The results showed that the only the percentage of incorporated EPS beads impacted the thermal performance of the concrete mixtures while the EPS diameters have a negligible effect on the thermal properties of the concrete samples.

## 1. Introduction

Buildings are globally accountable for a paramount depletion of energy. Inside them, electrical power is used for an extensive variety of applications. One of the applications is a direct relation to the equipment required to deliver thermal comfort to occupants, which may be responsible for a significant amount of whole-building energy consumption. The amount of power needed by HVAC (Heating, Ventilation and Air Conditioning) systems rely on many factors and, one of the major factors is the conduction load via the building envelope. A report by the International Energy Agency [1] suggests that the current energy usage on heating and/or cooling on account

*Corresponding Author:
Emilio Sassine,
Lebanese University, Habitat and Energy Unit, Group of Mechanical, Thermal and Renewable Energies - Laboratory of Applied Physics (LPA-GMTER), Faculty of Sciences, Fanar Campus, Lebanon;
*Email: emilio.sassine@ul.edu.lb*

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of thermal comfort consists of 60% of global energy consumption in buildings. With the need for energy that is assumed to be tripled by 2050, it is essential to concentrate on initiating techniques to either create clean, eco-friendly energy or limit the energy needs in buildings. One of the appropriate ways for the latter approach is to generate contemporary construction materials with magnified insulating properties to reduce the heat flow in and out of the buildings, consequently cutting down the necessity for energy needed to preserve indoor thermal comfort.

Concrete masonry blocks are largely used in building envelopes for what they offer as advantages such as their low cost, their low maintenance, their ease of implementation, and their fire resistance [2]. However, one of the biggest drawbacks of this technology is its relatively low thermal performance, which makes concrete blocks need lots of improvements to meet the recent requirements in terms of energy efficiency and comfort.

Hollow concrete blocks can be thermally enhanced by either adding insulation materials into their cavities, by modifying their shapes (modifying the shapes of the cavities, adding bulkheads, increasing the thickness of the block), or by incorporating some materials into the concrete mixture composition.

In the last couple of years, deep research attempts have been done in order to recycle wastes for probable utilization for the manufacturing of concrete services [3]. That's the reason why the blocks of concrete have been considered the best choice for the consolidation of recycling materials from waste due to its small amount of quality needs materials. One of the major components in the concrete block is known as Aggregate, which contributes to 80% of the complete volume. It is very crucial in affecting the blocks of concrete characteristics. As long as the traditional aggregate utilization does not serve the environment and will lead to a reduction of normal assets as it is stated by Medina et al. [4]. The wide range of materials generated from waste has been reproduced in which it will be utilized as aggregate in the concrete block's manufacturing.

Yoshida et al. [5] have stated that the universal disposal of cathode ray tubes (CRT) is able to gain its maximum in the following five years between 2015 and 2020. And that will make the government put a massive effort to discover a reasonable option for CRT waste disposal. As has been investigated by Zhang et al. [6], a massive quantity of waste from plastic materials has been released and neglected in landfills. They have also stated that these wastes should be used in construction services.

Medina et al. [4] have studied the use of ceramic waste as aggregate during the manufacturing of concrete blocks. They have discovered that it has many beneficial characteristics such as long service life, massive resistance from abrasion resistance as well as fire and heat resistance. Furthermore, the elevated insulation characteristics such as thermal insulation are considered the most significant benefit of the use of Crumb Rubber (CR) during the manufacturing of concrete blocks. Mohammed et al. [7] have also stated that conventional block of concrete has greater thermal conductivity compared to CR concrete blocks. In fact, expanded polystyrene (EPS) which is classified as an ultra-lightweight aggregate is one of the promising aggregates, owing to its properties of ultra-low density, thermal insulation and energy absorption compared to ordinary concrete. According to Chen et al. [8], restricted crushed waste from EPS straight in concrete has been used as it is known as the most economical usage of EPS.

Khatib et al. [9], and Bhutta et al. [10], declared that EPS has been utilized as an insulating material, due to its low density, thermal insulation, nonabsorbent as well as its low cost. During the experimental work of Khatib et al. [11], the thermal properties of the natural aggregates were achieved using EPS in order to reduce costs and protect the environment. Emilio et al. [12] studied the influence of adding EPS beads to the concrete mixture. Four different hollow block samples were produced using different EPS ratios (0 g, 6 g, 12 g, and 18 g) and tested in order to find their thermal resistances. As a result, they found that the outcome was encouraging in terms of a thermal point of view, where adding 18 g of EPS beads increased the thermal resistance from 0.16 $m^2KW^{-1}$ to 0.31 $m^2KW^{-1}$.

Ganesh et al. [13] used two different sorts of EPS beads in their investigation with various dimensions of 4.75 mm ~ 8 mm having a bulk density of 9.5 $kg/m^3$, and 2.36 mm ~ 4.75 mm with a bulk density of 20 $kg/m^3$. Their study indicates that the EPS concrete mixes manufactured with processed fly ash represent less water absorption amounts in comparison with the usual concrete material. Sayadi et al. [14] have focused on the influence of EPS particles on the fire resistance of foamed concrete as well as the thermal conductivity, and they discovered that when the volume of EPS increases, the fire resistance, as well as the thermal conductivity of the concrete decreases.

Moreover, the concern for the environment which has been related to the disposal of different types of waste materials has increased at an alarming rate. Annually, various kinds of waste have been produced in massive amounts depending on local industries. Consequently, the need for further sustainable procurement has increased the necessity of constructing a green environment.

As it is mentioned in the research of Karade [15] and Xuan et al. [16], massive quantities of waste materials generated are either burnt or landfilled and this leads to contamination as well as environmental pollution. As a result, there is a huge pressure applied to enhance the reuse value of waste materials. Besides this, it is found that the use of crumb rubber leads to better insulation properties and improved toughness, while the insertion of waste glass aggregate improves the values of concrete blocks [17,18].

The aim of this work is to investigate the thermal advantages of producing concrete mixtures with EPS beads aggregates as a substitution for stone aggregates.

For this purpose, different cubic samples (10 cm × 10 cm × 10 cm) were produced with different beads diameters and different EPS volumetric rations in order to assess and compare the influence of these two parameters on the thermal performance of the concrete mixtures using experimental measurements.

The thermal study is complemented and supported by an economic and environmental evaluation of the analyzed samples in order to stress the feasibility and sustainability of the proposed technology.

## 2. Experimental Approach

### 2.1 Preparation of the Concrete Mixtures

#### 2.1.1 EPS Beads Properties

The polystyrene beads were provided by a local Lebanese supplier with three different nominal diameters (3 mm, 4 mm, and 5 mm). In order to have a better accuracy, the EPS beads diameters and masses were first determined in order to calculate their density on the one hand, and also to determine the mass required to reach the required volumetric ration on the other hand.

A caliper was used for measuring the average diameter of the polystyrene aggregates and ten measurements were performed from each EPS beads bag (Figure 1); also, the ten beads from each category were weighed using a digital balance (Figure 2).

The average values of the ten measurements for the different nominal diameters are reported in Table 1.


**Figure 1.** Three different dimensions of EPS aggregates.

The volume and density of EPS beads aggregates are calculated using the following equations:

$$V = \frac{4}{3}\pi r^3 \tag{1}$$

$$\rho = \frac{m}{V} \tag{2}$$


**Figure 2.** Mass determination using a digital balance.

**Table 1.** Properties of EPS beads.

| EPS dimension (mm) | 3 | 4 | 5 |
|---|---|---|---|
| Average diameter (mm) | 2.668 | 3.955 | 4.897 |
| Average mass (g) | 0.00032 | 0.0009 | 0.00155 |
| Average volume (mm$^3$) | 9.94 | 32.37 | 61.45 |
| Average Density (g/L) | 32.2 | 27,78 | 25.22 |

#### 2.1.2 Preparation of the EPS Concrete Samples

The mixtures were studied according to two parameters, the amount of EPS beads aggregate (percentage of lightweight aggregate volume with respect to the total concrete volume) and the diameter of EPS beads. Four different volumetric ratios were used (20%, 40%, 60% and 80%), and three different diameter categories (3 mm, 4 mm, and 5 mm); this results in twelve different EPS concrete mixtures (C2-C13) with one reference concrete mixture without EPS aggregates (C1).

The ingredients used to prepare the concrete reference mixture (C1) are: 350 g of type 1 cement, aggregates used in two sorts (700 g of sand and 1050 g of crushed dust) and the amount of water used during the mix 300 g. These ingredients are generally used to prepare the concrete mixtures of traditional Lebanese hollow blocks and were used in this experiment to prepare the reference sample cube (C1). This concrete mixture has a density of 1400 kg/m$^3$ and a water-cement ratio ratio r/c is 0.6.

In the twelve remaining concrete EPS mixtures (C2-C13), EPS beads were used as a substitution to stone aggregates in different diameters (2 mm ~ 3 mm), (3 mm ~ 4 mm) and (4 mm ~ 5 mm) and in different volumetric proportions of 20%, 40%, 60% and 80%. The amount of cement used for all cubes is the same whereas the amount for aggregates differs from one cube to another depending on the number of EPS added (Table 2).

Figure 3a shows the materials used to prepare our mix design, whereas Figure 3b displays how the sand is sieved over 4.75 mm in order to be used during the mix preparation. The ingredients were very well mixed to guarantee as

**Table 2.** Cubes characteristics.

| | EPS Diameter (mm) | Volumetric EPS percentage (%) | Cement (g) | Water (g) | Crushed dust (g) | Sand (g) |
|---|---|---|---|---|---|---|
| C1 | - | - | 350 | 300 | 1050 | 700 |
| C2 | 2-3 | 20 | 350 | 300 | 945 | 630 |
| C3 | 2-3 | 40 | 350 | 290 | 840 | 560 |
| C4 | 2-3 | 60 | 350 | 280 | 735 | 490 |
| C5 | 2-3 | 80 | 350 | 270 | 630 | 420 |
| C6 | 3-4 | 20 | 350 | 300 | 945 | 630 |
| C7 | 3-4 | 40 | 350 | 290 | 840 | 560 |
| C8 | 3-4 | 60 | 350 | 280 | 735 | 490 |
| C9 | 3-4 | 80 | 350 | 270 | 630 | 420 |
| C10 | 4-5 | 20 | 350 | 300 | 945 | 630 |
| C11 | 4-5 | 40 | 350 | 290 | 840 | 560 |
| C12 | 4-5 | 60 | 350 | 280 | 735 | 490 |
| C13 | 4-5 | 80 | 350 | 270 | 630 | 420 |

(a) (b) (c)

**Figure 3.** Materials preparation (a), aggregate (Sand) sieving (b), and mix preparation (c).

much as possible the homogeneity of the mixture (Figure 3c). The following step is to weigh all the required materials using a digital balance. Then, we use a steel bowl to mix all the materials.

Figure 4a shows how the materials are mixed using a concrete mixer. All the materials are mixed approximately for two minutes. Then they are stopped and rested for roughly one minute. The following step is to use a small spoon to mix all the materials properly and gently. Afterward, we turn on the mixer to mix the materials for another two minutes. Then, we remove the steel bowl from the concrete mixer in order to check if the materials are ready for the next step which is preparing all required concrete cubes as it is shown in Figure 4b.


(a) (b)

**Figure 4.** Concrete mixer (a) and concrete mixture (b).

After preparing the concrete mix, the cubic samples were made by pouring the concrete mixtures into the cubic formworks. After proper lubrication of the formwork to avoid any cracking when demolding, the cubic formwork was filled in three layers with 25 blows per layer. The third layer was finished with a nice and flat upper surface.

After finishing the pouring phase, the cubes were covered with a plastic bag and a rubber band to make them tight enough and stored in a room temperature environment. After 24 hours, the cubes were watered by adding half a cup of water to each sample once every day for approximately four days to avoid any cracking. Then the samples were tested after 14 days after the preparation of the mixtures to make sure they reached their final thermo-physical properties. Figure 5 shows the first cube with no EPS added and the other 12 cubes which are made using different percentages as well as different diameters of EPS.

## 2.2 Thermal Characterization of the Concrete Mixtures

### 2.2.1 Thermal Experimental Setup

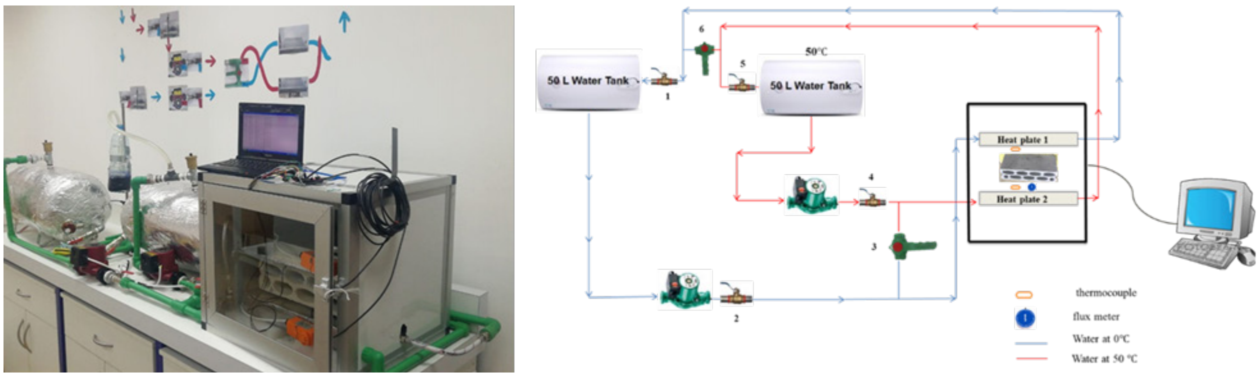
In order to investigate the thermal performance of the prepared samples using the flux metric method (NF EN 12939) [19] for the characterization of the thermal performance, an in-house manufactured thermal characterization setup is used. A water tank is left at ambient temperature while the other one is heated to 50 °C. The hot water is circulated to the bottom heat plate through a circulating pump and the tested samples are sandwiched between the two heat plates; a thermocouple and flux meter are placed straight under the sample and another thermocouple is placed over the sample (Figure 6). The fluxmeter and the two thermocouples are connected to a data acquisition of an electronic system to record the evolution of the heat flux $\varphi$ and the temperatures $T_1$ and $T_2$. Each water tank is left for about one hour to warm up before recording any experimental data. Then, all data are recorded and each test is done three times in order to clarify the stability and the accuracy of the results. The heat flux increases gradually, then it decreases slightly until it becomes stable. Each test takes approximately 120 minutes before stability occurs. All the experimental components are placed in an insulated chamber and the tested samples are wrapped laterally with mineral wool insulation material in order to decrease the lateral heat losses and insure unidirectional heat transfer. The type of heat flux which is used during the experiment is known as HPF01 as it is used to estimate the heat flux through the object in $W\cdot m^{-2}$. As for heat flux measurement in buildings and soil, HFP01 is known as the most popular sensor. This sensor is very stable and strong. In order to determine the difference in temperature, the sensor in HPF01 which is known as thermopile is used. The thermopile is known as a passive sensor that does not need any power. However, in order to find out the heat flux, the output of HPF01 (small voltage) is divided by the sensitivity which has been equal to 62.51 $\mu V\cdot W^{-1}\cdot m^{-2}$. In addition, the temperature interval is ranged between –30 °C and + 70 °C, as well as the interval of the measurement which is ±2000 W. The other characteristics of HPF01 are: a plate diameter of 80 mm, a plate thickness of 5 mm, and a weight of 200 g without cable.

### 2.2.2 Experimental Method

In our experimental work, the tested concrete cubes are laterally insulated to ensure a unidirectional heat transfer flow between the two faces of the block at $T_1$ and $T_2$, where $T_2 > T_1$ (according to Fourier's law). The following assumptions are considered: No heat generation, permanent regime, constant thermal conductivity and unidirectional conduction. The thermal resistance is determined using Fourier law applied to a unidirectional system in a permanent mode such as:

(a) (b)

**Figure 5.** Cube 1 without EPS (a) and cubes 2-13 with different percentages and different diameters of EPS beads.




(a) (b)

**Figure 6.** Photography (a) and schematic representation (b) of the experimental set-up.

$$R = \frac{T1-T2}{\varphi} \tag{3}$$

where $R$ is the thermal resistance of the sample in $m^2K/W$.

In order to validate the thermal conductivity of cube one without EPS, the last is placed between the hot plate and the cold one. The heat flow and the temperatures on both sides of the sample are recorded using computer software (Arduino). Then, the thermal resistance is found using Equation (3) when the temperature and the heat flow reach their stabilities. After that, the thermal conductivity $\lambda$ is obtained using the following Fourier's law equation:

$$\lambda = \frac{e}{R} \tag{4}$$

## 3. Results and Discussion

### 3.1 Experimental Measurement Results

The block is heated from the bottom side (temperature $T_1$) until reaching a steady state condition while the second side is kept at ambient temperature conditions. The results show that the steady is reached after about two hours (Figure 7). The hot side temperature $T_1$ reaches a steady state value of 40.57 °C whereas temperature $T_2$ slightly increases to reach 30.79 °C. The heat flux reaches a maximum of 420 $W{\cdot}m^{-2}$ after 18 minutes then starts to decline and stabilizes at a value of 169.57 $W{\cdot}m^{-2}$.

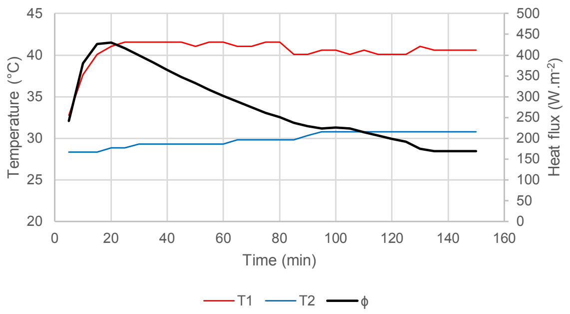



**Figure 7.** Heat flux and Temperatures variation for C1.

Based on the experimental measurements and Equations (3) and (4) the thermal conductivity can be computed. The measured thermal conductivity was found to be 1.734 $W{\cdot}m^{-1}{\cdot}K^{-1}$; this value is in the range of the thermal conductivity values of traditional concrete which can be found in the range of 1.5 $W{\cdot}m^{-1}{\cdot}K^{-1}$ to 2 $W{\cdot}m^{-1}{\cdot}K^{-1}$. Indeed, the Brazilian association of technical standards [20] stated that the thermal conductivity of concrete with a density between 1600 $kgm^{-3}$ ~ 2100 $kgm^{-3}$ is in the range of 1.40 $W{\cdot}m^{-1}{\cdot}K^{-1}$. Similarly, Leiva et al. [21] tested conventional concrete blocks and found that the thermal conductivity is equal to 1.63 $W{\cdot}m^{-1}{\cdot}K^{-1}$.

In the same way, the thermal conductivities of samples C2 – C13 were computed and reported in Figure 8.

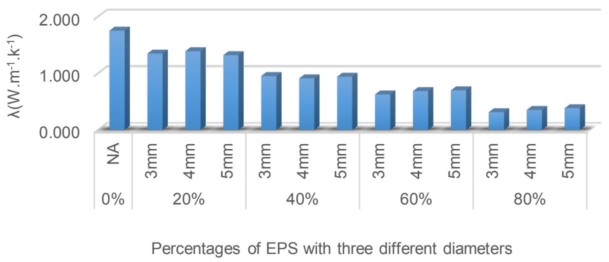



**Figure 8.** Thermal conductivities for 13 tested specimen.

### 3.2 Numerical Validation

To validate the experimental measurements concerning numerical models used for concrete mixtures, the experimental results were compared to the Maxwell-Eucken model (MEM) [22] to evaluate the validity of the results. Composite or heterogeneous materials have been extensively used in the applications of heat transfer processes, where thermal conductivity has been hugely affected by its structure as well as its composition. The thermal conductivity of all materials having a simple physical structure can be demonstrated using a prevailing ultimate structural model. This model is one of the most common models, which is used for all materials with sophisticated physical structures. Equation (5) is the key to proving the effectiveness of our model:

$$\lambda = \lambda_1 \frac{2\lambda_1+\lambda_2-2(\lambda_1-\lambda_2)V_2}{2\lambda_1+\lambda_2+(\lambda_1-\lambda_2)V_2} \quad (5)$$

where λ is the effective thermal conductivity, $\lambda_1$ and $\lambda_2$ are the thermal conductivities of each phase (concrete and EPS beads respectively), and $V_2$ is the respective volume fraction of EPS beads.

The EPS beads thermal conductivity was assumed to be equal to 0.04 $W \cdot m^{-1} \cdot K^{-1}$ [23-25].

Table 3 shows the experimental thermal conductivity $\lambda_{Exp}$ (3 mm) which is compared to the MEM model. The comparison between the experimental results and the MEM model shows very similar results with relative errors of less than 10%.

**Table 3.** Comparison between our Experimental results and MEM model result.

| $V_2$ | λeq,num (MEM) | λExp (3 mm) | Relative Error (%) (2-3 mm) |
|---|---|---|---|
| 0.2 | 1.287 | 1.345 | 4.31 |
| 0.4 | 0.900 | 0.949 | 5.16 |
| 0.6 | 0.570 | 0.624 | 8.65 |
| 0.8 | 0.287 | 0.311 | 7.72 |

### 3.3 Influence of EPS Diameter on the Thermal Performance of EPS Concrete Mixtures

Figure 9 indicates that for each EPS ratio (20%, 40%, 60% and 80%), the effect of the diameter of the bead (3 mm, 4 mm, 5 mm) on the equivalent thermal conductivity of the concrete sample is very low and the values for the same EPS ratio are in the same range (flat curves). As a result, it can be concluded that the EPS diameter variation has a very slight effect on the thermal conductivity of the EPS concrete mixture.

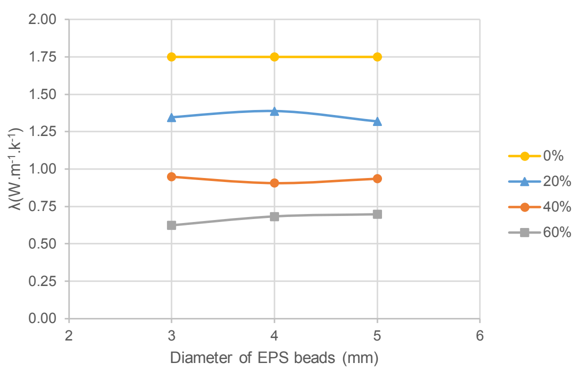



**Figure 9.** Effect of EPS beads diameter on the thermal conductivity for different volumetric ratios.

### 3.4 Influence of the EPS Percentage on the Heat Transfer

The analysis of the impact of the EPS ratio on the equivalent thermal conductivity of the EPS concrete mixture clearly shows that the thermal conductivity decreases linearly with the increase of the EPS ratio (Figure 10). The three curves representing the three different studied diameters represent the same decreasing shape. The equivalent thermal conductivity decreases by 0.18 $W \cdot m^{-1} \cdot K^{-1}$ (around 10%) for each 10% of EPS beads replacement.

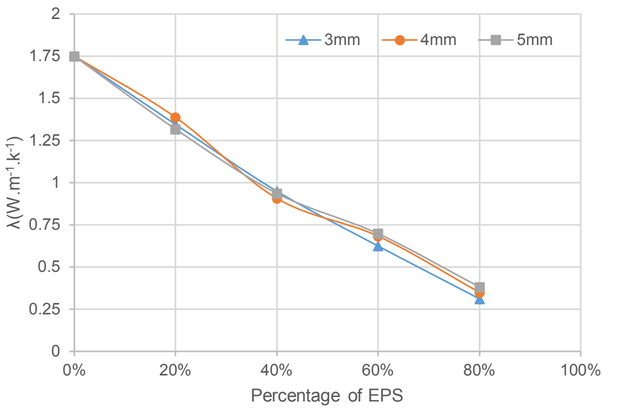



**Figure 10.** Effect of the volumetric ratio on the thermal conductivity for different EPS beads diameters.

## 4. Economic and Environmental Impact

One of the major benefits of adding recycled aggregates to construction materials is to reduce their environmental impact and their manufacturing cost. It is thus interesting to assess and compare the benefits of incorporating EPS beads in the hollow blocks concrete mixture on their cost and the environmental benefits of this substitution.

The aim of the economic study is to display in detail all the required materials used during the experimental laboratory work as well as their prices in US$ in order to evaluate the financial impact of this substitution.

One of the main important factors that influence the cost analysis is the price of the EPS beads. The beads can be bought from the market in bags but they are relatively expensive (around 0.5 US$/kg), especially when dealing with large amounts such as building applications. It is thus more relevant to use other resources for EPS beads at a more affordable price. In this case study a 2 kW shredder is used capable of delivering two cubic meters per hour (Figure 11).

The cost of bulk polystyrene wastes is assumed to be 0.05 US$/kg, and the electricity cost is assumed to be 0.15 US$/kWh. Based on these assumptions, to be able to produce one cubic meter of polystyrene (35 kg), the electric energy needed is 1 kWh and the cost of needed bulk wastes is 1.75 US$. The total cost of one cubic meter of shredded EPS beads is thus around 2 US$ including the manpower cost.


**Figure 11.** Example of EPS shredder.

Table 4 summarizes the unit costs of the different ingredients used in the preparation of the EPS concrete mixture.

**Table 4.** Unit prices of the used materials.

| Material | Cost (US$) |
|---|---|
| 1 cubic meters of EPS | 2 |
| 1 ton of cement | 110 |
| 1 ton of sand and gravel | 10 |
| 1 cubic meters of water | 2 |

In what follows, the cost comparison will be based on the samples C1 – C5 where C1 represents the sample without any EPS content and C2, C3, C4, and C5 represent the samples with 2 mm EPS beads with 20%, 40%, 60%, and 80% volumetric ratios respectively.

Based on the above assumptions, the mixture content and prices of the EPS concrete mixtures are reported in Table 5.

**Table 5.** Estimated cost of one cubic meter of EPS concrete for samples C1, C2, C3, C4, and C5.

| Sample | C1 | C2 (20%) | C3 (40%) | C4 (60%) | C5 (80%) |
|---|---|---|---|---|---|
| EPS (kg) | 0 | 7 | 14 | 21 | 28 |
| EPS (US$) | 0 | 0.4 | 0.8 | 1.2 | 1.6 |
| Cement (kg) | 350 | 350 | 350 | 350 | 350 |
| Cement (US$) | 38.5 | 38.5 | 38.5 | 38.5 | 38.5 |
| Water (kg) | 300 | 300 | 290 | 280 | 270 |
| Water (US$) | 0.6 | 0.6 | 0.58 | 0.56 | 0.54 |
| Coarse and fine aggregates (kg) | 1750 | 1575 | 1400 | 1225 | 1050 |
| Coarse and fine aggregates (US$) | 17.5 | 15.75 | 14 | 12.25 | 10.5 |
| Total cost (US$) | 56.6 | 55.25 | 53.88 | 52.51 | 51.14 |

The results of the economic analysis show that the use of recycled EPS as replacement for stone aggregates not only improves the thermal insulation of the concrete elements, but also reduces the cost of the concrete by up to 10% for 80% of EPS replacement.

Furthermore, the analysis also shows that the maximum price of EPS that does not induce a raise in the concrete cost is 9 US$. Above this value the price of EPS concrete will start to be greater than the normal concrete (C1).

On the other hand, the use of EPS concrete mixture also saves EPS wastes to be dumped in landfills especially that these wastes are not recyclable and they require a large volume due to their very low density. The use of 1 cubic meter of sample C5 (80% EPS ratio) can thus save 800 liters of EPS to be dumped and will also save the excavation of 800 liters of rocky soil.

## 5. Conclusions

In order to enhance the thermal properties of concrete building materials, insulating aggregates can be incorporated into the composition of concrete mixtures. One of these potential materials is the EPS (Expanded Polystyrene) beads. Due to the massive production of EPS, huge quantities are treated as material waste despite their importance in terms of thermal insulation applications. Three different diameters of EPS (3 mm, 4 mm and 5 mm) were used with different percentages (20%, 40%, 60% and 80%) in order to investigate the effect of EPS on the thermal properties of concrete. The results showed that the percentage of incorporated EPS reduces the thermal conductivity linearly with a rate of 10% decrease in thermal conductivity for every 10% increase in EPS volumetric ratio. On the other hand, the EPS beads' diameters have a negligible impact on the thermal performance of the concrete tested samples.

This work delivers valuable data to enhance the understanding of the thermal properties of a mixture by underlining the effect of the aggregate size and ratio on the thermal performance of concrete cubes. It also provides a better understanding of the thermal influence of aggregates on concrete mixtures, which should be addressed in order to determine the ideal cement/aggregate proportions to evaluate the ratio of solid waste leading to the greatest thermal physical properties. The economic analysis also highlighted the cost and environmental benefits of using recycled wastes in concrete mixtures. The use of EPS as a substitution for concrete aggregates in construction applications would thus reduce the number of materials sent to landfill, and preserve natural materials for future use by improving the thermal performance of the building through its low thermal conductivity.

The main limitation of this paper is that it does not analyze the shredded polystyrene shapes and their impact on the thermal properties of the resulting mixture but rather assumes that the obtained aggregates are perfectly spherical; this factor will be addressed in future research works by comparing manufactured EPS beads through the pre-expansion process with recycled EPS aggregates.

## Conflict of Interest

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript.

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