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Experimental feasibility for the incorporation of solid waste aggregates in masonry hollow blocks

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Abstract

The aim of this study is to investigate the use of three different solid waste materials sawdust, polystyrene, and rubber as waste aggregates for replacement of mineral aggregates in the Lebanese hollow. The experimental work was focused on investigating different types and ratios of wastes aggregates to be used in the hollow blocks for determining their thermal performance and their mechanical behavior. The results proved that the blocks with recycled aggregates were much more thermally efficient than the regular hollow block but less efficient structurally. While the regular block was found to have a thermal resistance of $0.156 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$, the recycled aggregates mixture blocks presented thermal resistances varying between $0.152 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ and $0.219 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ for 1.5L aggregates, between $0.181 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ and $0.245 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ for 2L aggregates, and between $0.217 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ and $0.266 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ for 2.5L aggregates. On the other hand, the addition of solid waste aggregates was found to reduce the compressive strength load from about 3.2 MPa for the normal block to a range of 1.2 to 2 MPa for the recycled aggregates mixture blocks. Furthermore, the economic analysis proved that the cost of these blocks is very competitive making them a potential innovative and marketable product.

Keywords: Lebanese concrete hollow block, Thermal resistance, Mechanical resistance, Solid waste aggregates, Economic analysis.

1 Introduction

One of the major issues of this century is global warming due to the continual increase in energy consumption. This generates problems of environmental degradation and energy crisis that have become increasingly evident since the last century [1]. Primary energy consumption experienced strong growth in Lebanon after the end of the civil war since 1990 to exceed 5.4 million tons of oil equivalent (toe) in 2008 [2]. This energy is mainly provided by imported fossil fuel power stations which increases the environmental impact and the economic burden of energy consumption. The need to undertake noticeable efforts at the consumers' level is thus a necessity for all energy sectors including the building sector where heating represents almost the half of total energy consumption share in households' energy consumption [3].

The processes and materials used for wall construction in Lebanon has changed over time from using thick stone walls in the beginning of the 20th century, until using masonry hollow blocks since few decades. The thermal insulation is usually neglected for economic reasons and lack of technical expertise. The hollow blocks are made of cement, aggregates and water, they have similar shapes but with different thicknesses. This type of construction has the advantage of being simple and fast for implementation and having a relatively low cost. On the other hand, these traditional methods lack sufficient technical control, they are very often built in an artisanal way and their energy performance is not taken into account. The improvement of the understanding of the physical properties of these blocks and the improvement of these properties is thus a necessity for improving the building envelope properties of Lebanese buildings while preserving the implementation techniques and the materials cost.

The masonry hollow block can be thermally improved by either filling its hollow by insulation materials or by improving the concrete composition. Indeed, Davraz et al. [4] studied the effect of foam concrete as filling material on thermal conductivity of lightweight masonry block and found that the thermal conductivities of foam concrete-filled blocks were 4 times lower than the non-filling blocks.

In this study, the thermal and mechanical performance of the Lebanese traditional concrete hollow block is compared to similar blocks having a modified concrete mixture obtained by integrating recycled waste materials into these blocks.

The main ingredients in the production of normal weight concrete are: coarse and fine natural aggregates, cement and water. By substituting natural aggregates with recycled waste, it is possible to both reduce energy consumption in buildings and reduce the total cost of blocks. Among the most well-known recycled waste are the expanded polystyrene beads (EPS) representing several advantages: they are hydrophobic, inert, insulating, light and at low cost. Michels et al. [5] evaluated the thermal performance of four building roofs; the 1st used as a reference, while the 2nd, 3rd and 4th had respectively white painted tiles; radiant barrier and thermal insulation based on expanded polystyrene (EPS). Khatib et al. [6] studied the physical, chemical, mechanical and thermal properties for the partial or total substitution of

natural aggregates by expanded polystyrene beads for the aim of reduction costs and preserving the environment. They found that the increase in the EPS content in the block will result in weaker concrete block. In addition, the compressive strength of EPS concretes is directly proportional to the density of the concrete, i.e. the compressive strength of the EPS concrete block increases with increasing concrete density. Moraes et al. [7] fabricated acoustic and thermal insulators using expanded polystyrene waste and a ceramic shell recycled in the foam, by evaluating the influence of the quantity of EPS beads on the microstructure, thermal conductivity, sound absorption and compressive strength. Bai et al [8] performed two tests (Split Hopkinson Pressure Bar test and Direct-impact Hopkinson Pressure Bar test) to explore the dynamic responses of 4 modes of EPS measurements and to characterize the dynamic behavior of materials, i.e. their behavior in the event of an impact. Cui et al. [9] replaced the natural aggregates with polystyrene beads having different dry densities and with different volume fractions of EPS, by studying their stress-strain properties on the basis of axial compression tests. They found that EPS concrete exhibited higher compressive strength with the increasing of dry density and curing age. Dixit et al. [10] developed the cement composite with lightweight EPS, having improved insulating capacity as well as compressive strength satisfactory for structural applications. Sayadi et al. [11] studied the impact of expanded polystyrene (EPS) particles on the fire resistance, thermal conductivity and compressive strength of foamed concrete. The results prove that increasing the volume of EPS leads to a reduction in thermal conductivity, fire resistance and compressive strength of concrete. Solomon et al. [12] explored the compression characteristics of EPS blocks and insulated concrete form (ICF) blocks under standard conditions. It is concluded that thermal insulation of ICF blocks can reduce energy demand, which in turn makes the building more energy efficient. Liu et al. [13] determined the mechanical properties of EPS concrete by comparing the compressive, tensile and flexural strength of EPS concrete with different sizes of EPS particles. They concluded that the mechanical properties of EPS concrete are related to the size of the EPS particles and the granule content.

Xu et al. [14] used wood fibers that are produced by wood waste (e.g. pine waste) in autoclaved aerated concrete to study their physical and mechanical properties. The results show that increasing the addition of wood fiber decreases the fluidity, the porosity, the swollen height and increases the volume density and the thermal conductivity. Bhardwaj et al. [15] added foundry sand waste in concrete as a partial or total replacement for regular sand to study their mechanical, chemical and physical properties. They found that it is more appropriate to use foundry sand as a partial replacement for regular sand in concrete; moreover, they found that this type of waste improves durability and mechanical properties. Chandni et al. [16] studied the compressive strength of the recycled materials like crushed glass and plastics in foam concrete as a substitute for fine river sand. Fraile-Garcia et al. [17] added rubber particles with different amounts (0%, 10% 20%) in lightweight concrete to study the thermal behavior of building elements. It was found that the thermal behavior depend on the percentage of rubber particles added in concrete and this percentage should be kept below 20% to avoid negative influences on the mechanical properties of concrete for a better thermal insulation capacity. Kus et al. [18] replaced natural aggregates with pumice

stone aggregates to study the hygrothermal performance of hollow concrete block walls . This type of block has good thermal insulation and low environmental impact. The cavities of these blocks perform better in terms of thermal transmission than the solid parts. Meng et al. [19] used different recycled wastes in the production of concrete blocks (recycled concrete, crushed brick, a soda lime glass, ceramic ...) in order to study the common properties of concrete blocks. Prusty et al. [20] examined the different properties of fresh and hardened concrete, durability and thermal conductivity when are mixed with agro-waste. Yan et al. [21] used three types of waste, polypropylene fibers, recycled polystyrenes and recycled glass, as a replacement for fine aggregates by volume or weight of the block, to study their thermal conductivity and the compressive strength . The results show that the use of 100% of the recycled glass as fine aggregates was beneficial for the preservation of the compressive strength, which then leads to a better thermal insulation property of the block. Yao et al. [22] used only solid waste to prepare porous and lightweight concrete pastes which can be ready for use in a short time. Basha et al. [23] studied the mechanical and thermal properties of blocks by replacing natural aggregates with aggregates of recycled plastics. Gil et al. [24] studied the compressive strength, density and dynamic modulus of elasticity of mortar reinforced with sawdust waste. Wang et al [25] evaluated the mechanical performance and durability of the combination of macro polypropylene (PP) fiber and rubber concrete. De Souza Kazmierczak et al. [26] analyzed the mechanical properties of a mortar by integrating the crumb rubber as a partial replacement of the aggregate in the mortars, in quantities of 0%, 2%, 4% and 6%. Feng-Chen An et al. [27] studied the influence of the mechanical properties of concrete on the behavior at the FRP-concrete (fiber-reinforced polymer) interface.

Compared to previous work, our work is focused on the Lebanese concrete hollow block. This block has a special shape which is made up of elliptical and circular cavities. One can find in Lebanon this block with different sizes and shapes. It has several advantages over other blocks in terms of weight, thermal insulation, durability and low cost. The difficulty and the interest of our study are the fully understanding of the convection and the conduction heat transfers and also the mechanical behavior of this kind of concrete hollow block that contains several cavities of different shapes. In this work, three different types of waste materials are incorporated into the Lebanese hollow block and a comparison of the thermal and mechanical properties of these different mixtures with each other and with the normal block is undertaken. This research completes the works of Sassine et al. [28], [29], and [30] studying the thermal performance of the Lebanese traditional concrete hollow block and the EPS concrete Lebanese hollow blocks experimentally and numerically as well as the effect of bulkheads on the thermal and mechanical performances of concrete hollow blocks. In this work, the mechanical and thermal properties of concrete blocks are simultaneously determined for studying the effect of different types and concentrations of waste aggregates incorporated into these blocks. A special attention is also attributed to the economic evaluation of the proposed samples.

2 Experimental protocol

2.1 Samples preparation

Sawdust, crumb rubber, and polystyrene were provided by Lebanese local providers and then filled inside 0.5L bottles as shown in Fig. 1. The bottles were weighed before and after being filled with aggregates using a digital balance in order to calculate the density of their content and keep track of the exact aggregate volume in the blocks later prepared. For each aggregate, three samples were prepared, each containing 1.5L (3 bottles), 2L (4 bottles) and 2.5L (5 bottles) of added waste aggregate, respectively. The blocks were manufactured in a local handcraft facility capable of producing around 100 blocks per hour with a prepared standard mixture of sand, cement and mineral aggregates with a concrete solid volume of 4.8L.

The aggregate mixture for the traditional (normal) hollow block is made of 25% of fine gravel aggregates (4 - 8 mm) and 75% of powdered stone dust (0.5 - 4 mm). One cubic meter of aggregates is mixed with 50 kg of Portland cement and 50 liters of water to form the solid matrix mixture. The composition of the used Portland cement is reported in Table 1.

Component/Ingredient	Percentage range
Portland cement	100
Tricalcium silicate	20 - 70
Dicalcium silicate	10 - 60
Tetracalcium aluminoferrite	5 - 15
Gypsum (calcium sulfate)	2 - 10
Tricalcium aluminate	1 - 15
Limestone (calcium carbonate)	0 - 20
Magnesium oxide	< 1 - 4
Nuisance dusts (particulates not otherwise regulated)	< 1 - 5
Crystalline silica (Quartz)	0 - <1

Table 1- Composition of the Portland cement used in this work

The polystyrene aggregates have a density of 10 kg.m^{-3} , the rubber aggregates have a density of 445 kg.m^{-3} , and the sawdust aggregates have a density of 83 kg.m^{-3} .

Three sets of three blocks each were prepared containing respectively 1.5L, 2L, and 2.5L of each waste aggregate, by thoroughly mixing the waste aggregates with the standard block mix mentioned above. As example, for the 1.5L samples, 1.5L of waste aggregates is added to 3.3L of the standard mix to reach the block volume. Then, the mixture was transferred to the press mold and pressed in the same technique as a regular block: applying vertical pressure to the contents of the mold while vibrating the bloc to release the air and then form a block *40 cm* length, *10cm* width and *20 cm* height. Finally, each block was transferred out of the mold to a sunny location to dry them well. This finally gives nine hollow block samples with different densities.

The respective masses and dry densities of the manufactured blocks are listed in Table 2.

	Aggregates total volume (L)		
	1.5	2	2.5
Mass of the EPS block (kg)	10.5	9.71	9.53
Dry density of the EPS block (kg.m ⁻³)	2187.5	2022.92	1985.42
Mass of the Rubber block (kg)	10.39	9.99	9.28
Dry density of the Rubber block (kg.m ⁻³)	2164.5	2081.25	1933.33
Mass of the Sawdust block (kg)	10.76	10.54	9.26
Dry density of the Sawdust block (kg.m ⁻³)	2241.67	2195.83	1929.17

Table 2- Measured masses and densities of the different tested samples



Figure 1- Phases of preparation of the hollow block samples

A particular attention was accorded to the analysis of the aggregates dimensions by measuring the average diameter of the rubber and polystyrene aggregates, and the dimensions (length, width, and thickness) of the sawdust aggregates (Fig. 2a) using a caliper. As shown in Fig. 2b, the polystyrene beads and the shredder rubber particles present slight variations in their size, while sawdust particles present more random variations in their size.



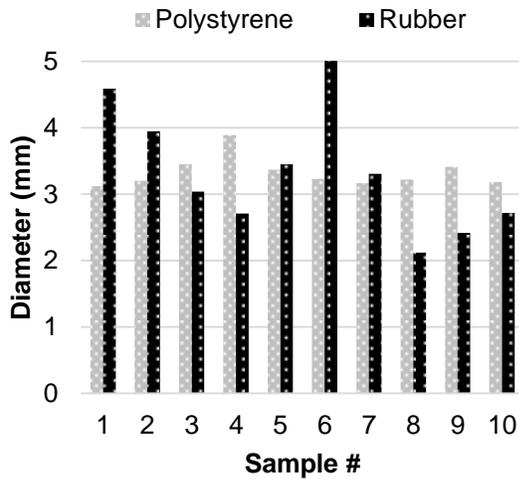
(a)



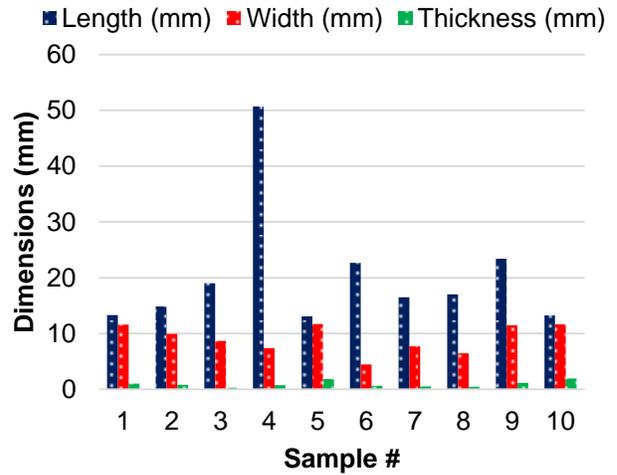
(b)

Figure 2- Average diameters for Polystyrene and rubber aggregates (a) and dimensions of the sawdust particles (b)

The dimensions of ten samples of each aggregate were measured and the results are reported in Fig. 3. The polystyrene particles are homogeneous with less than 0.5 mm difference in size between the measured samples, while the rubber particles are less homogeneous with around 3 mm maximum difference in size between the ten measured samples (Fig. 3a). The average polystyrene diameter is 3.32 mm, and the average rubber diameter is 3.34 mm. The sawdust aggregates are much more randomly sized and have a bigger size reaching around 5 cm (Fig. 3b). The average length is 20.34 mm, the average width is 9.05 mm, and the average thickness is 0.89 mm.



(a)



(b)

Figure 3- Average diameters for Polystyrene and rubber aggregates (a) and dimensions of the sawdust particles (b)

2.2 Thermal experimental setup

An in-house manufactured thermal characterization setup was used to assess the thermal performance of the prepared samples using the fluxmetric method (NF EN 12939 [31]) for the characterization of the thermal performance of the prepared samples. A water tank was heated to 50°C while the other was left at ambient temperature. The hot water is circulated to the bottom water plate via a circulating pump and the tested samples were sandwiched between the two water plates (as shown in Fig. 4); a thermocouple and flux meter were placed directly under the sample and another thermocouple was placed over the sample. The fluxmeter and the two thermocouples were connected to a data acquisition of electronic system to record the evolution of the heat flux ϕ and the temperatures T_1 and T_2 . All the experimental components were placed in an insulated chamber and the tested samples were wrapped laterally with mineral wool insulation material to reduce the lateral heat losses and insure unidirectional heat transfer.

HUKSEFLUX HFP01 fluxmeter was used in this experiment; its sensitivity is $62.5 \mu\text{V W}^{-1} \text{m}^{-2}$, the temperature interval is between -30°C and $+70^\circ\text{C}$, the measurement interval is $\pm 2000 \text{ W.m}^{-2}$, the plate diameter is 80mm, the plate thickness is 5mm, and the weight is 200g without cable.

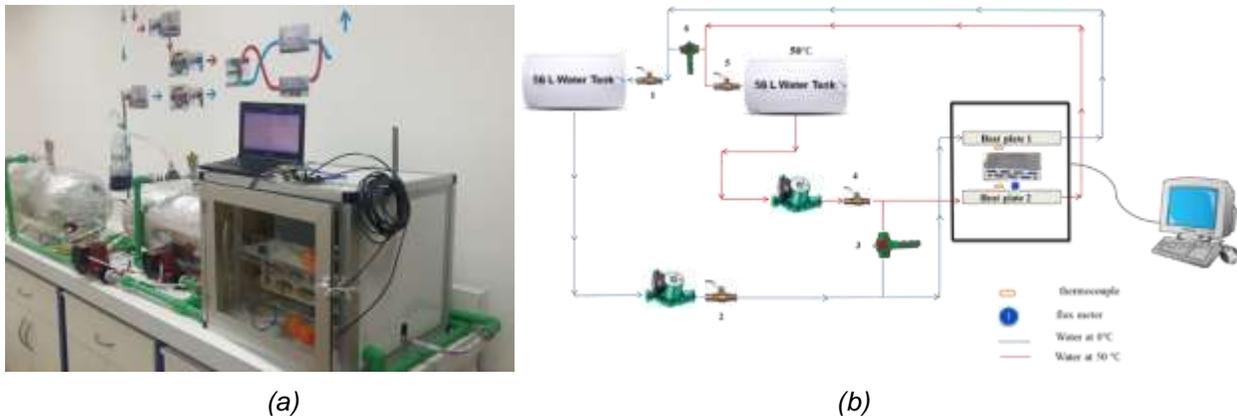


Figure 4- Photography (a) and schematic representation (b) of the experimental set-up

In our experimental work, the tested hollow blocks were laterally insulated to ensure a unidirectional heat transfer flow between the two faces of the block at T_1 and T_2 , such as $T_2 > T_1$ (according to Fourier's law). The following assumptions were considered:

- No heat generation (no energy storage)
- Permanent regime: $\partial T / \partial t = 0$
- Thermal conductivity is constant
- Conduction is unidirectional

The thermal resistance can thus be computed using Fourier law applied to a unidirectional system in permanent mode such as:

$$R = \frac{\Delta T}{\phi} \quad (1)$$

Where ΔT presents the difference in temperature applied to the surface of the sample, ϕ presents the heat flux through the sample (W/m^2); and R is the thermal resistance of the sample ($m^2 \cdot K / W$).

2.3 Mechanical experimental setup

The mechanical strength was also determined for the ten tested block specimens in order to compare the effect of adding aggregates on the mechanical strength of the masonry units [32-34].

The load (N) and the displacement (mm) were recorded while applying a compression test using the hydraulic press (Fig. 5). The principle of the machine is first to determine the density of these samples, then these concretes are subjected to loads to determine the mechanical properties.

The tested specimens are placed between two hardened steel plates as shown in Fig. 5a so that the contact between the plate and the concrete generates as little friction as possible. The compressive load is determined through the integrated hydraulic pressure sensor allowing reading up to 30 metric tons. In addition, the displacement of the specimens (compression) is read through a comparator mounted on the system as shown in Fig. 5b.

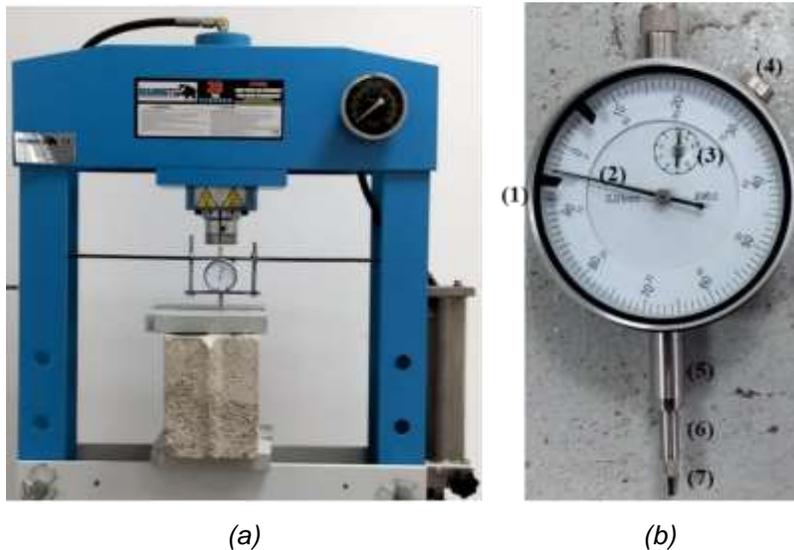


Figure 5- Hydraulic press (a) and comparator (b)

The displacement of the comparator is transmitted to a mechanical device transforming the translation of the rod into the rotation of a needle. This device is made up of a rotating graduated dial (1) allowing the user to materialize the 0 mm point by a simple orientation, the main needle (2), allowing the user to read hundredths of a mm, a totalizer (3) indicating the number of turns made by the needle, a Bezel lock (4) preventing the rotation of the graduated bezel, a fixing element (5) where the comparator fixed in the

support, a sliding probe (6) connected to the mechanism, and the key (7) screwed onto the probe and having a ball at its end.

The faces of the plates are cleaned to ensure that the contact is quite uniform. Then, the dial gauge is set so that the main needle starts at 0mm. The loading speed must be constant throughout the test. Compressive stress is subsequently applied to each sample, with individual force from above and below using a stick that exists in the press (Fig. 5a). Each time the load increases by one unit (1 metric ton), the comparator value is recorded. The experiment is sustained until reaching a limit value where crack develop and the block fails.

3 Results and discussions

3.1 Thermal resistance

In this system at different temperatures, the hotter side gives up heat to the colder one. The heat flow and temperature on both sides of the sample are measured by Arduino. Then the thermal resistance R can be determined using Eq. (1) when the temperature and heat flow conditions are stable, i.e. when reaching steady state.

Fig. 6 shows how the steady state is reached after around 150 minutes (2.5h) from the beginning of the experiment. The steady state can be confirmed when the heat flux ϕ reaches a constant value.

In the normal hollow block example case shown in Fig. 6, the heat flux reaches a constant value of 52.8 W.m^{-2} when $T_1=31.8^\circ\text{C}$ and $T_2=39.5^\circ\text{C}$ which leads to a thermal resistance of $0.156 \text{ W.m}^{-1}.\text{K}^{-1}$ by applying Eq. (1). This value is very similar to that found in the work of Sassine et al [28] ($0.151 \text{ W.m}^{-1}.\text{K}^{-1}$).

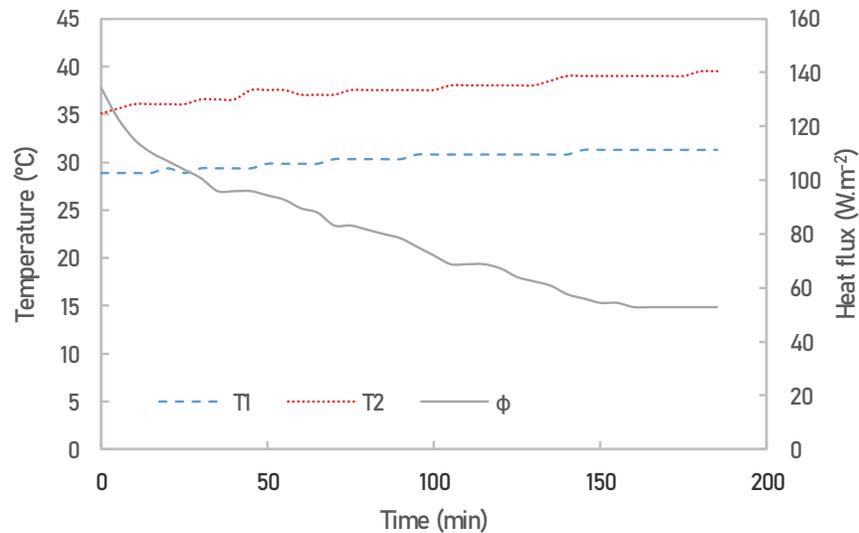


Figure 6- Evolution of temperature and heat flux during the determination of thermal resistance of the normal block

Likewise, the thermal resistances of the nine solid waste aggregate blocks were determined and summarized in Fig. 7.

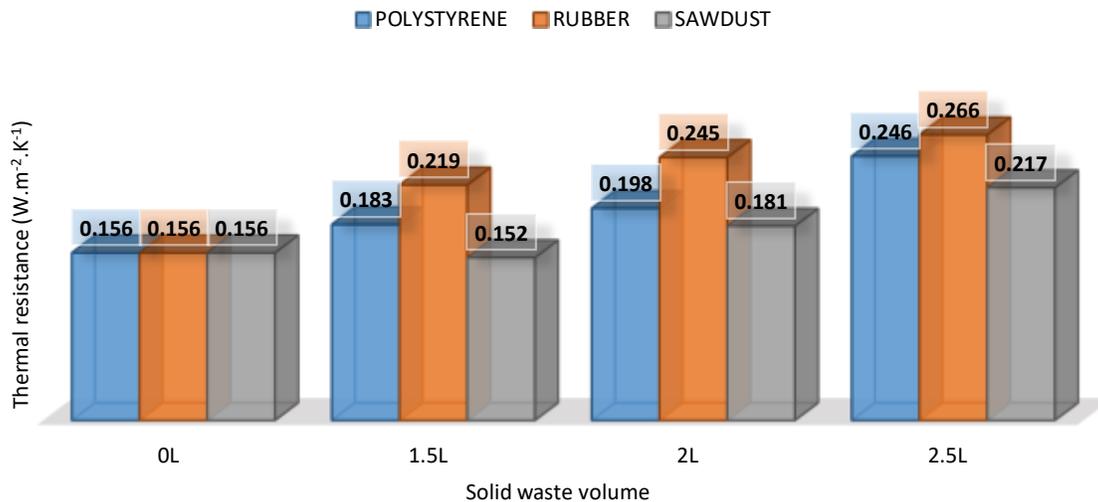


Figure 7- Thermal resistances of the hollow block samples with different aggregate concentrations and different aggregate types

The thermal test results displayed in chart 11, clearly showed that all 3 incorporated materials have led to an increase in the blocks' thermal resistance compared to the normal one, and that criteria kept improving with higher waste aggregate content. This data also shows how the different materials and different volumes of these materials have different impacts on the block. Blocks with crumb rubber had the best performance in the thermal test, whereas blocks containing sawdust were much less efficient: the sample containing 1.5L of sawdust had a slightly lower thermal resistance than the regular block.

Blocks with crumb rubber had the best performance in the thermal test, the sample containing 2L of rubber performed almost identically to the block containing 2.5L of polystyrene, the other 2 blocks containing polystyrene also gave good results, whereas blocks containing sawdust were much less efficient: the sample containing 1.5L of sawdust had a slightly higher thermal resistance than the regular block, and the other two samples containing 2L and 2.5L of sawdust gave nearly identical results as the samples containing 1.5L of polystyrene and 1.5L of rubber respectively.

3.2 Mechanical resistance

3.2.1 Qualitative analysis

Hollow concrete blocks with solid aggregates generally present poor mechanical characteristics. In this part, the mechanical characteristics of the tested samples are qualitatively analyzed. The blocks were loaded with a hydraulic press that deforms the blocks until reaching a total failure. Many small cracks parallel to the direction of loading appeared on the surface of the blocks, that is, horizontal cracks. As the compressive load increases, these cracks will be larger on the surface of the nine prepared samples. The

higher the volume content of EPS, rubber and sawdust, the number of cracks increases. As in the work of Ali et al [35], the increasing the EPS dosage presented more dispersed spalls and cracks. Cracks took the longest to appear, in the case of a normal block and a 1.5L block of sawdust. In the other cases, cracks appeared at approximately the same time.

In rocks and rock-model materials, two types of cracks are observed: wing cracks, and secondary cracks. The behavior of these cracks is represented in Fig. 8d and clearly discussed in the work of Bobet [36].

Wing cracks are tensile cracks that initiate at the tips of pre-existing cracks (flaws) and propagate in a stable manner towards the direction of the maximum compressive stress (in this case the vertical direction). This case is clearly visible in Fig. 8a where a vertical crack propagates from the upper EPS block edge towards its bottom. Soto et al [37] concluded that in most cases, vertical cracks developed in the prisms.

Secondary cracks initiate also from the tips of the flaws, propagate in a stable manner, and have been recognized by many researchers as shear cracks. This case is encountered in Fig. 8b and Fig. 8c for the Rubber block and the Sawdust block respectively. In the case of the Rubber block (Fig. 8b), two neighboring horizontal cracks develop at the facing short edge of the block. In the same way, in the cases of the Rubber block and the Sawdust block in Fig. 8b and Fig. 8c, a crack appears in the rear right corner of the block and propagates in the diagonal direction of the long right edge. Like in the case of Al Tamimi et al. [38], longitudinal cracks were initiated at the shorter side of the hollow blocks. These secondary edges are mainly due to the imperfections in the adhesion of the concrete mixture thus creating some flaws in the block. This will need to be improved in the upcoming research work by improving the concrete mixture in different ways:

- Increasing the cement content in the concrete mixture.
- Add some fine particles into the mixture to improve its adherence such as fly ashes.
- Decrease the size of the aggregates (Solid waste aggregates and mineral aggregates).
- Ensure a better mixing and slightly increase the water content in the mixture for a better homogeneity.
- Ensure that the mold is clean and the block press is working correctly.

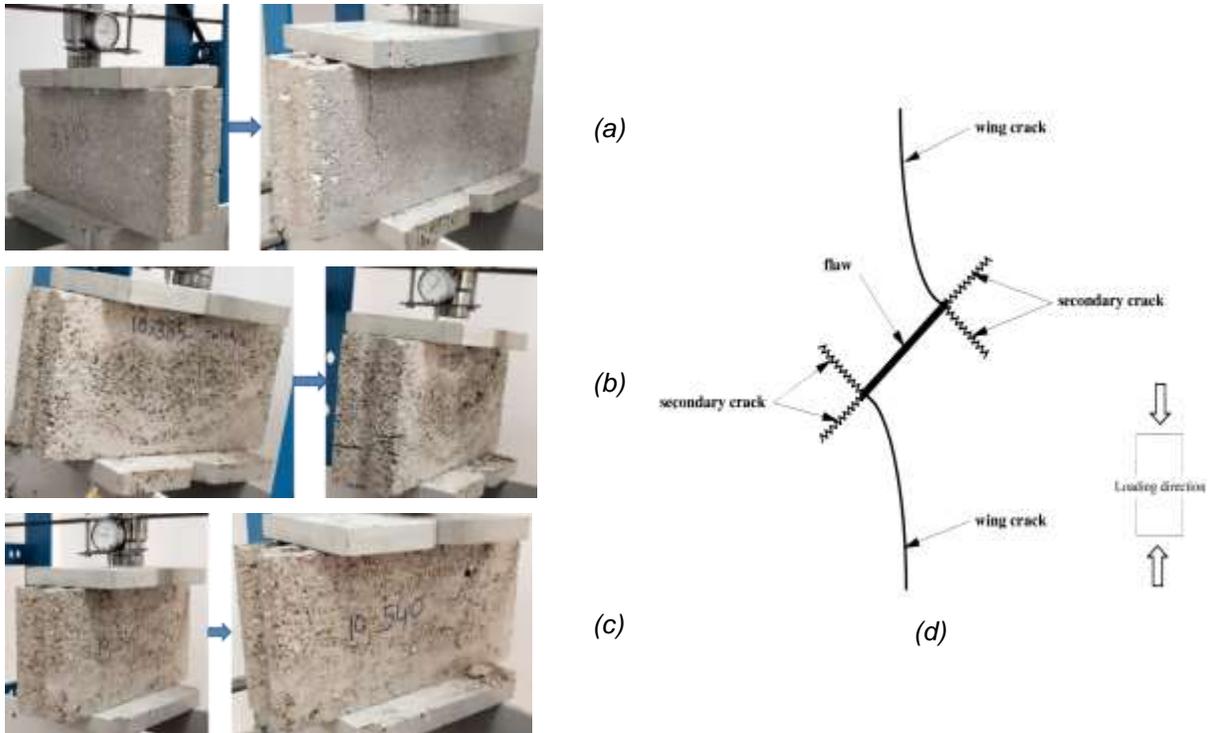


Figure 8- Development of cracks in the EPS block (a), the rubber block (b), the sawdust block (c), and the crack types (d)

3.2.2 Quantitative analysis

The mechanical performance of these blocks is analyzed using the compression test. It indicates the maximum force capacity of the blocks in a simple and effective way. The mechanical properties of the material can be represented graphically by the stress-strain profile or the load-compression profile. This profile can be plotted using;

$$\sigma = \frac{P}{A} \quad (2)$$

$$\varepsilon = \frac{\delta}{L} \quad (3)$$

Such that, σ is expressed in N/mm^2 , P is the compressive force applied in N , A is the cross section on the face of the force in mm^2 , ε is the strain of the considered sample and is dimensionless, δ is the vertical compression or height reduction in mm and L is the height of the sample in mm .

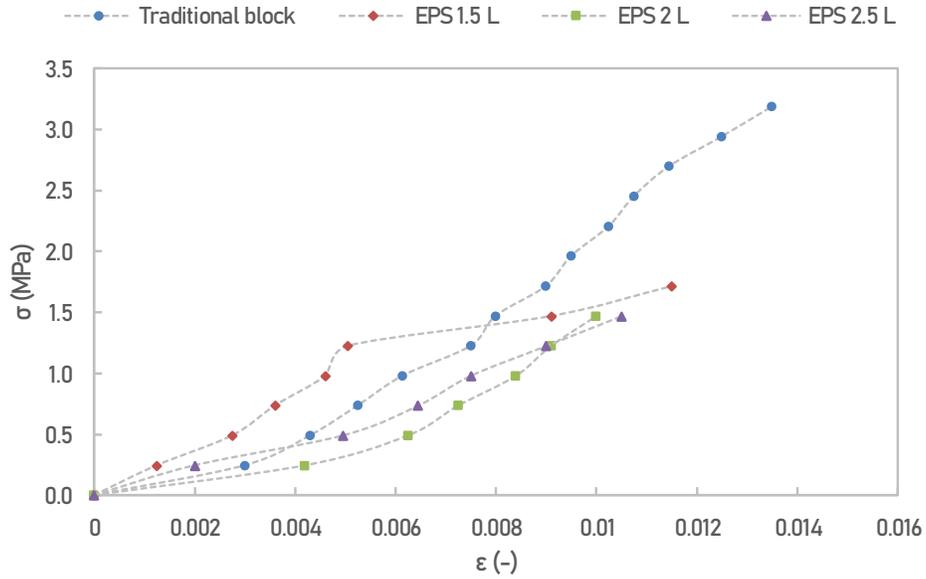


Figure 9- Stress-Strain diagram for the EPS hollow blocks with different EPS aggregate volumes

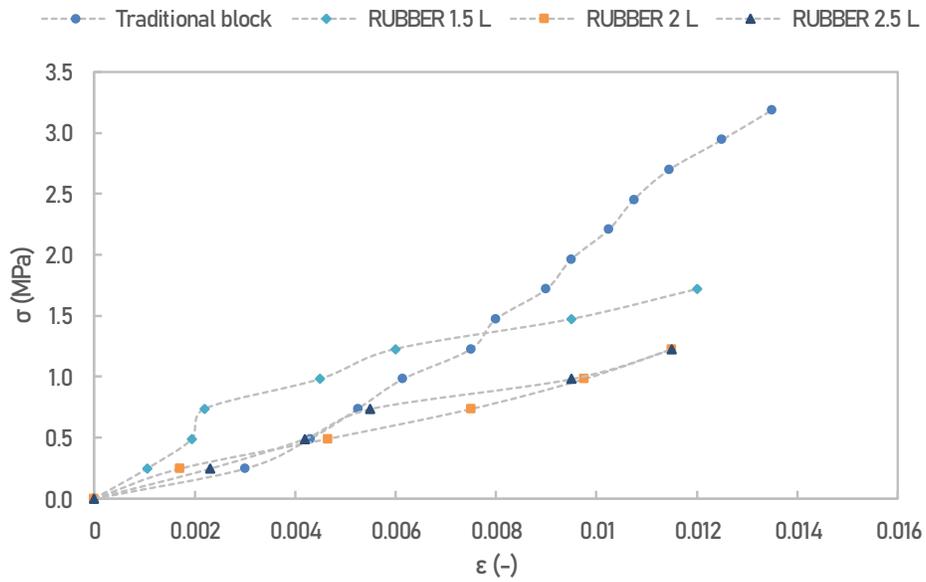


Figure 10- Stress-Strain diagram for the Rubber hollow blocks with different Rubber aggregate volumes

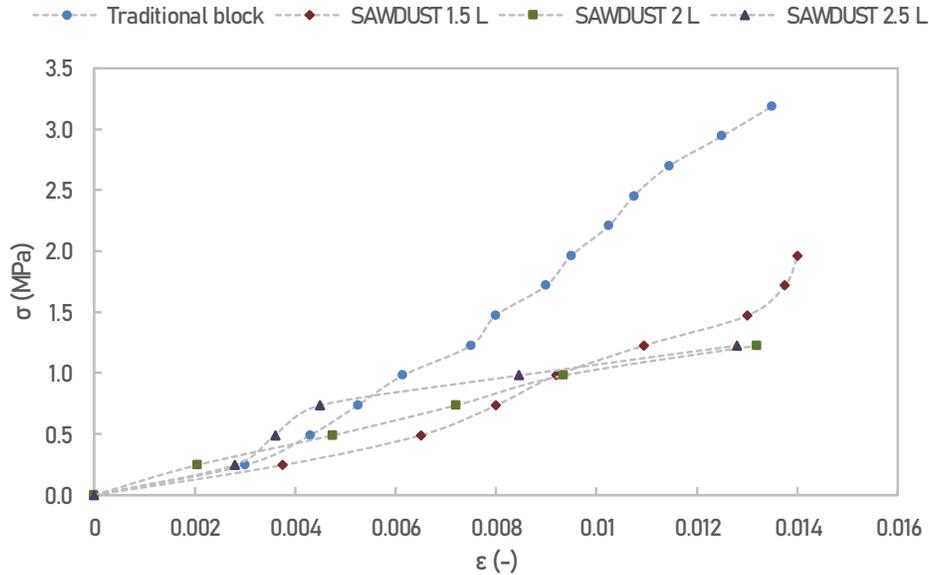


Figure 11- Stress-Strain diagram for the Sawdust hollow blocks with different Sawdust aggregate volumes

Fig. 9, Fig. 10, and Fig. 11 represent the Stress-Strain diagrams for the EPS aggregates, Rubber aggregates, and Sawdust aggregates respectively. In each case, the mechanical behavior of the three aggregates volume cases (1.5L, 2L, and 2.5L) is compared to that of the traditional hollow block.

At the first instant, when the strain ϵ varies between 0 and 0.002, the stress (σ) varies between 0 and 0.5 MPa. At this moment, the micro-cracks inside the concrete remain stable and parallel to the direction of loading. The different samples are slightly compacted. Then, the stress (σ) varies between 0.5 and 1.5 MPa for the different samples, the strain (ϵ) varies between 0.002 and 0.008 for the EPS blocks and 0.002 and 0.01 for the two other cases. Larger cracks are found in all of the blocks and internal cracks start developing. Finally, when ϵ is greater than 0.01, (σ) varies between 1.45 and 1.71 MPa for the EPS blocks, between 1.22 and 1.71 MPa for the rubber blocks, and between 1.22 and 1.96 MPa for the sawdust blocks. At this moment the cracks are much more developed.

The mechanical tests lead to conclude that the strain (ϵ) increases by increasing the stress (σ), until failure. In all the tested samples, the maximum stress at failure (σ_c) was found to decrease by increasing the portion of solid waste aggregates in the concrete mixture. The traditional normal concrete hollow block was thus found to be the strongest mechanically. This leads to give more attention to the mechanical investigation of the hollow blocks integrating solid waste aggregates; the thermal improvement of these block should not compromise their mechanical strength and their usability.

4 Technical and economic evaluation

4.1 Technical evaluation

Fig. 12 shows the compressive strength (Mpa) versus the thermal resistance ($m^2.K.W^{-1}$) for the different tested specimen. The results clearly show that the incorporation of solid waste aggregates into a traditional (normal) block improves its thermal resistance by up to 71% but also reduces its compressive strength between 46% and 61%. It can also be seen that the concretes with the highest compressive strength have the lowest thermal resistance as in the case of normal block and block of 1.5L of sawdust. On the other hand, those with the lowest compressive strength have the greatest thermal resistance as in the case of blocks of 2L and 2.5L of rubber respectively.

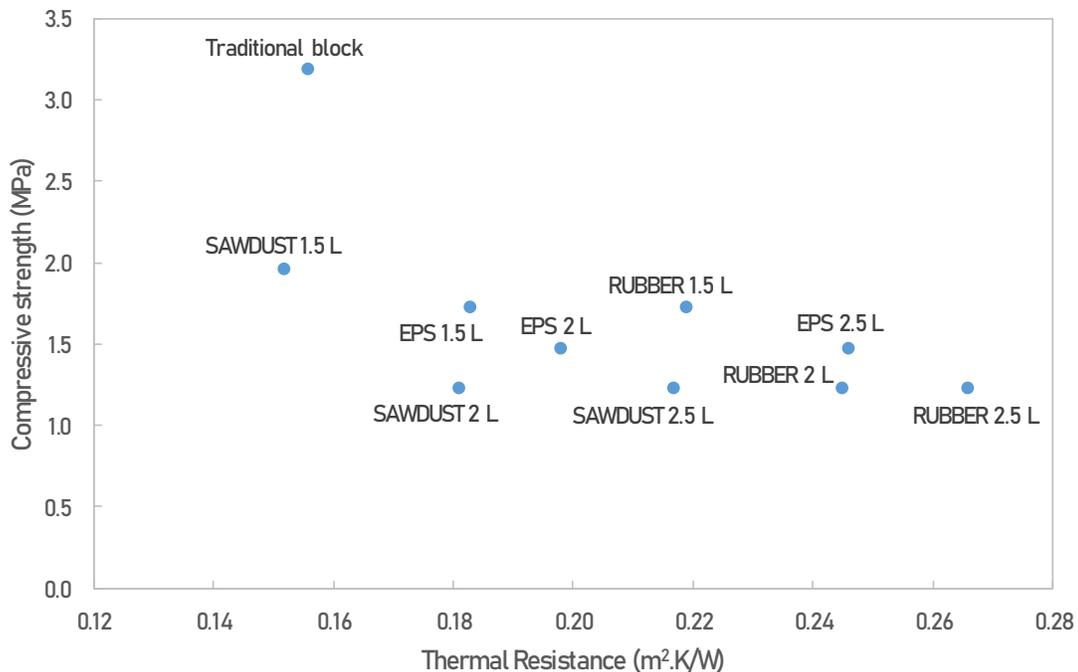


Figure 12- Comparison between the compressive strength and the thermal resistance for the different tested specimen

Table 3 shows how wastes are adding value to the blocks by significantly improving their thermal characteristics over the normal block. The efficiency of the blocks can be translated to a monetary value; the more efficient the block is at preserving an indoor cool temperature in hot summers and an indoor warm temperature in cold winters, the lesser the energy needed to maintain the desired temperature, therefore the smaller the energy bill at the end of the month.

Aggregate volume / Aggregate type	Sawdust	Polystyrene	Rubber
1.5L	-3%	17%	40%
2L	16%	27%	57%
2.5L	39%	58%	71%

Table 3 – Thermal efficiency of blocks containing waste aggregates compared to the standard block (%)

4.2 Economic evaluation

A conventional 10 cm thick normal hollow block masonry unit costs about US\$0.3. In order to estimate the cost of hollow blocks with solid waste aggregates replacements, details about the aggregates cost were collected during a field investigation interviewing different national stakeholders in the Lebanese market. The unit prices for the different aggregates are summarized in Table 4.

Aggregate	Cost US\$ / ton	Density (kg.m ⁻³)	Cost US\$ / m ³
Polystyrene	400	10	4
Rubber	300	445	133.5
Sawdust	250	83	20.75
Mineral aggregate	50	1475	20

Table 4 – Unit cost (US\$) of different aggregates

Hollow Block cost (US\$)	1.5L	2L	2.5L
Sawdust	0.301	0.302	0.302
Polystyrene	0.276	0.268	0.260
Rubber	0.470	0.527	0.584

Table 5 – Block cost (US\$) by waste type and volume content

The estimated costs of the different studied hollow blocks with aggregate are listed in Table 4 based on the data of Table 4. The analysis of Table 5 proves that the modified blocks would still be affordable for the different studied cases. The polystyrene replacements will lead to a potential decrease in the hollow block cost while the sawdust replacement will lead to a very similar cost compared to the conventional hollow block since waste aggregates and mineral aggregates have very similar costs as shown in Table 3. The differences in densities between the Rubber and the other solid waste aggregates explains the significantly higher cost per Liter of rubber aggregates. Based on these findings, the polystyrene aggregates seem to be the most profitable for integration in hollow block manufacturing, due to their relatively low density, their low cost, and their high thermal performance. Sawdust is the second most profitable but blocks incorporating it performed relatively poorly in the thermal test. Rubber, being relatively dense, was the least profitable solid waste aggregate; although blocks incorporating it had the

highest thermal resistance among the three tested wastes, it presented a relatively higher cost compared to the two other options.

The cost of the hollow block unit as function of the type and volume of the solid waste aggregate is shown in Fig. 13. The addition of EPS beads decreases the unit cost by about 0.015US\$/liter, the addition of Sawdust to the hollow block has almost no impact on its total cost, while the addition of Rubber increases its cost by 0.114US\$/liter.

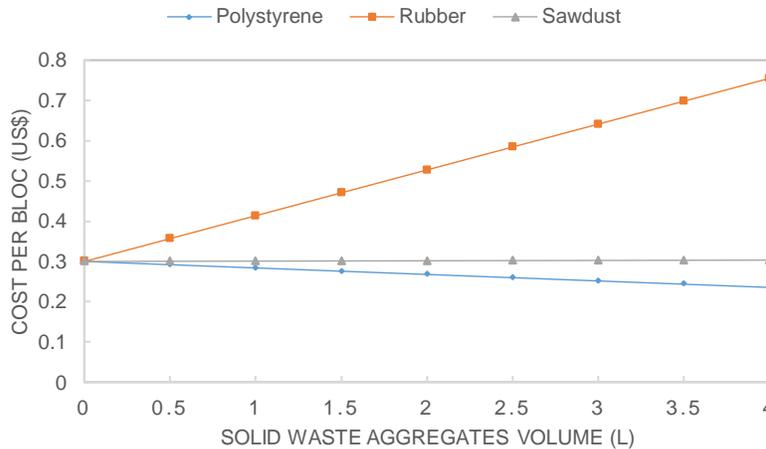


Figure 13- Evolution of the hollow block cost with respect to the solid aggregate volume for the three tested aggregate materials

5 Conclusions and perspectives

This work provides interesting experimental database results allowing to understand the thermal and mechanical impact of incorporating solid waste aggregates in hollow block masonry units using the Lebanese traditional hollow block configuration. This work studied and compared the thermal and mechanical performances of the normal traditional Lebanese hollow block with others concrete mixtures prepared by integrating 1.5L, 2L and 2.5L respectively of EPS, rubbers and sawdust.

Concrete blocks with the highest compressive strength were found to have the lowest thermal resistance as in the case of a normal traditional block and a 1.5L block of sawdust, having 13 and 8 tons respectively. In contrast, those with the lowest compressive strength have the greatest thermal resistance as in the case of 2L and 2.5L blocks of rubber having a compressive strength of 1.23 MPa. These results showed that substantial thermal improvements can be reached by adding solid waste aggregates to the concrete mixture making it possible to tackle the environmental issue of the disposal of some waste materials on the one hand, and the thermal insulation issue of buildings on the other hand by providing an innovative energy efficient sustainable construction material. The mechanical performance was also

experimentally investigated using a hydraulic press and the results were discussed on both qualitative and quantitative levels. The economic and technical analysis favor the use of EPS beads in hollow blocks for their lowest price and satisfying thermal and mechanical behaviors.

The traditional Lebanese hollow block configuration presents miscellaneous practical advantages such as the ease of craftwork demolding, the ease of implementation by being easy to break to obtain fraction of blocks (half block or quarter block), and the ease of creating passages for the pipes and electric cables in masonry walls without crumbling the blocks. The improvement of the solid waste mixture thus allows to preserve these configurations while improving their thermal performance and preventing additional manufacturing cost using solid waste aggregate materials. Furthermore, producing these blocks will not only improve the thermal efficiency of new buildings by improving the thermal resistance of their external walls, but also will lead to a reduction in the amount of unprocessed wastes being sent for landfills due to the unavailable access to recycling and treatment facilities in most Lebanese regions.

The conclusions drawn from this work provide valuable data for improving concrete hollow blocks mixture by highlighting the influence of the mixture composition on the thermal and mechanical performance of concrete masonry hollow blocks.

A better understanding of the mechanical and thermal impact of aggregates on concrete mixtures should be addressed in order to determine the optimal aggregate/cement proportions in the concrete mixture to determine the optimal solid waste ratio leading to the best thermal and mechanical physical properties. Additionally, the thermal and mechanical behavior at wall scale will be addressed on both numerical and experimental levels.

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