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Evaluation of the thermal performance of foamed glass cladding panels in mitigating the cooling load for the buildings in hot dry zone

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Abstract

Excess heat through external walls in the summer time can be eliminated by replacing common cladding sheets by effective thermal insulation panels made of foamed glass. These materials have several interested features as well like: acoustic insulation, water proofing, anti-corrosion, durability and sustainable environmental effects. The current work introduces thermal behavior of foamed glass in reducing the cooling load which has been compared to panels made of plastics that used as common external reflective sheets. The specimens have been processed manually in the labs as well as experimental measurements for man samples of several blowing agent content. The aim is to determine density, porosity, expansion ratio and thermal conductivity coefficient. Images of SEM have been taken for selected samples to recognize the morphology and structure of the foamed glass. The results show that minimum density of the foam was 0.3 g/cm3 at 3% wt of blowing agent, and maximum porosity of the foam was 89%. Also, the thermal conductivity of the foamed glass can be decreased by 90% due to the expansion by 4 times with respect to the solid glass. The cooling load for a typical building that use foam glass panels has expected an energy saving by 41% with respect to the conventional one.

1. Introduction

The Foamed glass is the cellular form of the glass. It is fabricated by heating an amount of glass grains after the addition of a blowing agent, which is usually a chemical powdered formulation. During the melting process, a gas is released from the agent, which is responsible for the foaming in the glass. The product is a rigid material with gas-filled into closed-cell pores with some open cells. The density is between 120-200 kg/m^3. The porosity is usually between 75-90%, with a pore size between 0.4-5 mm. This material has many applications in buildings, pavements, roads, industrial and agricultural. In the building section, the material considers as light weight, high strength, thermal and acoustic insulation, fireproofing and waterproofing [1-2].

Nowadays glass foam manufacturers use about 98% of various glass waste and only 2% of pure glass. The processing begins by crushing the glass into particles, and grinding into a powder less than 0.1 mm size. The powder is mixed with the foaming materials, such as silica carbide (SiC). The glass mixture is then passed through a furnace. The furnace heats the powder to a temperature of 800-900 °C. This causes the glass mass to expand to 2-5 times its original size and it subsequently

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cools and hardens into foamed glass. Usually, 92% of foamed glass is composed of air vacancies. Rapid cooling leads to break the foam into aggregates [3-4].

Regarding the blowing agents, many formulations can be implemented to release gases required for foaming during the heating period. These formulations are classified as redox, neutralization agents and decomposing agents. Redox and neutralization additives include non-oxide materials (carbides or nitrides), while decomposing additives include sulfates and carbonates [5-8].

By reviewing the available studies within this field for the last decade, it can be noticed that majority of the works were experimental based with a number of theoretical studies including mathematical models, numerical analysis or computational processing. However, numerous of review studies [9-14] have been conducted to introduce a general overview upon the development in foam glass in the aspects of processes and applications. They propose some examples of the current applications and available data. The current review studies focus upon various configurations, such as:

- Select suitable methods and procedures to form the glass foam.
- Select suitable combinations of waste or virgin glass materials and their corresponding effects on the glass foam.
- The effect of different blowing agents on the glass foam.
- The effect of melting point and reaction temperature on the glass foam.
- The effect of the released gas on the glass foam.
- The development in the manufacturing and production line.
- Properties of glass foam.
- Applications of glass foam.

The literature involves the applications of foamed glass, especially thermal insulation and soundproofing, with some examples of their thermal and acoustic performances depending on available data. The studies focus upon various configurations for the production of foam glass as aggregates, rocks, bricks, panels and composite materials. These research works included developed suggestions for energy conservation purposes in buildings. They show reliable research works focusing upon the improving in the characteristics. The studies looked into the selecting of proper materials depending on the resultant structure or to satisfy optimum heat insulation features.

There are many research studies involving the manufacture of foamed glass for thermal insulation purposes primarily, and it may be accompanied by other purposes such as sound insulation, waterproofing. Early studies [15-17] focused on the method of preparing and grinding glass cullet, mixing it with a blowing agent, and placing it in the oven in a traditional manner. Subsequent research works [18-23] have dealt with the development of the blowing agent, control of its components and addition ratios, as well as controlling the foaming step. Some studies [24-25] have used microwaves to improve the foaming process. Numerous investigations [26-28] have introduced mathematical relationships to connect between microstructure of the foam and the corresponding thermo-physical properties, as well as certain design parameters; like the compaction ratio [29]. The evaluation of glass foam for practical engineering applications was the goal for some works [30-32]. Recent works still look for developing the composing and manufacturing of foam glass by involving advanced materials combined with the main component (waste glass), such as nanoparticles [33] and aerogel [34]. Some orientations look to combine the glass with ceramic materials that have Alkali activation [35], marble waste [36], general ceramics [37], or even red soil [38]. A few studies suggested mixing the waste glass with ash of agricultural waste such as rice husk [39], and sugarcane bagasse [40].

Thermal conductivity of a foamed panel is related to the pore structure; as the porosity increases, the effective thermal conductivity of a material decreases due to the low thermal conductivity of air comparing to solid material. Also, small pores generally reduce conductivity via convection heat transfer. Pores of polygon shapes have less conductivity than spherical ones [41].

Iraq is located in a hot arid region, where the summer season is extremely hot and long. Therefore, cooling of the building by air-conditioning system consumes the majority of the power supplied. In order to minimize the energy consumption, there is a need to look for ways to enhance the performance of buildings using appropriate and sustainable insulation techniques.

The aim of the current research is manufacturing of foamed glass panel made of waste glass cullet that mixed with certain amount of blowing agents. The contribution of this study includes many factors: the addition of graphene oxide (GO), the processing method and the connection between the foam cladding and cooling load when these panels are suggested as thermal insulation for a typical building in hot air region (Iraq).

2. Materials and Methods

The cullet glass served as raw material for the preparation of foam glass, where pieces of waste glass (broken window glass) have been collected locally. The pieces then cleaned; crushed and sieved to be particles of less than 75 micrometer or mesh 200 (recommended [19]). According to the chemical analysis that conducted by CAC laboratories in Baghdad, the composition of the particles was as follows: 69% SiO_2, 13% Na_2O, 5% CaO, 4% Al_2O_3, 3% K_2O, 3% MgO, 2% BaO, 1% B_2O_3. An amount of the glass particles (95-99 %) is mixed with 1-5 % of the foaming agent (blowing agent). Silicon carbide (SiC) was served as a blowing agent which is commonly used in high-temperature ceramic processing [42]. Furthermore, graphene oxide (GO) nano-powder has been added to enhance the blowing since graphene oxide (GO) acts as a versatile agent in foaming, functioning as a nucleation site and sometimes even generating gas, leading to reduced density, increased strength, and improved thermal insulation in materials [43]. The ratio of GO was 0.5%, which is compensated from the blowing agent content (For example, 3% blowing agent has included 2.5% SiC + 0.5% GO).

The method of obtaining the foamed glass is based on the sintering of the glass particles. The mixture was heated under pressure optimized to 250 kPa [44], and with an initial relative humidity of 40% to ensure better foaming stability [45]. The oven utilized for the study is the common atmospheric Muffle Furnace which is assigned for metals and ceramics. The oven is manually modified to employ higher pressures by connecting its chamber to a compressor. The processing started by putting the mixture of particles in the oven in an ambient condition, and well-closed. The initial pressure inside the chamber was atmospheric. Then the mixture is subjected to a controlled pressure in the oven (200 kPa). As the temperature increased the internal pressure raised reaching approximately 250 kPa. The heating process led to increase the temperature up to 850 °C for 20 minutes (with heat rate of 10 °C/min) to ensure the foaming. After the forming of foamed glass, the pressure should be released to atmospheric pressure again. The sample is left to cool slowly inside the oven to ensure sufficient crystalline structure, and allows the material to develop higher mechanical strength. Figure 1 clarifies the main procedures in the process of the foamed glass.

The total number of specimens is five (one for each blowing agent content) plus the solid glass one (reference). Some undesired samples were ignored due to irregular morphology appeared and arbitrary distribution of the structure. The SEM observation allowed seeing clearly the structure of the foamed glass. In this study, VEGA-II TESCAN device was used to provide SEM images for the samples. This test has been conducted according to ISO 13322-1:2014. The samples have been weighted to determine the mass and corresponding bulk density. The porosity can be measured by subtracting the volume of the porous parts in the foamed sample from the original volume of the reference sample (solid glass). The expansion occurred to the initial glass is also determined.

To measure the thermal conductivity of the foamed glass, the samples were cut into square shapes of 50x50 mm^2 with a thickness of 8 mm, according to ASTM C177 for thermal conductivity test. The sampling required some treatments, such as removing useless ends or smoothening the frames. Thermal conductivity has been measured using MED-103 thermal conductivity meter. The sample has inserted in a space between two sides: hot one connected to the heater and cold one connected to an extension surface. Values of temperatures on the both sides have been recorded at steady-state condition. These values substituted in modified Fourier equation (one-dimensional steady-state heat equation) assigned for this device. The thermal conductivity measurement has been repeated two times for each sample and took the average to satisfy the reliability of the results. The whole steps in the preparation and manufacturing of the samples, as well as the tests have been conducted at the Laboratory of Materials Tests at Mustansiriyah University.

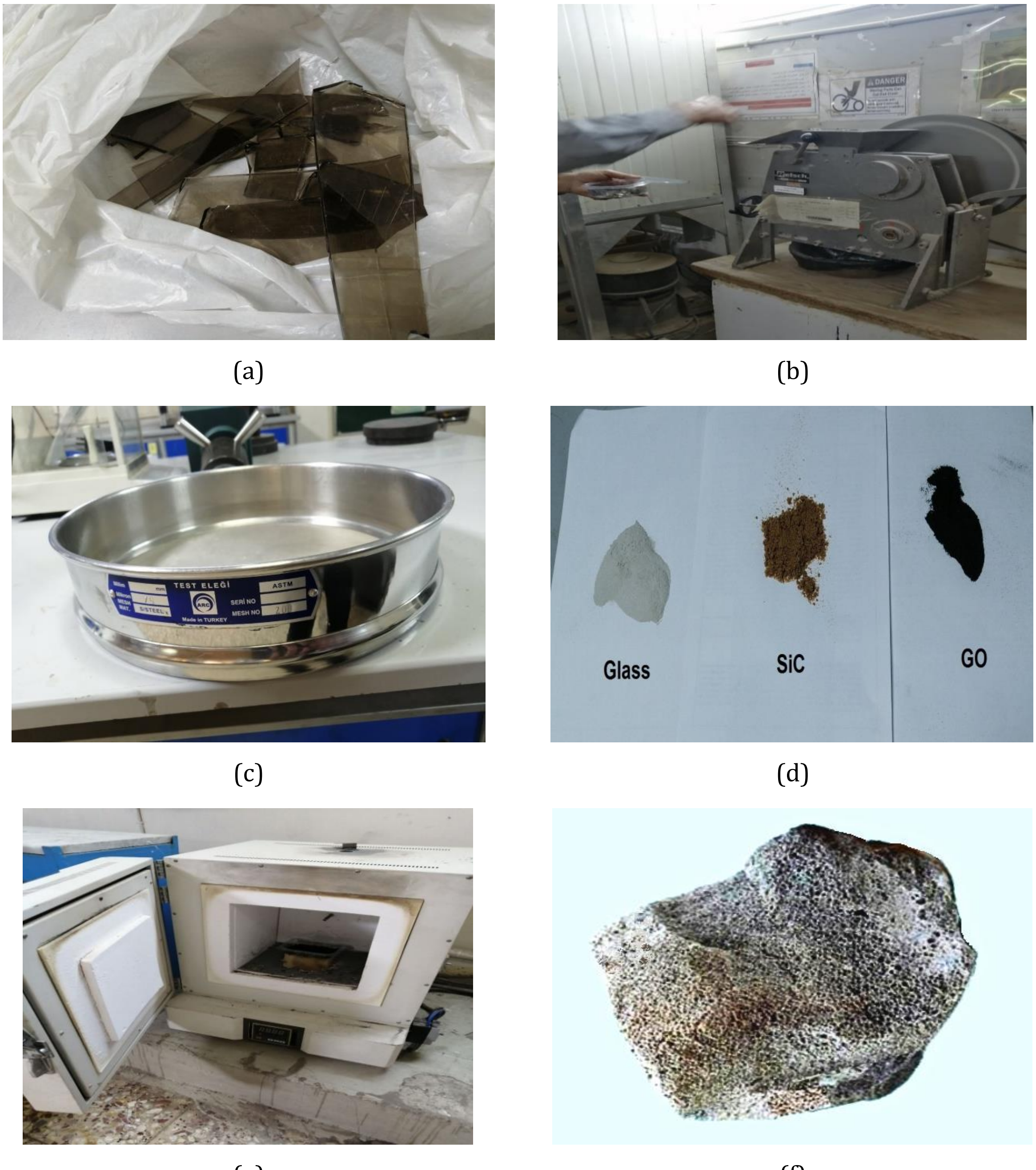
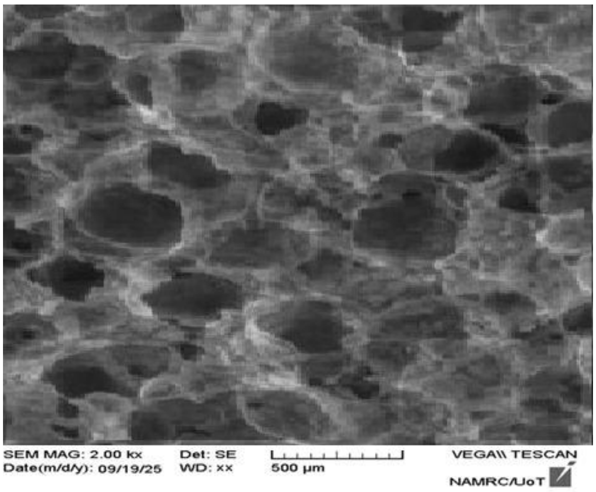


Fig. 1. Process of the manufacturing of the foamed glass (a) Collecting pieces of waste glass, (b) Grinding the glass, (c) Sieving used, (d) Preparation of tiny particles, (e) Heating the mixture in the oven, and (f) Final shape of the foam glass

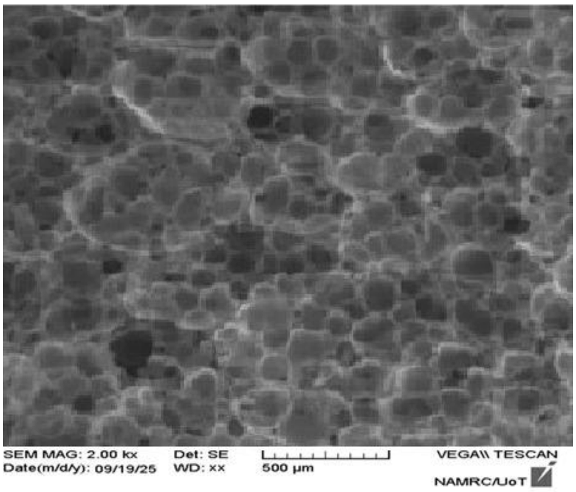
3. Results and Discussion

3.1 SEM Images

The SEM image represents the sample's morphology for internal parts taken from the specimen, as shown in Figure 2 for some samples (1, 3 and 5% wt). Generally, the images illustrate connected crystalline cells characterized as packed and gathered. The structure is quite uniform and clear, and has homogenous distribution with micro-sized pores. Foam glass has many sizes and types of pores and distribution. The large pores are surrounded by medium and small pores. The average size of the pore is about 250 mm. The pores are primarily open-cell with some closed-cells, uniformly spherical (or hexagonal). This is due to the good dispersion of the foaming agent into the melted glass particles and as a result of the small particle size. The regional analysis between the images clarified the variation in cell size and corresponding structures.



(a)



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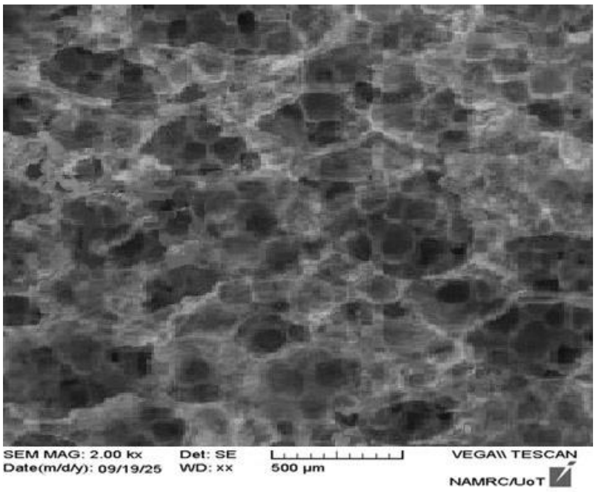

(c)

Fig. 2. SEM images of the foamed glass (a) Foaming agent content (1% wt), (b) Foaming agent content (3% wt), and (c) Foaming agent content (5% wt)

3.2 Porosity and Pore Sizes

The average diameters and distribution of pores in 10 mm^3 volume for the selected samples according to the amount of agent added were computed from the images of SEM, as presented in Table 1. In general, the quantity and the size of the pores have augmented via the rise of the weight percentage of blowing agent, and this can be ascribed to the phenomena of coalescence, which being preferred via a rise in the concentration of blowing agent. Eventually, this lowers the apparent density.

Table 1. Diameters and distribution of pores in 10 mm^3 volume

Sample (foaming agent%)	Distribution	Diameter of pore (μm)			
		<100	100-250	250-500	>500
0%	Quantity	-	-	-	-
	Percentage	-	-	-	-
1%	Quantity	90	25	4	4
	Percentage	74%	20%	3%	3%
2%	Quantity	110	40	5	6
	Percentage	70%	25%	3%	2%
3%	Quantity	150	60	9	6
	Percentage	66%	27%	4%	3%
4%	Quantity	120	45	6	6
	Percentage	68%	26%	3%	3%
5%	Quantity	130	40	5	5
	Percentage	72%	22%	3%	3%

The increase of blowing agent motivates the release of gas due to decomposed moles at elevated temperatures. This raises the internal gas pressure, which aid the expansion of pores [23]. The porosity is the ratio of the volume of air inside the sample to the total volume of the material [46]. By determining the volume of the pores (estimated as spherical shapes), the porosity can be found. Where, this is done by calculating the pore size within the foam and multiplying it by number of pores for each range of pore sizes mentioned in Table 1. For example, the total porosity of 1% wt sample is calculated as:

$$(90x4\pi/3{r_a}^3) + (25x4\pi/3{r_b}^3) + (4x4\pi/3{r_c}^3) + (4x4\pi/3{r_d}^3) = 5.2 \quad (1)$$

Where: r_a, r_b, r_c and r_d are the average radii for each range of pore sizes mentioned in Table 1; i. e., 70, 150, 400 and 600 μm. The result (5.2 mm^3) is divided by the total volume of the solid sample that employed in SEM (10 mm^3), then the total porosity is 0.52 (52%). And so on for other samples. Therefore, the total porosity has increased from 0% for the solid glass to 52, 75, 89, 78 and 66% for the foamed glass with 1, 2, 3, 4 and 5% addition of the blowing agent, respectively.

3.3 Density and Expansion

Before measuring the density, it is important to determine the range of expansion happening to the solid glass due to the addition of the foaming agent. This will give reliability to the resultant value of the density, where the expansion in the specimen is proportional similarly to the reduction in the density as overall. Therefore, the expansion ration was measured for several specimens with the agent contents of (0, 1, 2, 3, 4 and 5%), as shown in Table 2. The dimensions of the solid glass sample under consideration were 100x100x2 mm^3.

The results of the expansion ratio show that the foaming agent takes a significant part in glass expansion. The material is expanded as four times as its original size by adding 3% agent. However, the expansion ratio in the foamed glass could reach to 5 times [17]. Now, bulk density of the samples of the foamed glass was obtained as a function of foaming agent content, as shown in Figure 3. As expected, due to the expansion happened by foaming agent, the bulk density has decreased from (2.4 g/cm^3) for the solid glass to (0.3 g/cm^3) for the foamed glass sample by adding

(3%) of blowing agent. The reduction is attributed to the presence of pores inside the material. This reduction in the density behaves closely to that obtained by other results [15-20]. However, the density of the samples introduced in the mentioned studies can be reduced down to 0.2 g/cm^3 [19].

Table 2. Measured values of expansion due to foaming agent

Blowing agent content (%)	Expansion ratio (%)
0	-
1	128
2	233
3	398
4	270
5	210

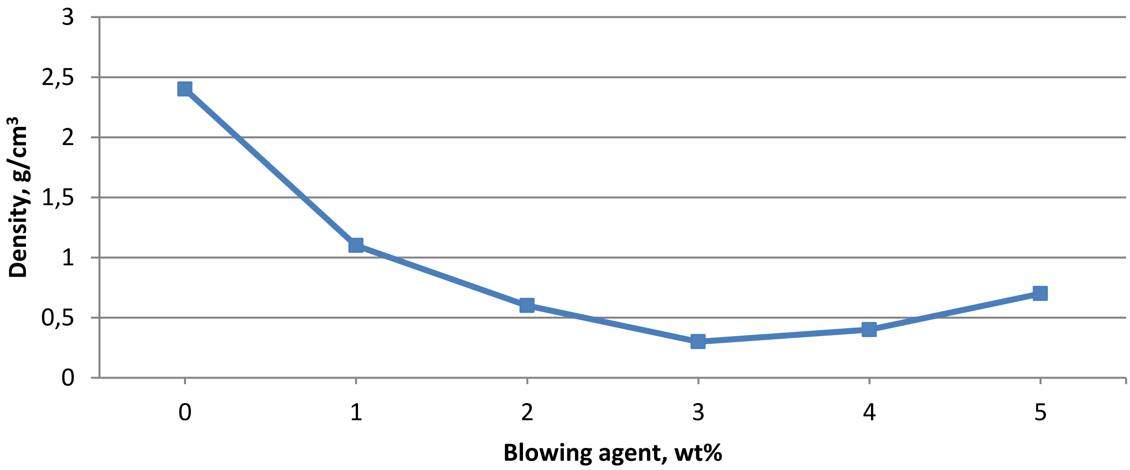

Fig. 3. Density in terms of the foaming content

3.4 Thermal Conductivity

These measurements serve to determine the thermal conductivity of the foamed glass for different combinations. The results of the thermal conductivity (k-value) for the selected specimens are shown in Table 3.

Table 3. Thermal conductivity values

Specimen	Combination	k-value (W/m.K)
1	Solid glass	0.92
2	Foamed glass with 1% of blowing agent	0.31
3	Foamed glass with 2% of blowing agent	0.17
4	Foamed glass with 3% of blowing agent	0.09
5	Foamed glass with 4% of blowing agent	0.14
6	Foamed glass with 5% of blowing agent	0.22

The shown data fundamentally revealed the decreasing in the k-value of the foamed glass comparing to the solid due to the presence of pores. The minimum k-value was 0.09 W/m.K (90% reduction) at 3% content of blowing agent. By increasing the loading of agent content beyond this percentage, the k-value gets higher which is undesirable and out of the goal. The limited decreasing in the k-value beyond this ratio is due the agglomeration of glass particles and thus irregular forming and displacing of pores; which is required to pronounce the reduction in thermal conductivity effective [47]. By looking at the distribution of the pores, it can be seen less generation of small size pores which is necessary to reduce radiation heat transfer [48]. An excessive foaming agent content leads to the increase of water absorption of the sample; thus, the convective heat transfer of the gas phase increases in thermal conductivity term [23]. However, the resources have advised to incorporate blowing agent with a concentration of no more than 2% [18]. Data from sources have shown that k-value can be as low as 0.03 W/m.K [15].

The values of thermal conductivity can be analyzed in perspective to the images taken by SEM as following. In the SEM image for the 1% wt blowing agent content, the structure was less uniform comparing to other images and the pores with different sizes were distributed randomly. The structure has less number of pores, and most of them were small sizes. Therefore, k-value was lower. Note that the air content plays the major role in decreasing the overall k-value of the sample. With the increasing of blowing agent to 3% wt, the structure become more homogenous, and has higher number of pores with small and medium sizes. This will help to satisfy less k-value since air has less thermal conduction that solid material. Beyond this percentage, the structure return to be less organized with less pores slightly. This can be attributed to coalescence phenomena. The thermal conductivity went higher again. Also, the thermal conduction behavior become ineffective due to the presence of relatively large pores which have higher convection and radiation heat transfer comparing to small pores. Note that the quality of SEM images can be affected by accelerating voltage of the beam and spot size during the test [49].

3.5 Comparison

By comparing the results of many studies including the current study, as shown in Table 4, it can be noticed the following points:

- The most effective blowing agents are: Sic, $CaCO_3$, $NaCO_3$ $MnO_2$with some additives like ash, acid and biodiesel. The addition of foaming agent is mostly between (1-5%).
- The furnace temperature is commonly between 700-900 °C. There is once case that temperature was more than 1000 °C [24], and one case the temperature was less than 600 °C [37].
- The values of thermal conductivity usually range between 0.05-0.1 W/m.K.
- The values of density usually range between 0.3-0.5 g/cm^3.
- The values of porosity usually range between 60-90%.
- The values of pore size usually less than 500 μm.

Table 4. Comparison some parameters between selected studies

[Ref.]	Blowing agent (%wt)	Furnace temperature (°C)	Thermal conductivity (Wm.K)	Density (g/cm^3)	Porosity (%)	Pore size (μm)
Current	SiC + graphene (1-5)	850	0.09-0.31	0.3-1	52-89	50-750
[15]	$CaCO_3$(1)	850	0.03-0.05	0.25	85	100-300
[18]	Na_2CO_3(1-7) + biodiesel	850	0.24-0.40	0.47	50	< 500
[20]	$CaCO_3$(1-3) + graphite	850	0.05-0.10	0.3-0.5	75-85	< 50
[21]	SiC (1-2)	920	0.04-0.06	0.25-0.4	50	< 1000
[22]	MnO_2(2.5)	800	0.08-0.1	0.2-0.3	80-90	< 1000
[24]	SiC (2)	> 1000	0.03-0.04	0.2	93	< 1000
[25]	SiC (3.5-4.5)	850	0.05-0.06	0.2-0.25	90	< 900
[27]	SiC (4-5) + coal fly ash	975	0.05-0.07	0.3-0.36	82-86	> 1000
[33]	Nano-carbon (2-10)	700-900	0.11-0.28	0.2-0.3	60-70	< 500
[37]	Boric acid (2)	400-500	0.05-0.06	0.2-0.25	-	-
[39]	$CaCO_3$(6) + rice husk ash	750-850	0.03	0.25-0.3	85	< 500

3.6 Thermal Performance

Energy consumption for cooling of traditional building in extremely hot region such as Iraq might reach up to 725 kWh/m^2 annually [50]. Therefore, effective thermal insulation is necessary. Thermal performance of the foamed glass can be estimated by simulating a typical building in a hot arid region which is insulated with foamed glass and comparing it to a conventional one. A simulation program called Iraq Passive Planning Package (IPPP) adopted locally [51] and based on ASHRAE relations [52] has been used to calculate the cooling load for typical single floor building of 100 m^2 in Baghdad with and without the use of cladding panels. The total cooling load can be determined by:

$$Load = Q_{walls} + Q_{roof} + Q_{floor} + Q_{window} + Q_{door} + Q_{vent} \quad (2)$$

Where; Q represents the heat transfer through a certain element (wall, roof, floor, window and door), and it can be found by:

$$Q = U\ A\ \Delta T \quad (3)$$

Where, U is the overall heat transfer coefficient though the element, and A is the exposed surface area, while ΔT is the temperature difference across the element. The ventilation loses is given by:

$$Q = ACH\ V\ \rho\ Cp\ \Delta T \quad (4)$$

Where, ACH is the air-change in the room per hour. And, V is the volume of the room. Also, ρ and Cp are the density and the heat capacity of air, respectively. Materials, elements and limits assumed during the calculation are listed in Table 5.

Table 5. Features of the typical room assumed to determine the cooling load

Part	Characteristics
Construction	Typical space built of 100 m^2 in Baghdad.
Walls (in to out)	1 cm gypsum, 25 cm Brick and 1 cm cement plaster. There're (3) internal walls and merely one external wall.
Roof (in to out)	1.5 cm gypsum, 18 cm reinforced concrete, 8 cm soil, and 5 cm concrete tiles.
Floor	Marble tiles.
Window	2 m^2 of UPVC frame and south orientation.
Door	2.5 m^2 of wooden structure and internal.
Air quality	The indoor temperature is 24^{o}C, and the ACH for ventilation is 0.8.
Outdoor conditions	The highest range of temperature is within 39-50^{o}C at daytime, and the minimum range of temperature is 23-32^{o}C overnight. Humidity is within 20-45% with average radiation within 750-1100 W/m^2.

The common cladding panels in Iraq are made of plastic cores (4 mm thickness) and covered by reflective layers. The panel should be attached to the external wall by spacing of 5 cm of air gap. These panels can be developed by involving the foamed glass instead of the plastic. The results, shown in Figure 4 revealed that the average cooling load for a typical building in Baghdad in summer months (May to September) is 362 kWh/m^2. By using cladding panels made of foamed glass, the average cooling load will be 213 kWh/m^2. This means that there is an energy saving by 41% comparing to the case without cladding. Comparing with the results obtained from Mussa [53], it is observed that this ratio is higher than that recorded by using of cladding panel made of plastic (33%); and higher than that recorded by using of cladding panel made of wood plastic composite (37.5%). The layering of foamed glass panels will reduce the three forms of heat transfer. Where, there is an additional thermal resistance (2.05 m^2.K/W) due to the presence of 4 mm cladding panel plus 5 cm air gap. The air gap itself removes extra heat transfer by natural convection upward where there are some assigned openings in the frame. Also, the reflective layer on the cladding panel will eliminate the radiation heat transfer up to 20% [54]. Note that the contribution of air gap as well as the reflective layer is included in the simulation.

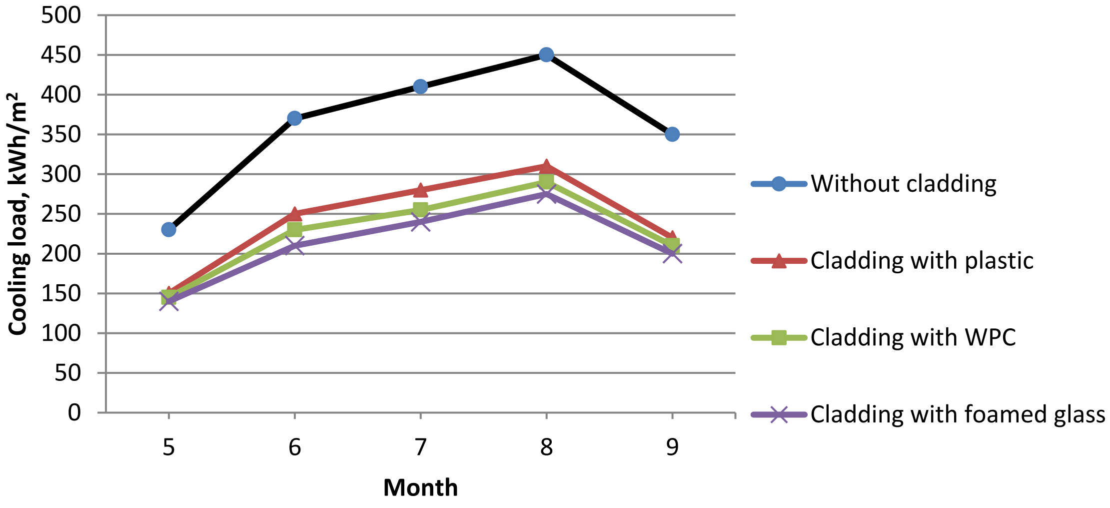

Fig. 4. Comparison of cooling load for different panels during the summer in Iraq

4. Conclusions

The role of foamed glass in the reduction of cooling load in hot arid region (Iraq) is investigated in the current study. Specimens of porous glass were manufactured by the experimental work with many combinations of blowing agent as well as a modified production method. The study included many factors: the addition of graphene oxide (GO), the processing method that employed a controlled pressure and the contribution of the glass foam cladding in the cooling load. Many parameters have been measured in the laboratory, such as: density, porosity expansion ratio and coefficient of thermal conductivity. The morphology of the internal parts of the foam has been analyzed based on SEM images. The thermal performance of foamed glass panels has been compared with common panels made of plastics that used for cladding. The results lead to the following conclusions:

- Minimum density of the foam was 0.3 g/cm^3
- Maximum porosity of the foam was 89%.
- Maximum volume expansion was almost 4 times its original volume.
- Minimum k-value was 0.09 W/m.K (reduction by 90% comparing to solid glass).
- Optimum ratio of blowing agent was 3% including 0.5% of graphene oxide. This ratio satisfied the minimum density and thermal conductivity.
- The cooling load for a typical building that use foamed glass cladding panels has expected an energy saving by 41%, which is higher than that recorded by using of plastic cladding (33%).

Furthermore, future works may consider many factors such as: the behavior of foamed glass with the variation of temperature or humidity, durability of the layers, performance of sound proofing or fireproofing, and mechanical features. New technologies can be implemented in the process like 3D printing [55]. Note that the main limitation of the current work is the consideration of the foamed glass as cladding panels for the building. Also, foamed glass is a highly brittle, rigid cellular material, and it easily cracks or breaks under stress, therefore it should install carefully.

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