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Experimental analysis of thermal insulation performance in concrete blocks integrated with recycled rubber crumbs

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A B S T R A C T

This paper presents an experimental investigation of thermal insulation in rubberized concrete blocks, where the fine aggregate size was replaced by rubber crumbs at varying ratios (0%, 10%, 20%, 30%, 40%, and 50%). The rubber crumbs used in this study ranged in size from 0-1mm, 1-3mm, and 2-4mm. A mixing ratio of 4:2:1 was employed, and simulated solar energy at a rate of 500 W/m^2 was applied to the outer surface of the test samples. Heat flux sensors were installed on both the internal and external surfaces to measure transient heat flux through the samples, while K-type sensors were used to measure surface temperatures. The samples were placed in an adiabatic room with an open front side for testing. The results of the study indicate that the addition of rubber crumbs to the concrete mixture improves thermal insulation properties, as evidenced by a decrease in thermal conductivity corresponding to the volumetric substitution ratio of rubber crumbs with the volume of sand in the sample. Particularly, a 50% incorporation of rubber crumbs led to a substantial 76.2% reduction in thermal conductivity, indicating the effective thermal insulation provided by rubberized concrete. These findings hold significant implications for energy conservation within the building sector, where the use of rubberized concrete can contribute to improved energy efficiency and reduced heat transfer.

1. Introduction

One sustainable solution to address the accumulation of tire waste and its detrimental impact on the environment and human health involves the development of thermal insulation by integrating tire waste with building materials. This integration aims to reduce energy consumption in the building sector, which represents the largest consumer of energy. In Iraq, the building sector consumes over 74% [1] of the total energy. Notably, In Al-Diwaniyah City for example, the electricity sector consumes 134,093 kW/h of electricity, accounting for 80% of the city's total electricity supply of 167,025 kW/h [1]. Globally, the annual production of automobiles reaches an estimated 1.5 to 1.6 billion vehicles, resulting in approximately one billion tons of tire waste [2]. In Iraq alone, cars exceeded 8 million vehicles in 2020, leading to an annual accumulation of approximately 10 million tons of tire waste [3].

Unfortunately, a significant proportion of these discarded tires are not appropriately recycled or disposed of concrete blocks are widely utilized in construction, and researchers have investigated the incorporation of tire waste into these blocks through various studies. However, most of these studies have primarily focused on examining mechanical properties, with attention given to thermal insulation properties. Piti [4] conducted an experimental study in which rubber crumbs replaced a portion of fine aggregate volume at rates of 10%, 20%, and 30%, and the results demonstrated a noticeable decrease in thermal conductivity, ranging from 0.303 to 0.476 (W/m.K) at 10% - 30%, respectively. Accompanied by a significant decrease in thermal resistance. Another study was done by Alirisa et al[5] utilizing Micro-CT-Scan analysis, which revealed a uniform distribution of rubber particles within the concrete mixture, alongside gaps surrounding these particles, contributing to a 20% reduction in thermal

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conductivity compared to conventional concrete. Mattew et al [6], conducted a study to explore how rubber is accepted within concrete mixtures and measured the time interval. The results indicated a significant time delay and minimal thermal fluctuation due to rubber's exceptional capacity to retain thermal energy. In another experimental study, Yesilata et al [7] built a test room entirely using rubber concrete blocks, replacing the volume with two different types of rubber crumbs. A separate room was constructed using traditional concrete blocks. Over a year, the thermal insulation of both rooms was assessed under real-life conditions. The finding demonstrated a decrease in the inner surface temperature of the rubber concrete block room with a time delay of 3.28 hours, which was lower than the time delay observed in the room built by the traditional block, measuring 2.96 hours. Alaa et al [8] replaced the size of the fine aggregate in the concrete block mixture with rubber crumbs at varying percentages of 5%, 10%, 15%, and 20%. The study observed a reduction in the internal surface temperature by 3 degrees Celsius and an 8.5% decrease in weight. These changes led to a notable increase in thermal resistance and a significant decrease in thermal conductivity. In a different investigation. Alaa and Husam [9] examined the thermal insulation properties of a wall by incorporating recycled rubber in both black and white colors as insulating materials. The experimental results revealed a decrease in the temperature of the inner surface of the wall by 3-4 hours. Additionally, when white recycled rubber was used, the time lag increased by 0.5 hours compared to the traditional wall, whereas the time lag was lower when black recycled rubber was utilized. . Husam and Alaa [10] They studied temperature changes between two sets of perforated brick walls in one of which a powder product from old tires (size 0-1 mm) was filled and embedded in the holes of clay bricks. The samples were exposed to a heat source for 8 hours. The results indicated that the incorporation of this material resulted in a decrease in the internal surface temperature by 2.56°C. Fraile et al [11] investigated the thermal behavior of lightweight rubberized concrete building elements by incorporating rubber crumbs with replacement ratios of 0%, 10%, and 20% in place of fine aggregate. Three closed test cells were constructed and subjected to cooling and heating cycles. The research highlighted the impact of rubber crumbs on the behavior of the cells. Specifically, at a replacement ratio of 20%, the temperature difference between the external and internal surfaces increased by 6.5% compared to the cell with a 0% replacement ratio. Moreover, the temperature within the cell remained constant despite fluctuations in external conditions.

In this work, the effect of volumetric replacement of fine aggregate on thermal behaviour in concrete blocks with recycled rubber crumbs was studied, and the replacement rates used were (10%, 20%, 30%, 40%, and 50%). Where the changes in temperature and the amount of thermal flux transmitted through the wall under test were studied as their effect on thermal insulation and thus reducing energy consumption inside the building.

2. Materials and methods

2.1. Recycling of rubber crumbs

The recycled rubber m that was used in the experiment was obtained from the Diwaniyah Tire Factory (Abraaj Al-Kut Factory), one of the branches of the Iraqi Ministry of Industry and Recycling. It was obtained in different sizes as shown in Table 1. And visually represented in Fig.1. It has two networks of sieves (40 mesh-120 mesh) and conforms to the standards ASTM D6814 [12]. Before use, steel fibers and fabric are removed from them. The specific properties of the crumb rubber used in this study are provided in detail in Table 2.

Table 1. The size of a crumb rubber. [12]

Particle size available
0-1 mm
1-3mm
2-4mm

Table 2. Properties of crumb rubber. [12]

No	Items	Specification	Test method
1	Specific gravity	1.1 to 1.3 gm/cm^3	D0297
2	Ash content	5.0% to 15%	D0297
3	loss of heat	1.0% max	D1509
4	Fiber content	0.5% max	D5603
5	Steel content	0.1% max	D5603
6	Sieve content	90%	D6503

Figure 1. Size of rubber crumbs.

2.2. Rubberized concrete blocks samples

In this experiment, test samples (gravel of small size) were prepared in an Iraqi factory specialized in the manufacture of concrete blocks, following the current Iraqi specifications code [13]. Raw materials such as coarse aggregate (gravel of small size 1-4 mm), fine aggregate (sand washed from salts), and Portland cement were mixed with the incorporation of recycled rubber crumbs by partial replacement of certain percentages of fine aggregate size as detailed in Fig. 2 and Table 3 With all quantities of raw materials remaining constant during mixing for all samples.

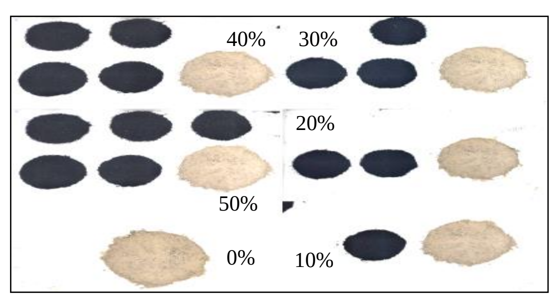


Figure 2. Replacement ratios of rubber crumbs added in block samples according to sand content volume

The rubber concrete block mixture was formulated by employing a water-cement ratio of 1/2 and a specific mixing ratio of 4 parts sand, 2 parts small gravel, and 1 part cement, following the guidelines provided in [14]. After meticulous preparation, the mixture was carefully poured into an iron mold measuring 33cm × 18cm × 16cm. To eliminate any trapped air, the mold was positioned on a vibrating table. Next, the sample underwent manual compression using a piston arm to ensure an even and uniform distribution of the mixture within the mold, as depicted in Fig.3. Once the mold was lifted, each sample was assigned a unique number corresponding to its specific proportion.

Table 3. Replacement ratios of rubber crumbs in block samples based on sand content volume.

Sample No.	Rubber ratio (%)	Rubber volume (litter)	Sand volume (litter)
1	00	0.0	16.0
2	10	1.6	14.4
3	20	3.2	12.8
4	30	4.8	11.2
5	40	6.4	09.6
6	50	8.0	08.0

(a) (b)

Figure 3. Preparing concrete block samples.

Once the samples have been left to dry and harden for 24 hours, they are subjected to a three-day water spraying process. This prepares the samples for practical experiments, as illustrated in Fig.4.

Figure 4. Water spray the rubberized concrete block samples and the final shape of the samples

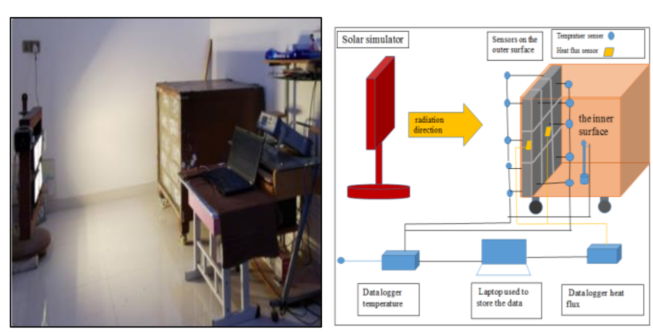
3. Practical experiences

To analyse the thermal behaviour and thermal insulation level of each test sample, an experimental model of an adiabatic room was constructed using plywood as shown in Fig.6a. This form ensures complete insulation and minimized heat loss between the experimental setup and the surrounding environment. One side of the model is designed as a wall, with the test specimens placed on the front surface facing a small heat preservation chamber. To simulate solar energy, a heat source was placed at a distance of 130 cm from the wall, directing thermal energy vertically toward it. An SP-216 solar energy meter was used to maintain a radiation intensity of 500 W/m^2. For measuring temperatures, K-type thermocouple sensors were evenly distributed on the inner and outer surfaces of the wall. Two additional K-type thermal sensors, together with an AT4516 temperature data logger [15] as dictated in Fig.5, recorded the experimental model's internal temperature and the laboratory zone temperature. This data logger is connected to a laptop computer for temperature collection and recording purposes. Heat flux transferred through the wall was calculated using two heat flux sensors connected to a COMPAQ heat flow data logger [16] as shown in Fig.5 which was also connected to a laptop computer for the duration of the experiment. For more details refer to Fig.6-b for a visual representation of the setup.

(a) (b) (c)

Figure 5. (a) A T4516 temperature data logger; (b) Metering solar energy SP-216; and (c) Heat flow data logger COMPAQ.

Before embarking on the experiment, two readings of all sensors were recorded without exposing the sample to solar radiation to ensure that all sensors work perfectly at the beginning of the experiment. The experiment took four hours of heating to bring the temperature of the external surface to a state of stability with a period of stability of an hour and a half and then followed by three and a half hours of cooling.



(a) (b)

Figure 6. (a) The model is under test setup; (b) Schematic diagram showing the devices used and the locations of the sensors within the wall's internal/external surfaces and zone under test.

This cycle was repeated for each sample, and the experiments were conducted in standard conditions, and the data of the thermal sensors were

programmed on the laptop every five minutes and the results obtained were compared with those of conventional samples as shown in Fig.6.
After completing the practical experiences, the data were gathered, and Fourier's law eq. (1) was used to determine the thermal conductivity.

$$q = -K \frac{\Delta T}{x} \tag{1}$$

Where:
q: heat transfer due to conduction (W/m^2)
k: thermal conductivity (W/m.K.)
ΔT: temperature difference across a material section (˚C)
x: material thickness (m)

4. Results and discussions

The results demonstrated a clear inverse correlation between the percentage of rubber crumbs and thermal conductivity. The thermal conductivity values varied from 1.45W/m.K to 0.345 W/m.K, showcasing a significant 76.2% reduction at a volumetric substitution ratio of 50% for rubber crumb with fine aggregate compared to the reference sample. This trend is visually depicted in Fig. 7. This decrease in thermal conductivity can be attributed to the incorporation of rubber particles in the mixture. Rubber particles possess properties such as a low thermal conductivity of 0.05-0.13 W/m.K. and a density of 1300 kg/m^3 when compared with the thermal conductivity of fine aggregate, which is 0.33 W/m.K., and a density of 2110 kg/m^3 according to [17]. In addition to the high thermal resistance of rubber [4], rubber also has the ability to store energy [6]. The thermal conductivity of a compound is influenced by various factors, including the properties and dry weights of its constituent materials as the unit weight of the concrete block decreases with an increase in the volumetric replacement ratio of rubber crumbs with the size of the fine aggregate.

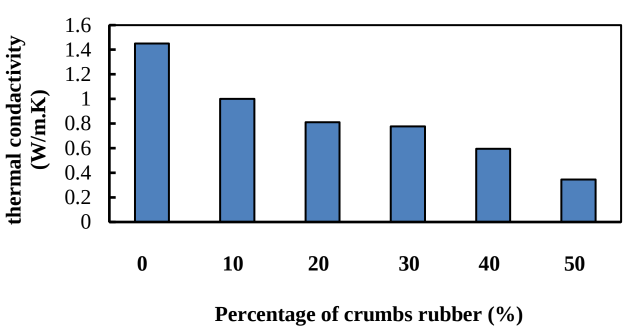


Figure 7. Effect of crumb rubber percentage on thermal conductivity of block samples.

The weight of the concrete block was calculated to be 12 kg when 50% of the sand was replaced with crumb rubber, which is 2 kg less than the reference sample, which weighed 14 kg, thus the density decreases and the ability to absorb water decreases due to the hydrophobic nature of the rubber [18]. The decrease in weight (density) produced a significant inverse relationship between the total weight of the compound and its thermal conductivity. Incorporation of rubber particles into the mixture increased the air content. This can be attributed to the non-polar properties of rubber particles, which have rough surfaces that facilitate air trapping. In addition, the hydrophobic nature of rubber attracts air due to its hydrophobic properties, resulting in air adhering to the rubber particles. This increase in air content, combined with a simultaneous decrease in thermal bridging within the composite matrix, enhances the overall insulating properties of the composite material. Incorporating rubber at a rate of 10% results in an increase in air content of 5%, and this percentage increases to 17% when the addition of rubber reaches 50% [19-20]. It is worth noting that there is a direct relationship between the percentage of trapped air and the size of the rubber particles inside the sample. Moreover, the sample BCR 50% exhibited the least heat flow passing through the walls, measuring at 39 W/m^2, which is lower than by 33% the heat flow observed in the reference sample (BCR 0%), as illustrated in Fig. 8.

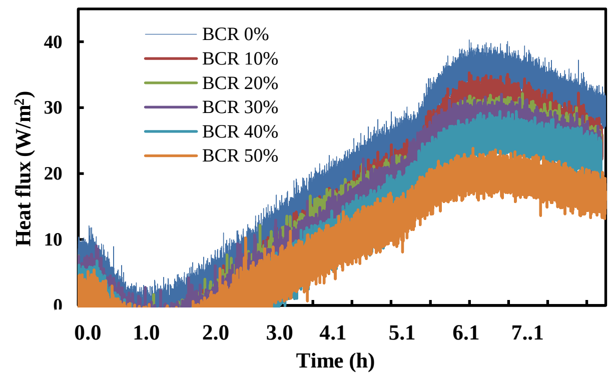


Figure 8. Distribution of heat flux on inner surfaces of various sample blocks.

The reduction in heat flux observed in the study can be attributed to the presence of thermal resistance provided by the rubber molecules. This thermal resistance acts as a barrier, impeding the transfer of heat flux towards the inner surface of the sample. As a result, thermal energy accumulates in the layers adjacent to the outer surface, leading to an increase in the temperature of the outer surface. Additionally, the rubber particles exhibit the ability to absorb and store thermal energy, further contributing to the accumulation of thermal energy near the outer surface.
As a result, an increase in the percentage of rubber particles within the sample corresponds to an increase in the temperature of the outer surface, as shown in Fig.9. The observed temperature difference between the outer and inner surfaces of the material can be attributed to the inclusion of rubber particles, which exhibit notable characteristics, including high thermal resistance, as reported in previous studies [4]. The presence of rubber particles hinders the transmission and conduction of heat towards the inner layers of the material. This thermal resistance leads to the accumulation of thermal energy in the layers near the outer surface, thereby causing an increase in the temperature on the outer surface of the sample. The relationship between the percentage of rubber crumbs in the sample and the temperature of the outer surface is direct. The highest recorded temperature, reaching 65°C, was observed for the BCR50% sample, while the reference sample exhibited a temperature of 56°C. The observations from Fig.10 indicate that the inner surface temperature is lowest for the BCR 50% sample, with a difference of 6.9°C compared to the reference sample BCR 0%. This decrease in inner surface temperature becomes more pronounced with an increase in the percentage of rubber particles within the sample. The temperature reduction on the inner surface reached as low as 32°C for the BCR 50% sample. The primary reason behind this temperature decrease is the presence of rubber particles, which possess low thermal conductivity and high thermal resistance to heat flux. These properties inhibit the propagation of heat waves within the wall and enable the absorption and storage of thermal energy. Additionally, the presence of air gaps surrounding the rubber particles further contributes to the low thermal conductivity.

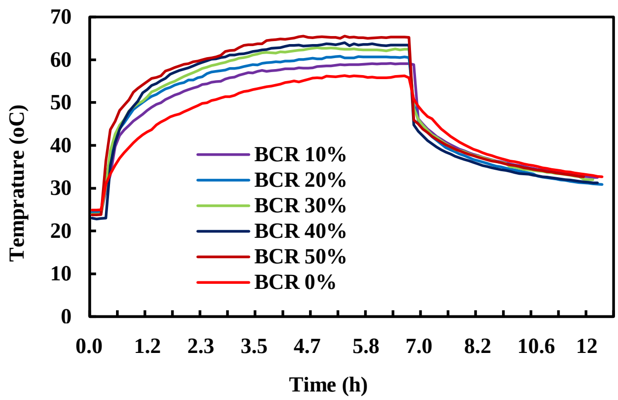


Figure 9. Temperature fluctuations on the outer surface of the wall sample built from blocks with different rubber ratio.

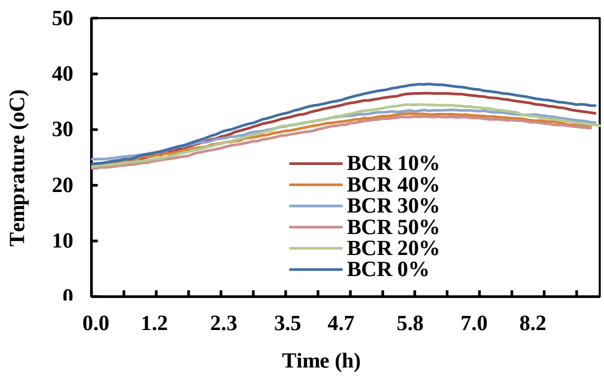


Figure 10. The wall inner surface temperature variation for walls with different rubber content.

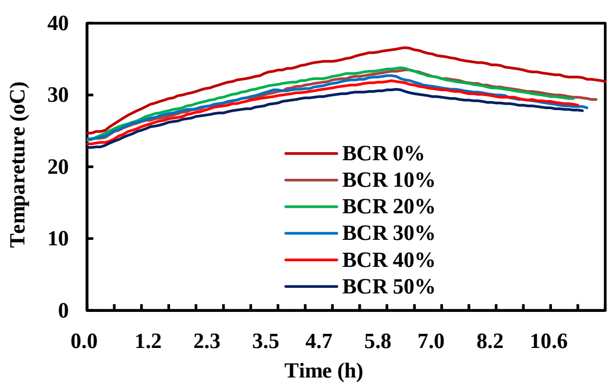


Figure 11. Air temperature variation for the box zone for walls with a different rubber content.

Consequently, these factors collectively reduce the thermal conductivity of the wall, enhance thermal insulation, and result in a decrease in the internal surface temperature, thereby promoting energy efficiency in the building sector. As depicted in Fig. 11, the temperature inside the small adiabatic box decreases with an increase in the percentage of rubber particles in the sample. This indicates an improvement in the thermal insulation of the wall, resulting in a reduction in the temperature inside the small adiabatic box. The incorporation of rubber particles in the sample enhances thermal insulation and reduces the thermal conductivity of the wall. With a higher percentage of rubber particles, the thermal insulation increases. The lowest recorded temperature inside the box was observed at 50% rubber particles, measuring 32.3ºC, compared to the reference wall, which recorded a temperature of 36.4ºC. This temperature difference of four degrees Celsius provides effective thermal insulation within the building, leading to reduced energy consumption.

5. Conclusions

- The incorporation of recycled rubber crumbs in concrete blocks improves their thermal insulation properties, as evidenced by a decrease in thermal conductivity with an increase in the replacement ratio of rubber crumbs with fine aggregate. The lowest thermal conductivity of 0.345 W/m.K was achieved when 50% of the fine aggregate (sand) was replaced with rubber crumb, resulting in a substantial 76.2% reduction in thermal conductivity compared to the reference sample. Additionally, the temperature inside the thermally insulated box experienced a decrease of 4°C, further indicating the effectiveness of the rubberized concrete blocks in providing insulation.
- There is a clear correlation between the percentage of rubber crumbs in the sample and the temperature of the outer surface. The BCR50% sample recorded the highest temperature of 65 °C, whereas the reference sample had a temperature of 56°C. This indicates that as the percentage of rubber crumbs increases, the temperature of the outer surface also rises.
- BCR 50% exhibited the lowest temperature on the inner surface, registering a notable difference of 6.9°C compared to the reference sample BCR 0%. The decrease in the inner surface temperature becomes more prominent as the percentage of rubber particles in the sample increases. Interestingly, the inner surface temperature reached a remarkable low of 32°C at BCR 50%.
- The heat flux exhibited a notable reduction of 33% when 50% of the rubber crumb was used as a replacement for the fine aggregate, in comparison to the reference sample.
- Incorporating rubber rubble into building insulation offers a sustainable solution that not only reduces energy consumption but also contributes to the preservation of the environment and conserves natural resources used in the production of concrete blocks.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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