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THERMAL CHARACTERIZATION OF CONCRETE MASONRY UNITS MANUFACTURED USING RECYCLED TIRES AS AN AGGREGATE

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ABSTRACT

The low thermal insulation capacity of concrete masonry blocks motivated the researchers to investigate the impact of adding recycled crumb rubber that came from scrap tires as an aggregate replacement in the concrete masonry unit production. Using the scrap tire rubber produced more sustainable construction units by using recycled materials and reduce the buildings energy consumption. An experimental investigation was conducted to explore the energy efficiency and thermal characterization effects of adding different ratios of crumb rubber as an aggregate replacement to concrete masonry units. Two different tests were performed, according to both ASTM standards C1363–11 and D5334–14, to find the thermal conductivity factor, energy saving, and thermal insulation for the whole masonry units and the new material itself. A guarded hot box was fabricated to simulate a real insulation case. The results indicated that adding the crumb rubber to masonry units had a positive impact on the energy saving. Units with 37% rubber replacement ratio reduced the energy consumption by 48% compared to a conventional masonry unit. A modified thermal needle probe procedure was used to find the thermal conductivity of the rubberized masonry blocks as a material, not a unit. The new rubberized material exhibited a remarkable reduction in thermal conductivity compared to many commonly used standard construction materials. The mechanical characterization and dimension requirements were reported to show that the new eco-friendly masonry units met the ASTM requirements for load-bearing concrete masonry units.

KEYWORDS: *crumb rubber, thermal conductivity, masonry, rubberized*

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INTRODUCTION

Global warming and climate change have increased the demand to produce and use more sustainable and energy efficient construction materials. Despite the importance of the concrete masonry unit (CMU) as a construction material, it is still generally produced by using conventional materials like mineral aggregate and Portland cement. The construction industry uses the largest amount of materials by weight compared to other industries in the United States [1]. Using these materials has a negative impact on the environment. The negative contribution of these materials comes from two sources. The first source is the impact of the production process. For example, 5% of oxygen dioxide emissions on the planet comes from the cement production industry[2]. Most of the activities associated with aggregate extraction and processing are responsible for increasing environmental devastations. This industry contributes negatively by increasing noise, dust, and impacts on surface and groundwater. The increase in desertification is related to the steady alternation of landscapes and habits. The second negative contribution is the high energy consumption of buildings that were constructed using these materials. Hence, a pressing need exists to produce eco-friendly construction units that use sustainable and energy efficient raw materials. Using crumb rubber as an aggregate replacement in concrete masonry unit production is one approach toward using sustainable materials with the potential to provide better thermal insulation.

Crumb rubber taken from scrap tires can be utilized as a replacement for aggregate in CMUs. The Rubber Manufacturer's Association reported that 233.34 million scrap tires were generated in the U.S. in 2013. Significantly, over the last 20 years, the constructive use of scrap tires has accelerated. This use alleviates the deeply rooted tire dump issues by dropping the stockpiled tires from one billion in 1992 to 75 million tires in 2013 [3]. Scrap tires are considered harmful waste because they leach harmful toxins into the environment. They serve as a home for mosquitoes, rats, and snakes. In addition, they are a tremendous fire hazard. Once a tire pile catches fire, it is very hard, if not impossible, to extinguish. Burning waste tires emit dangerous toxic gasses, such as CO, NO_2, SO_2 and oil runoff, that could result in severe pollution problems. Furthermore, two gallons of oil could be produced from each burned tire.

Historically, crumb rubber has been used in the construction field in the pavement. Arizona Department of Transportation started a project to use crumb rubber as a part of concrete pavement in 2001. They used 35 Kg. of crumb rubber for each cubic meter of pavement. They obtained a compressive strength of 22.5 MPa in one year [4]. A wide range of research has been devoted to investigating the impact of adding crumb rubber to different types of concrete. A clear reduction was noted in the unit weight of rubberized concrete as a result of the rubber particle's low specific gravity and increased conjugated air contents. Rubberized concrete provided sound and heat insulation, a higher sound absorption, a higher noise reduction coefficient, and lower heat transfer properties, according to reports [5-7]. Both load-bearing and lightweight rubberized masonry hollow blocks can be produced to meet the standard using rubberized concrete [8-10]. Fadiel, A., et al [11]tried to improve the thermal resistance of concrete mixtures by investigating the optimum crumb rubber replacement ratio that would give the least thermal conductivity. They noted that the size and amount of crumb rubber influenced the concrete thermal properties. Thermal characterization of masonry units made out fly ash and wood fiber was studied[12]. Al-Jabri, Hago [13] reviewed the attempts to use by-product materials (vermiculite and polystyrene beads) to improve the thermal insulation properties. They compared the thermal insulation of three types of concrete blocks. They noted that polystyrene beads improved the thermal insulation of the blocks when it was used as lightweight aggregate.

MATERIALS AND EXPERIMENTAL PROGRAM

Recycled crumb rubber was used as an fine aggregate replacement to produce masonry blocks with four different volume replacement ratios of rubber (0%, 10%, 20%, and 37%). All of the blocks were manufactured in a masonry plant in Jefferson City, Missouri using the standard manufacturing process for producing a rubberized concrete masonry block (RCMU). The aim of this study was to investigate the thermal characterization of RCMUs. Two different tests according to both ASTM standards C1363–11 and D5334–14 were performed to determine the thermal conductivity factor, energy savings, and thermal insulation for the whole masonry units and the new material itself. Finally, the thermal characterizations of RCMUs with different rubber ratios were compared with conventional and lightweight concrete masonry units.

Material characterizations

All materials used in this research were sampled and tested according to the appropriate ASTM standard test methods. The results gathered during the materials property tests are listed in Table 1. The rubber particles that were used during this study had three different sizes (Fig. 1). The grout was sampled and tested according to ASTM C1019–13. The mortar was sampled and tested for compressive strength according to ASTM C270−12a.

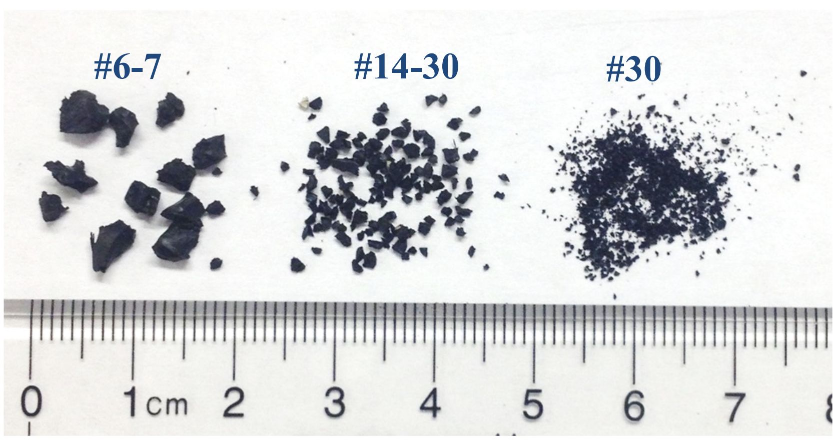

Figure 1: Different sizes of crumb rubber used in production of RCMUs

Table 1: Material properties

Items	Tests type	Results (MPa)	ASTM limits
Mortar	Compressive strength ASTM C109/C109M-13	19.44	Type S 12.4 MPa
Grout	Compressive strength ASTM C1019-13	29.23	14 MPa
RCMU	Compressive strength ASTM C140–14b	0% rubber 29.87 10% rubber 25.26 20% rubber 15.4 37% rubber 6.66	13.1 MPa
Rubber	Unit weight	640 kg/m^3	---------

TEST SET-UP AND INSTRUMENTATIONS

Thermal needle probe procedure

This test was performed according to ASTM D5334−14 using a transient heat method. This test measures the thermal conductivity using a metal probe that contain both heating source element and temperature measuring element. By inserting the probe in the sample, the heating element raised the temperature with time, and the temperature measuring element recorded the change over a period of time. The temperature decay with time after the cessation of heating was recorded to be included in the calculations to minimize the effects of temperature drift during measurement. The thermal conductivity can be calculated after several heating and cooling cycles. All the measurements and the analysis were performed using a fully portable field and lab thermal properties analyzer (Fig.2). The analyzer uses the transient line heat source method to measure thermal conductivity, resistivity, diffusivity, and specific heat.

This test was designed originally to determine the thermal conductivity of soil and soft rock by inserting the thermal needle probe in the soft material using hand pressure without creating any prior hole. Since it is impossible to insert the thermal needle probe in hard materials such as concrete or masonry using hand pressure, a modified method that used the same technology in ASTM D5334−14 was used. The modification came from using a 4-mm rotary hammer drill bit to create a properly sized pilot hole. Thermal grease was then squeezed up around the thermal probe (Fig.2) before inserting the probe in the hole to assure a full contact between with the thermal needle probe and the tested material. Using thermal grease eliminates any air gaps between the concrete and the probe surface larger masonry due to the drilling action.

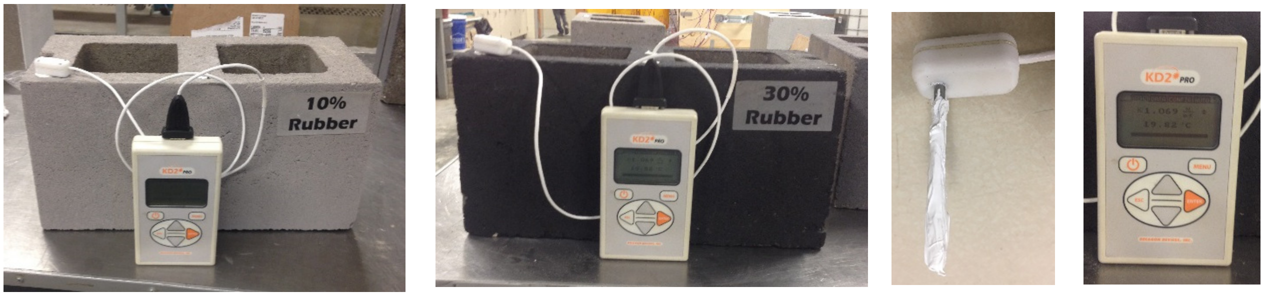

Figure 2: Thermal needle probe test using portable thermal properties analyzer

Due to the geometry of the masonry unit, the test was performed and compared to four different locations. For example, it was expected that the reading in the corners (where the face shell met the end shell) would be different from the reading in the middle of the web.

This method was checked and calibrated by testing materials with known thermal conductivity (Fig. 4a).

The guarded hot box method

A guarded hot box was constructed in accordance with ASTM C1363−11 in order to determine the steady-state thermal performance of building units exposed to a constant heat source. The box was constructed using 12.7 mm thick homogeneous plywood plates. The box was insulated from the inside by 50.8 mm thick Styrofoam with an R value equal to 10 to eliminate any heat loss (Fig.3). All of the parts were glued, tightened together, and inspected to minimize any heat leaks. It was very important to make sure that the expected transferred heat would only go through the masonry unit without any undesirable heat leaks through any gap between the masonry unit and the Styrofoam layer. Therefore, the Styrofoam sheets were shaped and engraved so that the concrete masonry unit fit in tightly, which eliminate any manufacturing tolerance in the masonry units. The tested masonry unit was located on one of the six sides of the guarded hot box. This test represented a close simulation of the thermal insulation of a building. The heat source was kept inside the box to keep the temperature between 45 °C and 55 °C, which represented a very hot weather during the Summer. The temperature outside the box was kept between 18 °C and 20 °C using the lab AC system to represent semi cool temperature inside a building. This test system shows the amount of the saved energy by comparing the power consumption required to keep the temperature between 45 °C and 55 °C using masonry block with varied rubber content. Since the tested masonry unit represented one of the six walls of the box and the consumed power was calculated for the whole box, calculating the energy that was consumed by the masonry unit only was necessary. This was done by using a unit that was fabricated using Styrofoam sheets (Fig.4-a). This unit gave an ultimate insulation with an R factor of more than 30 to find the energy consumed by the guarded box itself to keep the temperature between 45 °C and 55 °C. The energy consumed by the guarded box itself then was subtracted from the total consumption during the test. The energy consumptions were then calculated for rubberized masonry units and compared with the conventional masonry unit.

Fourier heat conduction equation (Eq.1) was used to calculate the thermal conductivity for each type of masonry blocks. The heat flow at steady state was assumed to be the same as the rate of heat output from the heat source. It was computed as 3.41 times the rate of the inputted electrical energy to the heat source. A sensitive meter was used to monitor and record the energy consumption during each test (Fig.3-a) to obtain the most accurate measurement of electrical energy consumption. The inside and outside temperature data were collected using two thermocouple wires that connected to a computerized data acquisition system. During the test, the guarded hot box was checked for heat leaking using a sensitive thermal camera. As shown in Fig. 3c, the heat was escaping out of the box through the tested specimen only.

a b c

Figure 3: The guarded hot box system (a) guarded hot box with energy consumption meter, (b) top view of the guarded hot box with heat source, and (c) thermal image of the test setup

The net exposed area of the tested masonry unit was calculated. The thermal conductivity factor was calculated using the measured heat flow and temperatures on both sides of masonry as follows:

$$k = \left(-\frac{qL}{A(t_1 - t_2)} \right) \qquad \text{Eq. (1)}$$

Where:

k = thermal conductivity, (W/m. °C), L =thickness of specimen at test temperature, m, A =area of specimen, m^2, t_1 =temperature at the inside face of specimen, degree °C, t_2 =temperature of outside face of specimen, degree °C,

q = rate of heat flow through the sample, W/hr. (q is assumed to be the same as the rate of heat output from the hot plate and is computed as 3.41 times rate of electrical energy input to the hot plate expressed in watts).

However, the calculated thermal conductivity factor had to be calibrated. The calibration was conducted by measuring the thermal conductivity of materials with known thermal conductivity. Six different materials (namely, gypsum board, oriented strand board (OSB), rigid foam Insulation sheet, Styrofoam sheet, cement board, and foam sheet in addition to conventional masonry units) (Fig.4-b&c) were tested for thermal conductivity. The relationship between the measured and calculated thermal conductivity was concluded to obtain the calibrated thermal conductivity factor for all different masonry units.

a **b** **c**

Figure 4: (a) Calibration Styrofoam block (b) oriented strand board (OSB) used for calibration (c) gypsum board used for calibration

RESULTS AND DISCUSSION

Two different methods were used to investigate the thermal characterization of rubberized masonry units. The results obtained from each method were not similar in values. However, the general trends were identical for all methods. The reasons behind this difference is one of the methods measures the thermal conductivity for the whole masonry unit, while others examined the solid material itself. Since testing the whole unit will consider the presence of the air cells that interrupt the heat flow path, it is expected to have lower thermal conductivity compared to solid un hollow materials. In general, replacing the conventional materials (cement, fine aggregate and coarse aggregate) by a recycled one (crumb rubber) improved the thermal insulation capacity by increasing the R factor, reducing the thermal conductivity factor, and reducing the energy consumption that required to keep a building in a certain temperature degree.

Thermal needle probe procedure results

As shown in Fig. 5, the impact of using crumb rubber was quite clear. Replacing 37% of the fine aggregate with crumb rubber dropped the thermal conductivity of the material from 1.99 w/m.k to 1.1 w/m.k, which represents a reduction of 45% (Fig.6).

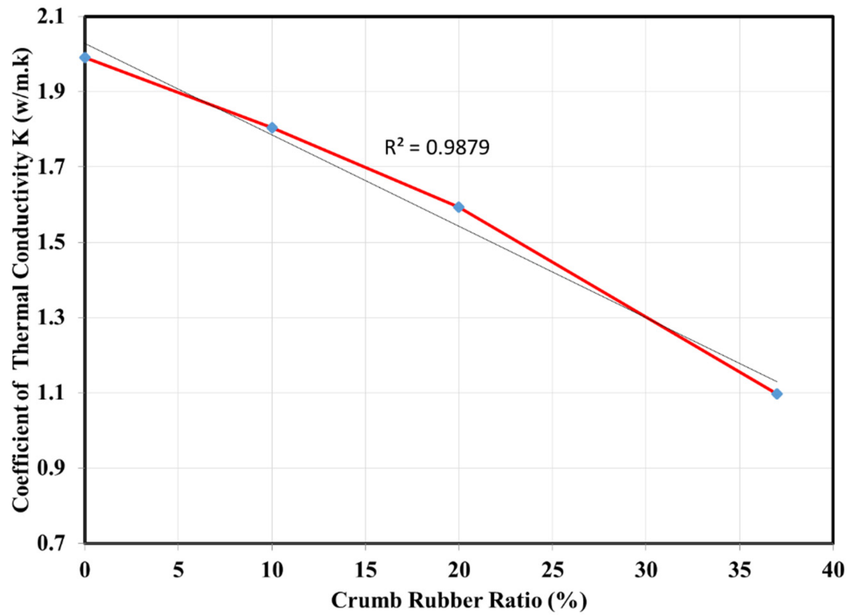

Figure 5: Thermal conductivity factor for masonry block materials with different rubber content using thermal needle probe procedure

The reduction in thermal conductivity was compared with both conventional and lightweight blocks. The relation between the rubber replacement ratio and the thermal conductivity factor was almost linear and consistent. As mentioned before, the measured thermal conductivity factors represented the materials themselves, not the whole units.

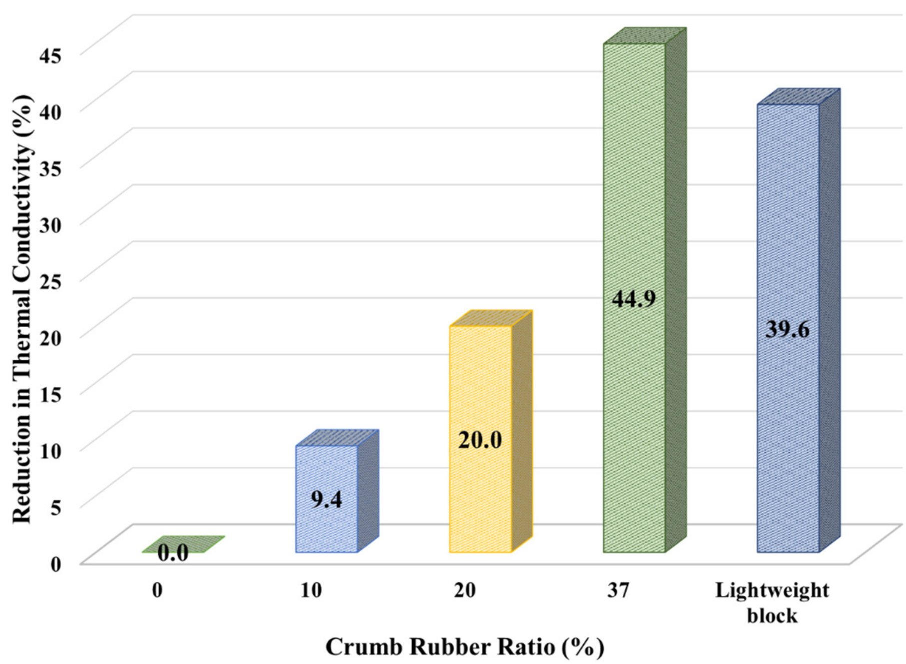

Figure 6: Reduction in thermal conductivity for masonry block with different rubber content using thermal needle probe Procedure

Guarded hot box method results

This method measured the thermal conductivity and the R-value for the whole units rather than the new materials themselves. The device was calibrated by conducting the test on materials with known thermal conductivities (Fig.4-b&c). The result of the calibration was a second-degree equation (Eq. 2) that yielded an R^2 value of 0.9707, which represents a strong correlation between the actual and the experimental measured thermal conductivity.

$$k_m = -0.1269 * \left(k_{exp}\right)^2 + 2.0155 * k_{exp} - 0.1584 \qquad \text{Eq. (2)}$$

where:

km = the calibrated thermal conductivity value.

kexp = the experimental thermal conductivity value.

As shown in Fig.7, the impact of using crumb rubber was very clear. Replacing 37% of the fine aggregate with a crumb rubber reduced the thermal conductivity of the whole unit by 34%. The calculated thermal conductivity of the whole unit was smaller than the thermal conductivity of the material itself with the same rubber content. This difference was due to unfilled cells (voids) in the concrete masonry units. These cells were filled with air, which has a relatively low thermal conductivity compared to concrete. Whenever the rubber was involved in the concrete matrix, the relation between the rubber ratio and the thermal conductivity factor was liner. However, a large drop was noticed in the thermal conductivity factor when 10% rubber was used. The reason behind that was the reduction in the thermal convection required to transfer the heat from the concrete face shell to the cells in the middle of the units.

This test was conducted for a standard lightweight block to have a comparison between the rubberized and the lightweight blocks. As shown in Fig.7, the thermal conductivity of a lightweight block was almost same as a rubberized block with 12% rubber content.

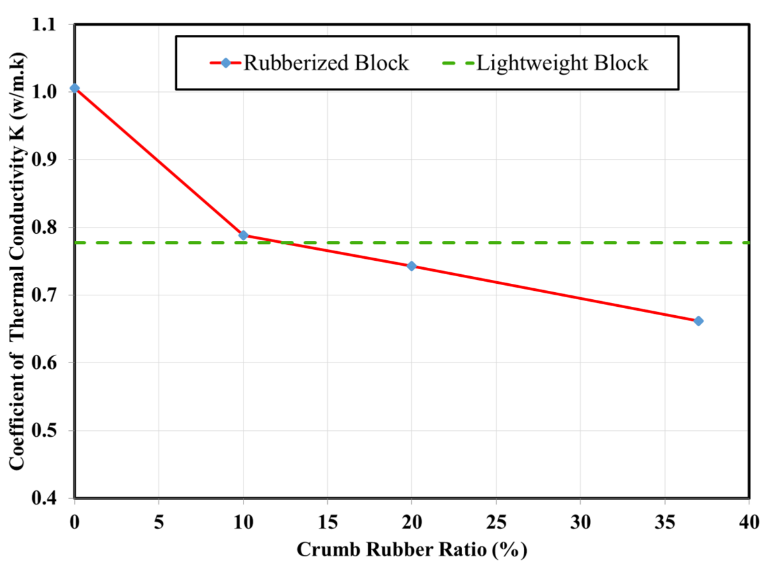

Figure 7: Thermal conductivity factor of different masonry blocks using the guarded hot box method

Energy efficiency eco-friendly block

This test measured the amount of energy that was consumed to keep the temperature inside at 50±5 °C and outside at 18.5 °C for each RMCU and compare it with both conventional and lightweight blocks. Reductions of 26%, 32%, and 41% were achieved when RCMUs with 10%, 20%, and 37% rubber content ratios, were used respectively (Fig.8). Reduction of 28% was recorded when lightweight masonry block was used. These reductions were measured using a constant and continues heating source for 24 hours.

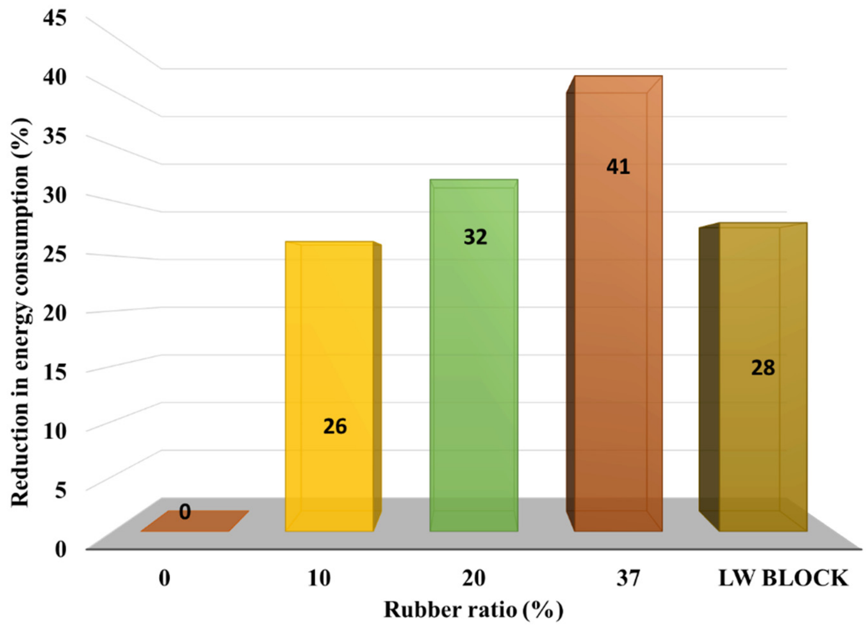

Figure 8: Reduction in energy consumption by using rubberized and lightweight masonry units

CONCLUSIONS

Four different ratios of crumb rubber were examined for the thermal characterization as a partial replacement for mineral fine aggregate in the masonry blocks. The thermal conductivity for both rubberized units and materials was measured. Finally, the energy efficiency for the new blocks was determined. Based on the experimental investigation, the following conclusions can be drawn:

- Crumb rubber can be used as a partial replacement for fine aggregate to produce a rubberized masonry block units that meet the requirements of the ASTM C90.

- The use of rubber in masonry block units has a positive impact on decreasing the coefficient of thermal conductivity for masonry as a unit and material which improve the thermal insulation of the masonry blocks.

- The energy saving was quite clear with using rubber in masonry blocks and it was mostly higher than the energy saving that achieved by using lightweight masonry units.

- The rubberized masonry block units have a lower unit weight that came from the increase of air voids which improves the thermal insulation.

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