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Thermal characterization of cleaner and eco-efficient masonry units using sustainable aggregates

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A B S T R A C T

With 4.5 billion structural concrete masonry units (CMU) been produced in the U.S during 2014 alone, CMU is one of the most important and widely used construction materials. CMUs are still produced using non-renewable natural aggregate which creates pressure on the natural resources and resulted in unsustainable production. Moreover, one of the drawbacks of using CMUs is its relatively high thermal conductivity and low thermal insulation capacity compared to other options such as lumber and dry walls. Motivated by the reasons above, an experimental investigation was undertaken where the mineral aggregate in CMUs was partially replaced by recycled rubber aggregate, manufactured from scrap tires, producing what is called rubberized concrete masonry units (RCMUs). This paper presents the results of the thermal conductivity and the energy efficiency of RCMUs having replacement ratios of 0%, 10%, 20%, and 37%. The thermal properties, including thermal conductivity, time to reach the thermal steady state and energy efficiency, were investigated at the material and unit levels using four different approaches. RCMUs with 10%, 20%, 37% rubber replacement ratio exhibited a reduction in thermal conductivity of 9.5%, 20%, 45% at the material level and 22%, 26%, and 34% at the unit level, respectively. Furthermore, RCMUs with 37% rubber replacement ratio cut the energy consumption by 41% compared to conventional CMUs. Results indicated that the RCMUs are more efficient by cutting both embodied and operation energy as well as it has lower thermal conductivity.

1. Introduction

Concrete masonry unit (CMU) is one of the broadly used construction materials with 4.5 billion structural masonry units been produced in the U.S during the year of 2014 (Pacheco-Torgal et al., 2015). However, the natural aggregate is still the major component of CMU matrix which put more pressure on the depleted natural resources. Furthermore, the cradle-to-gate energy processing of natural aggregate, including the extraction, manufacturing, and transporting, makes the embodied energy of the CMUs is the highest compared to other construction materials such as timber and stone which increase the environmental devastations (Hammond and Jones, 2008; Milne and Reardon, 2005). The high operating energy of masonry buildings also shows a pressing need to develop energy-efficient masonry units to reduce such energy (Cabeza et al., 2013). This paper reports on a study where crumb rubber, obtained from scrap tires, is used as an aggregate in CMUs producing rubberized concrete masonry units (RCMUs), which addresses all the above-mentioned challenges.

Large volumes of scrap tires are readily available in the U.S. For example, the Rubber Manufacturer's Association reported that 242.8 million scrap tires were generated in the U.S. during the year of 2015 alone (RMA, 2016). Tires are bulky, and 75% of the space a tire occupies is void, so landfilling requires a large amount of space. At the same time, tires are not biodegradable, so they serve as a home for mosquitoes, rats, and snakes and they represent a tremendous fire hazard. Once a tire pile catches fire, it is very difficult, to extinguish. Burning waste tires emits dangerous toxic gasses, such as CO, NO_2, and SO_2. Burned tires will also produce runoff oils that could result in severe soil and water pollution

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problems. For example, in 1983, a scrap tire bone yard near Winchester, Virginia caught fire. More than 7 million tires burned for almost 9 months (Poole, 1998). Visibility impairment accrued due to a dense black smoke plume that spread downwind distance for up to 80 km (Fadiel, 2013). In addition, 7.6 L of oil could be produced from each burned tire which creates a pressing challenge to deal with the disposing of scrap tires properly. Most states in the U.S. have enacted legislation that either restricts or bans dumping scrap tires in landfills.

Crumb rubber has been mainly used in pavement within the construction field (Carder and Construction, 2004). Comprehensive research has been devoted to characterize the fresh and hardened properties of rubberized concrete where crumb rubber replaced cement and/or natural aggregates. A reduction was noted in the unit weight of rubberized concrete because of the rubber particle's low specific gravity and increased entrapped air contents. Researchers reported also that there is a rubber content threshold; before that threshold adding rubber will increase slump values due to the hydrophobic nature of rubber which causes a water film coating on the rubber particles that reduce the friction with other particles. Beyond the threshold, the low unit weight of the rubber causes a reduction in slump (Gou and Liu, 2014; Siddique and Naik, 2004; Sukontasukkul and Chaikaew, 2006).

Both the compressive and flexural strengths were negatively affected when crumb rubber was used as one of the constituent of concrete mixture due to rubber's relatively low stiffness and the poor bond between the rubber particles and cement paste (Batayneh et al., 2008; Gou and Liu, 2014; Moustafa and ElGawady, 2016; Najim and Hall, 2010; Siddique and Naik, 2004; Thomas and Gupta, 2013; Youssf et al., 2017). However, rubberized concrete displayed higher energy dissipation, viscous damping and hysteric damping compared with the corresponding conventional concrete (Hernandez-Olivares et al., 2002; Moustafa and ElGawady, 2015, 2017; Moustafa et al., 2017; Xue and Shinozuka, 2013; Youssf et al., 2015, 2016; Zheng et al., 2008). Compared with conventional concrete, rubberized concrete provides higher sound and heat insulation, sound absorption, and noise reduction coefficient as well as lower heat transfer properties (Hall et al., 2012; Sukontasukkul, 2009; Turgut and Yesilata, 2008).

(Yesilata et al., 2011) reported that composite concrete-scrap-tire-pieces walls increased the thermal insulation of a model room by 11%. Using granulated rubber in the concrete of flooring and foundations was enough to have low-rise dwellings meet the UK Building Regulations in term of thermal insulations without the need to any additional insulating layers (Paine and Dhir, 2010). Both the amount of rubber and particles sizes has an impact on the thermal conductivity of rubberized concrete (Abu-Lebdeh et al., 2014). Using larger size of rubber particle in the production of rubberized gypsum board resulted in a better reduction in the thermal conductivity and the same trend was reported with cement mortar as well (Fadiel et al., 2014).

Very few researchers produced both load-bearing and non-load-bearing rubberized masonry hollow blocks (Gheni et al., 2017; Isler, 2012; Mohammed et al., 2012; Sadek and El-Attar, 2015) and rubberized brick (Gheni et al., 2017; Isler, 2012; Mohammed et al., 2012; Sadek and El-Attar, 2015) where mineral aggregates were partially replaced with crumb rubber. It was reported an improvement in thermal, acoustic, and electrical properties of rubberized masonry compared to conventional masonry.

2. Contributions of crumb rubber in the production of cleaner concrete masonry units

Construction activities were the largest consumer of natural materials in U.S. during the last century. By 1998, mineral fine and coarse aggregate production reached 1.12 Gigaton representing 73% of all used natural materials (Horvath, 2004). Therefore, construction activities are responsible for exhausting the environment and natural resources. However, there is an opportunity for reducing the impact of the construction industry on the environment by replacing a small portion of the mineral aggregate with a recycled one. For example, replacing only 10% of the mineral aggregate with recycled materials resulting in cutting of the annual total production of the natural aggregate by 112 million ton. Furthermore, concrete products have the highest embodied energy in buildings, compared to other construction materials such as timber and stone, due to the extraction process of its constituents, manufacturing, and transporting. For example, the embodied energy of concrete is 1.6–14.4 times that of steel, aluminum, copper, timber, plastic, brick, glass, plaster, stone, and ceramic which put another burden on the environment by increasing carbon dioxide emissions (Sajwani and Nielsen, 2017).

Using recycled crumb rubber as a mineral aggregate replacement is one of the alternatives toward a cleaner production of masonry units. Replacing mineral aggregate with recycled rubber potentially will cut both the embodied and operation energy of masonry buildings constructed out of rubberized masonry. Rubberized masonry will reduce the extraction and transportation energy due to its lightweight. Furthermore, it is anticipated that rubberized masonry will reduce the heating and cooling energy use in buildings, which represent 20–24% of the total energy consumed in the world (Papadopoulos and Giama, 2007; Yesilata et al., 2011).

This study focuses on the thermal characterization of RCMUs having rubber contents of 0, 10, 20, and 37% as a partial replacement of natural aggregate. As a preliminary investigation, cement paste mixtures with the same rubber ratios of 0%, 10%, 20%, and 37% were prepared and tested for their thermal performance. The differential scanning calorimetry (DSC), differential thermal analysis (DTA), and thermogravimetric analysis (TGA) tests were conducted to determine the specific heat, the change in the mass under elevated temperature, and the phase transition point. Then, another four tests were conducted to study the effects of rubber content on the thermal conductivity of RCMUs (ASTM C1363) or its material (ASTM D5334) and (CRD-C 45–65), energy consumption (ASTM.C1363), and the time needed to reach steady-state (ASTM C136) Fig. 1 illustrates a schematic overview of the whole paper.

3. Experimental program

Crumb rubber from scrap tires was used as a mineral aggregate replacement to produce rubberized concrete masonry blocks

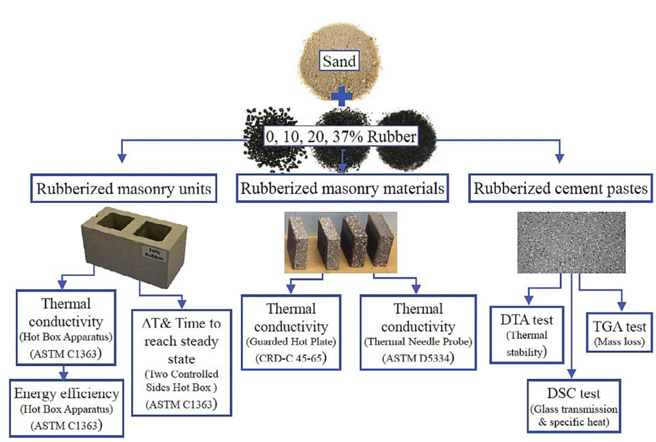

Fig. 1. Schematic overview of the work.