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Mechanical Characterization of Concrete Masonry Units Manufactured with Crumb Rubber Aggregate

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An experimental investigation was conducted to investigate the effects of replacing varying percentages of fine natural aggregates with crumb rubber in concrete masonry units (CMUs), creating rubberized concrete masonry units (RCMUs). The mechanical and physical characteristics of RCMUs having 0, 10, 20, and 37% crumb rubber were investigated and presented in this paper. The unit weight and water absorption of RCMUs were measured. A scanning electron microscope (SEM) analysis was used to study the global structure for RCMUs and the interfacial zone. RCMUs were also exposed to extreme weather conditions for 72 days inside an environmental chamber. Furthermore, RCMUs were subjected to rapid freezing-and-thawing tests. The RCMUs, as well as grouted and ungrouted masonry prisms, were tested under monotonic and cyclic axial loads.

The results indicated that RCMUs with high rubber content displayed higher values of axial ultimate strains. RCMUs exhibited a significant strain softening while, conversely, failure was quite brittle in CMUs. RCMU specimens exhibited an improvement in compressive strength after several cycles of severe weather exposure. The CMU specimens, however, exhibited degradation in their compression strength capacity. The water absorption was higher in RCMUs than it was in the CMU prisms.

Keywords: crumb rubber; masonry; rubberized concrete; sustainable materials.

INTRODUCTION

A concrete masonry unit (CMU) is an important construction material that is widely used around the world. One pressing need for the construction industry is to use more sustainable material. One approach toward achieving sustainable CMUs is to use recycled materials such as crumb rubber, produced from scrap tires, in replacing natural aggregates during manufacturing CMUs. Scrap tires are already available across the United States; for example, during 2013 alone, the United States generated 233 million scrap tires, as reported by the Rubber Manufacturers Association. Scrap tires are considered harmful waste that serves as a home for mosquitoes, rats, and snakes. They also represent a tremendous fire hazard. Once a tire pile catches fire, it is very hard to extinguish. Such fire would emit significant amounts of CO_2 and harmful dioxins into the surrounding environment. Many landfill operators do not accept scrap tires in their landfills. Most states in the United States have enacted legislation that restricts or even bans the disposal of tires in landfills. Using recycled tires as a filler to produce CMUs would reduce the amount of scrap tires placed in landfills. Recycled tires also have the potential to improve the mechanical and physical characteristics of CMUs. Yet, a very few studies investigated the effect of adding crumb rubber to masonry units as a replacement of natural aggregates, producing what is known as rubberized concrete masonry units (RCMUs). RCMUs can be produced as load-bearing and non-load-bearing blocks,[1,2] where the compressive strength of RCMUs is generally smaller than that of their conventional counterpart. While there have been few studies on RCMUs, several studies have been conducted on the fresh and hardened concrete properties from adding crumb rubber to concrete mixtures as a replacement of aggregate and/or cement. It was stated by Robisson et al.[3] that rubber and cement have been successfully combined before without any negative long-term interaction between them. For example, rubber particles have been added to cement to form a self-healing cement system for long-term durability. Rubberized concrete commonly displays smaller unit weight compared to conventional concrete because rubber particles have significantly lower specific gravity compared to natural aggregates. Furthermore, rubberized concrete has generally more entrapped air than its counterpart in conventional concrete. Rubberized concrete also has smaller slump compared to conventional concrete. Furthermore, the use of crumb rubber as a partial replacement for aggregate reduces the compressive strength, flexural strengths, and dynamic modulus of elasticity.[4-10] Damping properties, however, of rubberized concrete are higher than that of conventional concrete. Energy absorption and dissipation increased greatly when rubber replaced natural aggregate in concrete.[11] Recently, researchers proposed rubberized concrete as a structural material in high seismic regions to enhance energy dissipation capabilities—a crucial feature for structures built in high seismic regions.[12] Atahan and Yücel[13] performed drop-weight tests on rubberized concrete cylinders. They determined that replacing 20 to 40% of aggregates with crumb rubber creates concrete mixtures that are useful for concrete barriers panels. Moustafa and ElGawady[14] used free vibration on simply supported beams and static cyclic compression tests on concrete cylinder to investigate the concrete's dynamic properties. They reported that both the viscous damping and the average hysteresis damping increased as the rubber content increased.

Rubber also altered the physical properties of concrete. Rubberized concrete has higher sound absorption, a higher noise reduction coefficient, and lower heat transfer properties

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Table 1—Material properties

Items	No. of samples	Test type	Results	ASTM limits
Mortar	6	Compressive strength ASTM C270-12a	2820 psi (19.4 MPa)	Type S 1800 psi (12.4 MPa)
Grout	6	Compressive strength ASTM C476-10	4240 psi (29.2 MPa)	2000 psi (14 MPa)
RCMU	12	Compressive strength ASTM C90-12	0% rubber, 4332 psi (29.8 MPa) 10% rubber, 3664 psi (25.3 MPa) 20% rubber, 2234 psi (15.4 MPa) 37% rubber, 966 psi (6.7 MPa)	1900 psi (13.1 MPa)
RCMU	12	Absorption testing ASTM C90-12	0% rubber, 6.8 lb/ft^3 (109 kg/m^3) 10% rubber, 8.3 lb/ft^3 (133 kg/m^3) 20% rubber, 9.4 lb/ft^3 (151 kg/m^3) 37% rubber, 11 lb/ft^3 (176 kg/m^3)	13 lb/ft^3 (208 kg/m^3) (maximum)
RCMU	12	Density classification ASTM C90-12	0% rubber, 137.7 lb/ft^3 (2206 kg/m^3) 10% rubber, 132.5 lb/ft^3 (2122 kg/m^3) 20% rubber, 128 lb/ft^3 (2050 kg/m^3) 37% rubber, 119.4 lb/ft^3 (1913 kg/m^3)	Lightweight: less than 105 lb/ft^3 (1680 kg/m^3) Medium-weight: 105 to less than 125 lb/ft^3 (1680 to 2000 kg/m^3) Normalweight: 125 lb/ft^3 (2000 kg/m^3) or more
Masonry prism	50	Compressive strength ASTM C1314-12	Refer to Table 3	—
Rubber	—	Unit weight	40 lb/ft^3 (641 kg/m^3)	—

than those of conventional concrete. As a result, rubberized concrete has a greater ability to retain stored heat energy.[15-17]

The mechanical and physical characteristics of hollow CMUs having 0, 10, 20, and 37% crumb rubber replacement of natural fine aggregate by volume are presented in this manuscript. The compressive strength and ultimate strain under cyclic loads were investigated for masonry prisms constructed out of RCMUs. Both grouted and ungrouted prisms were examined. Masonry water absorption, unit strength, unit weight, and durability of RCMUs were compared with conventional CMUs. Scanning electron microscopy was performed for the different RCMUs.

RESEARCH SIGNIFICANCE

The concrete masonry unit (CMU) is a widespread construction material. More than 4.6 billion CMUs were produced in the United States in 2014 with a nearly 12% annual increase.[18] However, CMUs are manufactured today using conventional materials that have a negative impact on the environment. In addition, CMUs are quite a brittle material. Hence, a pressing need exists to produce CMUs that are more ductile and sustainable. One potential approach toward this good is to replace some of the natural aggregates with crumb rubber produced from scrap tires. In addition, finding a new home for non-biodegradable waste such scrap tire, which is an environmental concern, will minimize their negative environmental impacts.

EXPERIMENTAL PROGRAM

This manuscript presents the results of the mechanical characterization of RCMUs, including unit weight, water absorption, and unit compressive strength. The manuscript also presents the compressive strengths of RCMUs after they had been subjected to cycles of extreme environmental conditions such as freezing and thawing, high humidity, and high temperature. The results of scanning electron microscopy that was performed to study the interfacial zone between rubber from one side and cement paste from the other side, are also presented in this manuscript. Finally, grouted/ungrouted prisms were subjected to cyclic compressive testing and the results are presented. All results are compared to those of conventional CMUs and prisms constructed out of CMUs.

Material properties

Hollow concrete masonry units having 0, 10, 20, and 37% crumb rubber replacement of natural fine aggregate by volume were produced by a masonry plant in Jefferson City, MO, using a standard manufacturing process. These blocks were used during the course of this study. Based on earlier studies,[1,4,11,19] it was decided that a maximum fine natural aggregate replacement of 20% would potentially produce masonry blocks with minimal strength reduction that can be used in structural applications, while higher replacement values may be used for nonstructural applications. Hence, one replacement percentage of 40% was targeted during the mixture design. However, during the mixture process, the final rubber replacement was found to be only 37%.

All of the materials used during this research were sampled and tested according to the appropriate ASTM standard as listed in Table 1. The sieve analyses of the rubber and the fine aggregate that were used for block manufacturing during this research are illustrated in Fig. 1. The mixture of rubber that was used came from three different grades of rubber (Fig. 2). The grout was sampled and tested according to ASTM C1019-13 (Fig. 3). The mortar's compressive strength was sampled and tested according to ASTM C270-12a.

RCMU mechanical characterization

The unit weight, water absorption, and compressive strength of RCMUs were tested according to ASTM C140/C140M-14b. For each rubber content ratio, three individual RCMUs were tested for compressive strength. A fibrous composite laminated cap was used to distribute the load and prevent the stress concentrations. A rigid 24 x 12 x 2 in.

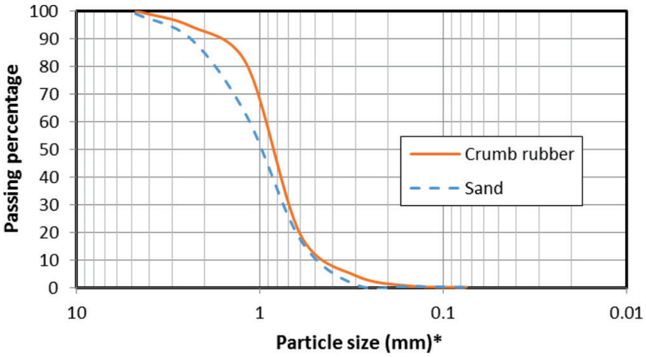


Fig. 1—Sieve analysis of used mixture of crumb rubber.

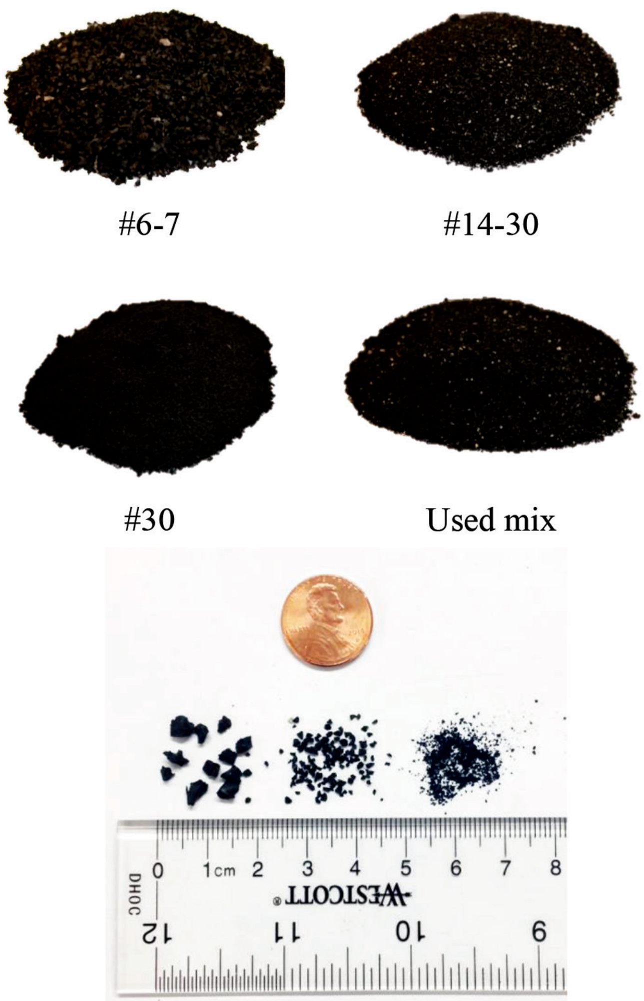


Fig. 2—Different sizes of crumb rubber used in RCMUs production.

(610 x 305 x 51 mm) steel loading plate was used to apply the loads (Fig. 4). The maximum stress was averaged for each rubber ratio. To find the absorption according to ASTM C140/C140M-14b, three RCMUs from each different rubber ratio were placed in an oven at 235°F (113°C) for 25 hours (Fig. 5). Whenever two successive RCMUs weighed at intervals of 2 hours showed an increment of loss not greater than 0.2% of the previous weight, the weight of the specimen was determined. The samples were then left outside the oven until they reached room temperature so that the oven-dry weight

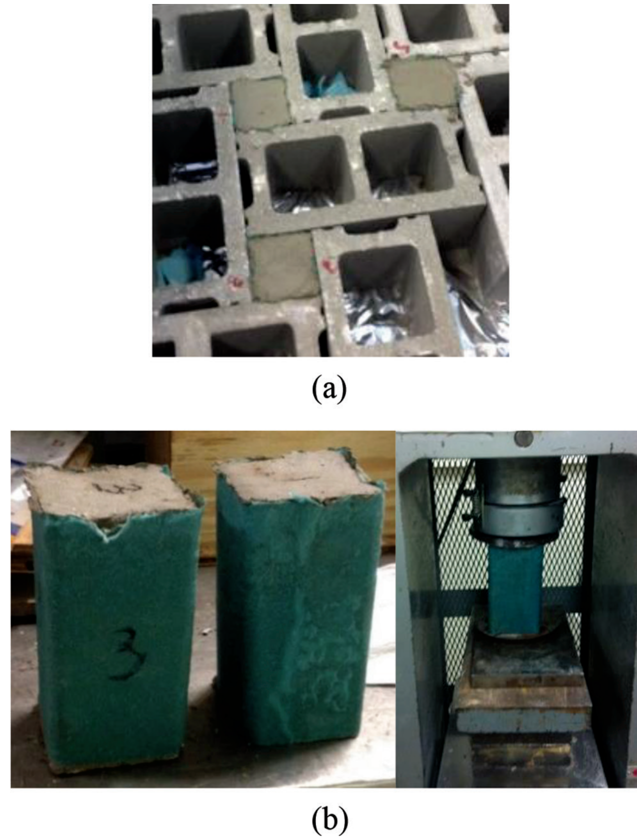


Fig. 3—Grout specimens.

Fig. 4—Compressive strength test setup.

W_d could be measured. Next, the samples were soaked in a large water container for 24 to 28 hours. The specimens then were removed from the water and weighted while they suspended by a metal wire and completely submerged in water and recorded (immersed weight W_i). The block was then removed from the water and all visible water was wiped before obtaining the saturated weight W_s. The absorption and unit weight were calculated using Eq. (1)

$$\text{absorption, kg/m}^3 = \frac{w_s - w_d}{w_s - w_i} \times 1000 \quad (1)$$

Fig. 5—Water absorption test.

Fig. 6—RCMUs in environmental chamber.

where W_s is saturated weight of specimen, kg; W_i is immersed weight of specimen, kg; and W_d is oven-dry weight of specimen, kg.

RCMU durability characterization

Five RCMUs from each rubber ratio were placed inside an environmental chamber (Fig. 6) for 73 days. These specimens were exposed to severe weathering cycles representing 20 years of harsh Midwest weather exposure[20,21] (Table 2 and Fig. 7). A computer-controlled environmental chamber was used to simulate 350 different environmental cycles, including the following: 50 freezing-and-thawing cycles representing cold days and 50 alternating cycles of high temperature and high relative humidity representing hot and humid days. The compressive strength of each RCMU was then tested according to ASTM C140/C140M-14b and compared to that of the unexposed RCMUs to better understand the crumb rubber's effect on durability. A similar test was carried out on reference CMUs.

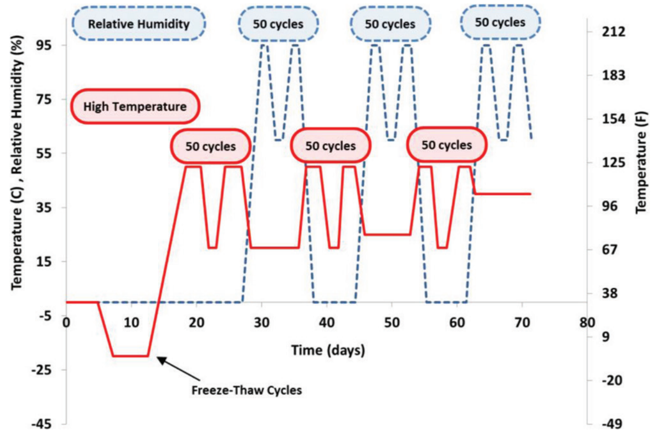


Fig. 7—Exposure regime for environmental chamber cycles.

Table 2—Environmental chamber cycles

Conditioning cycles	Conditioning extreme limits	No. of cycles
Freezing-and-thawing cycles	–20 to 10°C (–4 to 50°F)	50
High-temperature cycles	20 to 50°C (68 to 122°F)	150
Relative humidity cycles	60 to 95% RH at 20°C (68°F)	50
Relative humidity cycles	60 to 95% RH at 25°C (77°F)	50
Relative humidity cycles	60 to 95% RH at 40°C (104°F)	50

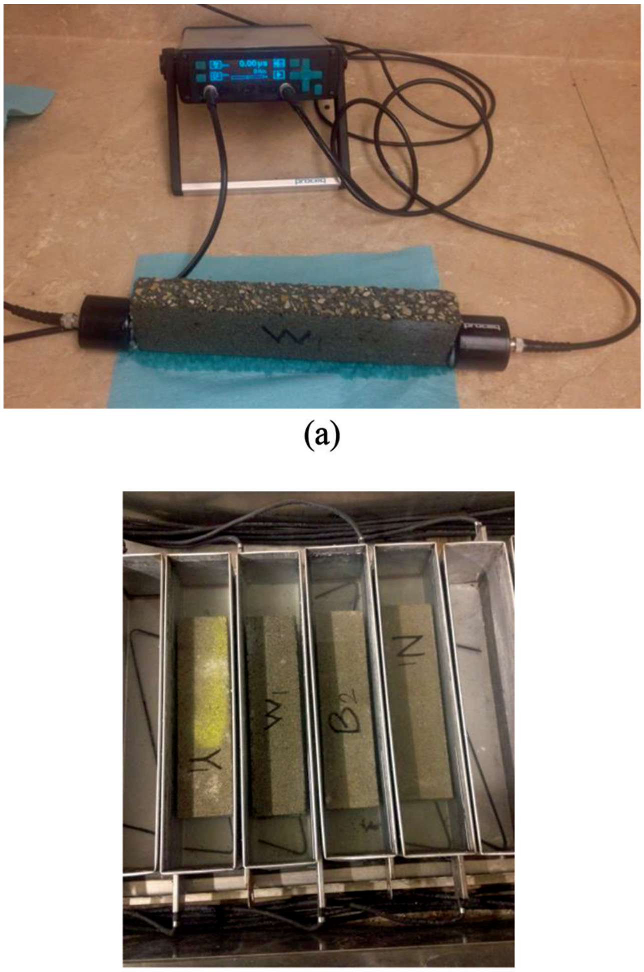
Rapid freezing-and-thawing test

A freezing-and-thawing resistance test was conducted according to ASTM C666 Procedure A, which involves both freezing and thawing specimens in water. Four specimens were tested for each ratio of rubber. The specimens were prepared by cutting an 11 x 3 x 1.5 in. (280 x 76 x 38 mm) prismatic piece from the face shell of RCMU (Fig. 8). Freezing-and-thawing tests began by placing the specimens in the thawing water at the beginning of the thawing phase. Then, the specimens went through cycles of freezing and thawing. After every 36 cycles, the specimens were removed from the apparatus in a thawed condition and the changes in weight and relative dynamic modulus of elasticity were measured for each specimen. The water was changed and the containers were washed after each set of cycles. The tests were continued and repeated for 300 freezing-and-thawing cycles or until the relative dynamic modulus of elasticity reached 60% of the initial dynamic modulus for each specimen whichever occurred first.

The relative dynamic modulus of elasticity was calculated using Eq. (2)

$$P_c = \frac{n_1^2}{n^2} \times 100\% \quad (2)$$

where P_c is the relative dynamic modulus of elasticity after c cycles of freezing and thawing, in percent; n is fundamental transverse frequency at 0 cycles of freezing and thawing; and n_1 is fundamental transverse frequency after c cycles of freezing and thawing. At the conclusion of this test, the durability factor for each specimen with different rubber ratios were calculated as follows



(a)

(b)

Fig. 8—Rapid freezing-and-thawing test: (a) ultrasonic test of RCMU sample; and (b) samples in freezing-and-thawing chamber.

$$DF = \frac{P \times c}{M} \quad (3)$$

where DF is the durability factor of the test specimen; P is the relative dynamic modulus of elasticity at c cycles, in percent; c is the number of cycles at which P reaches 60% or the 300 cycles, whichever is less; and M is the specified number of cycles at which the exposure is to be terminated.

Ultrasonic pulse velocity

An ultrasonic pulse velocity test was carried out on an 11 x 3 x 1.5 in. (280 x 76 x 38 mm) prismatic specimen (Fig. 9). Three replicate specimens were for each percentage of rubber tested.

Scanning electron microscope (SEM) analysis

Both light microscope and scanning electron microscope (SEM) analyses were conducted according to ASTM C1723-10 to evaluate the characteristics of the interfacial transition zone (ITZ) between crumb rubber particles and cement paste and to compare this with the ITZ between the mineral aggregate and cement paste. Both polished and fractured samples were examined during this investigation. The test was conducted for RCMU specimens having different rubber content.

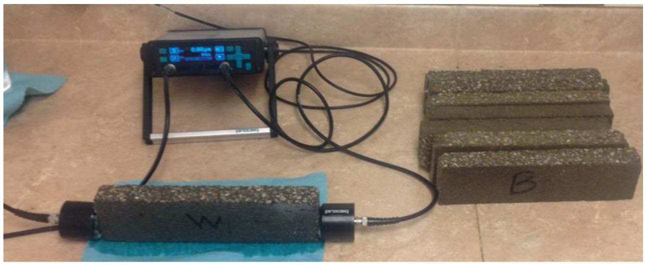


Fig. 9—Ultrasonic pulse velocity test.

Mechanical characterization of RCMU masonry prisms

Twenty-four masonry prisms, each with a height of four blocks, were constructed and investigated to determine the compressive strength of RCMUs, E-modulus, and ultimate strain. Three fully-grouted and three ungrouted masonry prisms were tested for each rubber ratio.

Each prism specimen was identified as follows: X-KK-Y, where X represents the amount of rubber replacement ratio (that is, 0, 10, 20, and 37); KK represents either a grouted (G) or an ungrouted (UG) specimen; and Y is the specimen replicate number within each replacement group. Thus, 10-UG-5 refers to the fifth replicate, ungrouted specimen that had a 10% rubber replacement ratio.

Professional masons constructed the masonry prisms according to ASTM C1314-12. A stack bond with a face shell bedding and portland cement lime mortar Type S were used. Both CMUs and RCMUs (each 7.63 x 7.63 x 15.625 in. [194 x 194 x 397 mm]) were used to build up the prisms. Each prism was one block long and four blocks high. Grouting was completed immediately after the prisms were constructed. A rod vibrator was used to consolidate the grout in each cell. The prisms were then exposed to ambient temperature in the lab conditions until testing.

Material samples were taken during the construction. Mortar cylinders measuring 4 x 2 in. (102 x 51 mm) and grout prisms measuring 4 x 4 x 8 in. (102 x 102 x 204 mm) were sampled according to ASTM C1019-11. The samples were tested on the same day the prisms were tested and at 28 days to determine the mortar and grout compressive strengths.

A displacement control compressive cyclic loading was used to test all of the specimens (Fig. 10). The cyclic compression consisted of full loading/unloading cycles. Each loading step was repeated for three times at a loading rate of 0.002 in./min (0.0508 mm/min) and with a loading step of 0.05 in. (1.27 mm).

Two linear variable displacement transducers (LVDTs) were fixed between the middle of the top and the bottom CMUs to measure the vertical displacement (Fig. 11). These displacements were used to calculate masonry axial strains.

EXPERIMENTAL RESULTS AND DISCUSSION

Table 1 presents the properties of the material and blocks used during the course of this study. It also presents any imposed limits by the appropriate ASTM standards. As illustrated in Table 1, RCMUs having up to 20% replacement of fine aggregate with crumb rubber meet the requirements of ASTM C90 in terms of unit compressive strength and water absorption. These RCMUs are also classified as normal-

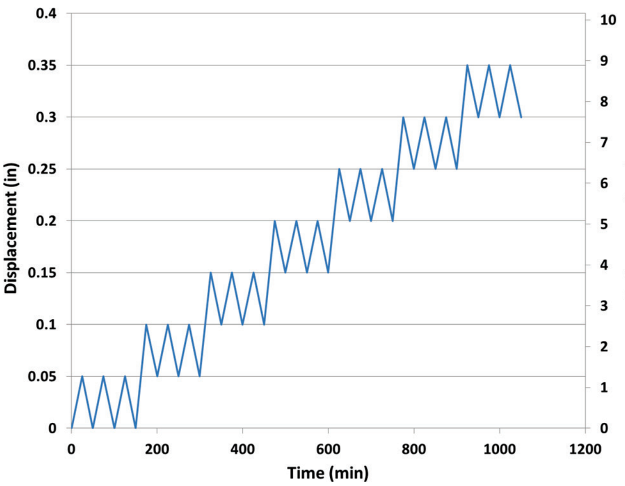


Fig. 10—Loading protocol.

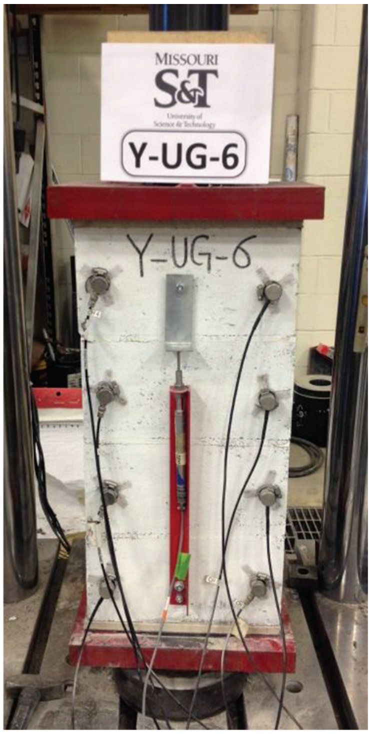


Fig. 11—Measuring strain of four-block-height masonry prism.

weight blocks because their unit weight exceeds 2000 kg/m^3 (125 lb/ft^3). However, RCMUs having 37% of fine aggregate replacement cannot be used for structural applications.

Unit weight

The effect of the rubber replacement on the unit weight of RCMUs and CMUs is illustrated in Fig. 12. As shown in the figure, the CMU's unit weight nonlinearly decreased as the rubber content increased. Increasing the rubber content from 0% to 37% decreased the unit weight from 137.7 lb/ft^3 (2206 kg/m^3) to 119.4 lb/ft^3 (1913 kg/m^3), representing a reduction of 13.3% in the RCMU's unit weight, while a rubber content of 20% decreased the unit weight from 137.7 lb/ft^3 (2206 kg/m^3) to 128 lb/ft^3 (2050 kg/m^3), representing a reduction of 7.1% in the RCMU's unit weight. This reduction occurred because the rubber particle's specific

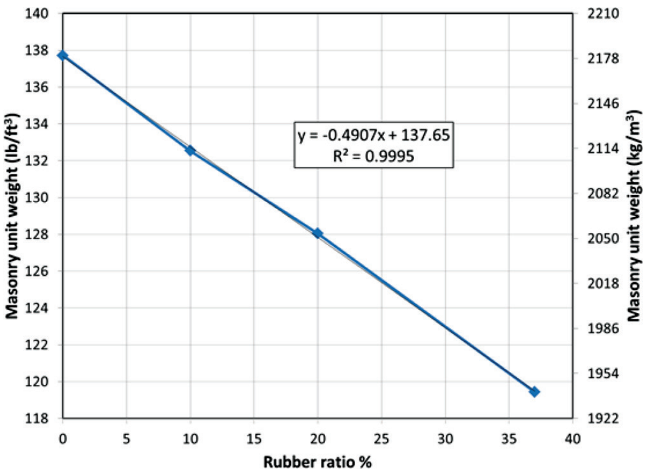


Fig. 12—Effect of rubber replacement ratios on unit weight of masonry unit.

gravity was only 32% of that of the fine aggregate. Furthermore, the air content increased with increasing the rubber content in the mixture, as indicated by the higher absorption rate (Table 1). Figure 13 shows the nature of the rubber particles' surface. The rubber particles have a rough, scratchy, nonpolar surface nature that is tends to entrap air within and around the rubber particles, which has been previously reported.[19]

As illustrated in Table 1 and Fig. 12, RCMUs having up to 20% replacement of fine aggregate with crumb rubber have unit weights exceeding 2000 kg/m^3 (125 lb/ft^3) and, hence, are classified as normalweight blocks. However, RCMUs having 37% rubber replacement are classified as medium-weight blocks.

Water absorption

The effect of rubber content on the water absorption is illustrated in Fig. 14. As shown in the figure, the water absorption increases as the rubber content increases. Increasing the rubber content from 0% to 37% increased the water absorption from 6.8 lb/ft^3 (109 kg/m^3) to 11 lb/ft^3 (176 kg/m^3), representing an increase of 61.7%. Despite this increase, the absorption rate of all RCMUs did not exceed the absorption rate allowed by ASTM C90-12 of 13 lb/ft^3 (208 kg/m^3) (Table 1). The increase in the absorption rate occurred because the rubber had a relatively larger particle size than the fine aggregate. This difference in the particle size created extra voids due to the shortage of the fine materials in the rubber particles. Moreover, it is related to the increase in the air voids explained earlier in this manuscript.

Unit compressive strength

The effect of rubber content on the unit compressive strength is shown in Fig. 15. As shown in the figure, increasing the rubber content nonlinearly decreased the masonry unit compressive strength. Increasing rubber replacement from 0 to 37% decreased the compressive strength by 77.5%. However, increasing rubber replacement from 0 to 20% decreased the compressive strength by 48.3%. Despite this decrease in strength, the compressive strengths of all RCMUs having rubber replacement up to

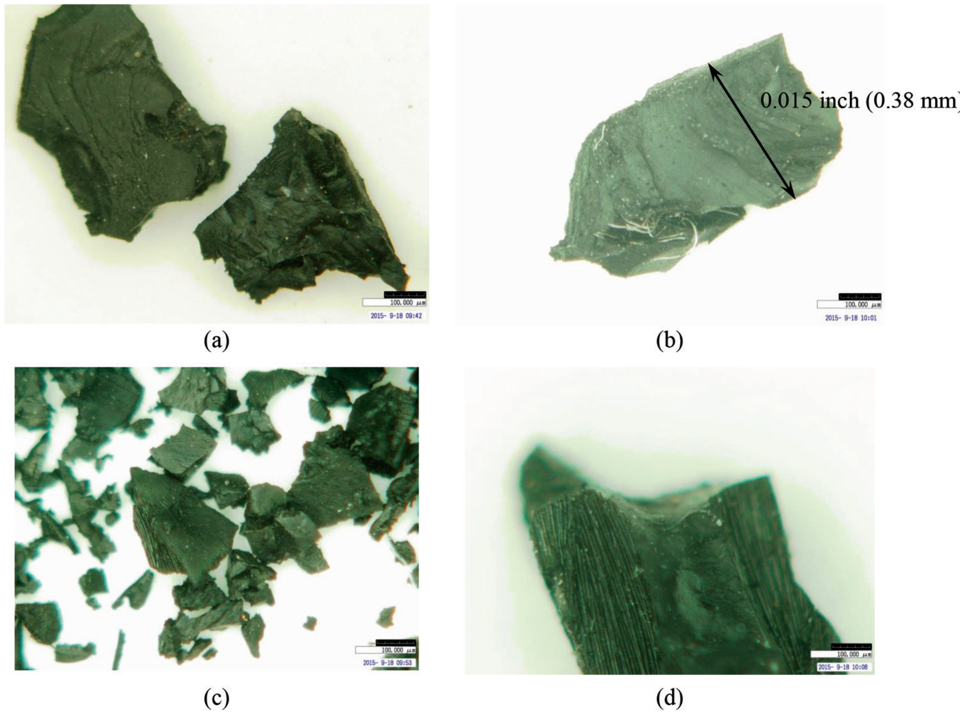


Fig. 13—Nonpolar nature of crumb rubber particles' surface.

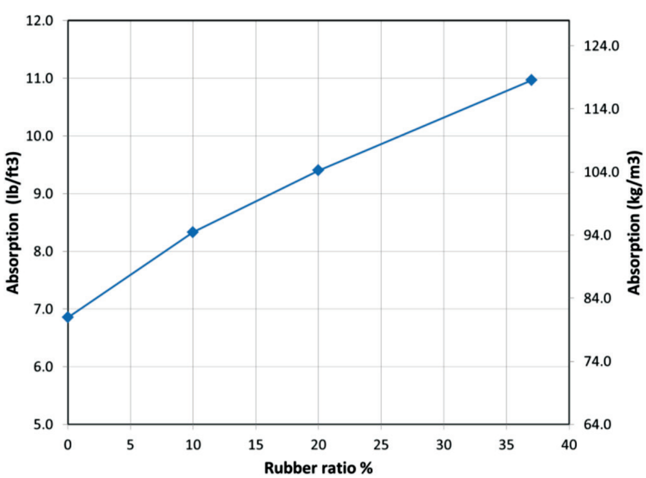


Fig. 14—Effects of different rubber replacement ratios on water absorption.

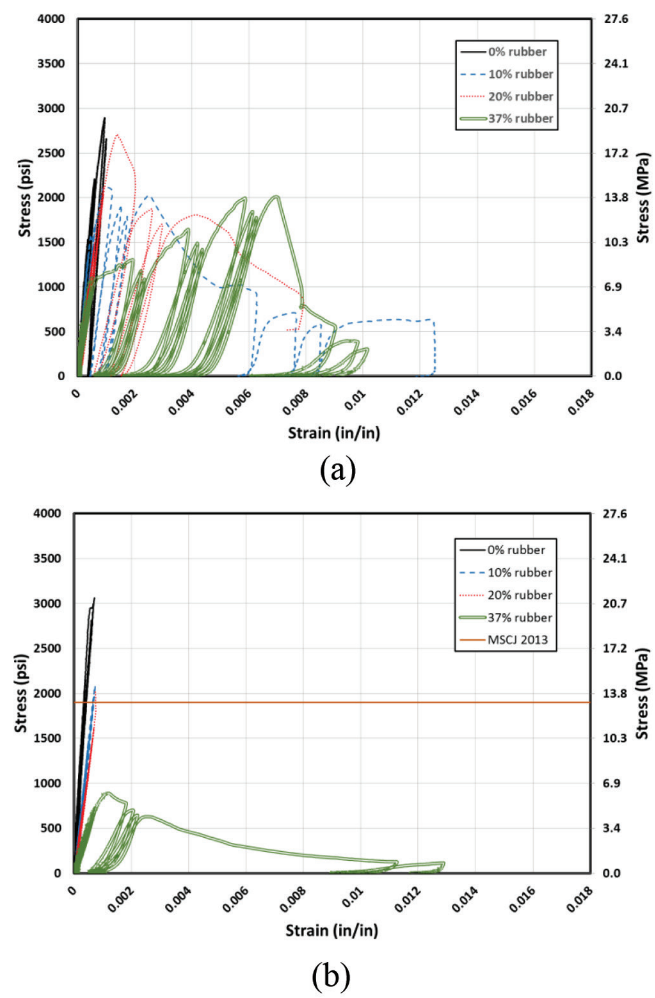


Fig. 15—Stress-strain curves for four-block prisms with different rubber content: (a) fully grouted prisms; and (b) ungrouted prisms.

20% exceeded the minimum required strength of the ASTM C90-12 of 1900 psi (13.1 MPa) (Table 1).

Compressive strength and stress-strain relationship

As mentioned, 40 four-block-high prisms, grouted and ungrouted, constructed out of RCMs and CMUs, were tested under axial cyclic loads. The average strengths, strains at peak loads, and initial stiffness of each five replicate specimens are listed in Table 3. Furthermore, the axial stresses versus axial strains for each prism is calculated. The axial loads measured during testing of each prism were divided by the prism cross-sectional area to calculate the axial stresses, while the LVDTs shown in Fig. 11 were used to calculate the average axial strains. The results of representative prisms are presented in Fig. 15. The results indicate that the crumb rubber replacement had significant effects on the strength, initial stiffness, and axial strain at peak loads of the investigated masonry prisms.

As shown in Fig. 15 and Table 3, using crumb rubber generally reduced the compressive strengths of the investigated ungrouted prisms with ratios ranging from 31 to 71% proportional to the rubber content. For grouted prisms, the reduction ranged from 6.3 to 30.5% based on the rubber content. However, the reductions in the case of grouted prisms were not proportional to the rubber content. The strength of the grouted prims results from two different components: the block strength, and grout. For a conventional CMU (0% rubber), the block is quite brittle due to the severe stress concentrations, which lead to very early failure of CMU face-shells and webs before the filler grout is subjected to high axial stress. During testing, for prisms constructed out of CMUs, the grout suffered few micro- to macro-cracks at rupture of the prisms (Fig. 16). Hence, the contribution of grout to prims strength was limited. Contrarily, RCMUs have the ability to go through higher axial deformation before failure, allowing higher grout deformations and higher grout contribution to the prism axial strength. However, the addition of rubber reduces the strength of the CMUs (Table 1).

Table 3—Test results for four-block-height prisms

Specimen name	Maximum stress, psi (MPa)	Microstrain at maximum stress, in./in. (mm/mm)	Initial stiffness, ksi (GPa)
0-G	3318 (22.88)	0.96×10^3	3400 (23.44)
10-G	2413(16.64)	1.0×10^3	2713 (18.7)
20-G	3108 (21.43)	1.4×10^3	2250 (15.51)
37-G	2307 (15.9)	7.0×10^3	1810 (12.48)
0-UG	3492 (24.1)	0.7×10^3	4500 (31.03)
10-UG	2396 (16.52)	0.75×10^3	2680 (18.48)
20-UG	2396 (16.52)	0.75×10^3	2312 (15.94)
37-UG	1021 (7.04)	1.2×10^3	955 (6.58)

Hence, there are two contradicting mechanisms that influence the strength of fully-grouted masonry prisms constructed out of RCMUs. For example, RCMUs having 37% rubber replacement had the ability to go through very high axial strains without failure, but also the high rubber replacement ratio had severe effect on the strength of the RCMUs. Hence, fully-grouted prisms constructed out of these blocks displayed a strength reduction of 30.5%. Similarly, RCMUs having 10% and 20% rubber replacement displayed a strength reduction of 27.3% and 6.3%, respectively.

Visual observations and calculations revealed a clear influence of RCMUs on prism stiffness (Fig. 17). For the grouted prisms, increasing the rubber content from 0 to 37% decreased stiffness from 3400 ksi (23,442 MPa) to 1810 ksi (12,480 MPa), which represents a reduction of 47%. Regarding the ungrouted prisms, increasing the rubber content from 0 to 37% decreased stiffness from 4500 ksi (31,026 MPa) to 955 ksi (6585 MPa), which represents a reduction of 79%. The influence of rubber on stiffness was less pronounced in the grouted prisms because all prisms had the same type of conventional grout (no rubber in the grout).

Prisms constructed using RCMUs displayed also very high axial strains at the peak loads. For the grouted prisms, 630%, 46%, and 4% increases in the axial strains corresponding to the peak loads were recorded when rubber replacement ratios of 37%, 20%, and 10%, respectively, were used (Fig. 15(a)), while 71%, 7%, and 7% increases in the axial strains corresponding to the peak loads were recorded with 37%, 20%, and 10% rubber replacement ratios, respectively, in the ungrouted prisms (Fig. 15(b)).

An observed beneficial feature for the rubberized prisms was the failure mechanism. Failure in the conventional masonry prisms—that is, 0% rubber replacement—was quiet brittle and sudden (Fig. 15(a)); the tested prisms could not resist any further load beyond the peak load. In contrast, prisms constructed using RCMUs behaved in a very ductile manner with a gradual failure. For example, prims constructed using 20% rubber-replacement RCMUs

(a) (b) (c)

Fig. 16—Failure mechanism of four-blocks CMUs prisms (no rubber): (a) rupture of webs; (b) rupture of face shells; (c) grout after failure (note minor cracking in grout in different pictures).

were able to resist three cycles at stress equal to 67% of the f_m' with a corresponding axial strain of 192% of its peak load strain (Fig. 15(a)). This feature represents pseudo-ductility for masonry that allows the engineers to do the required repair in particular compression failure zones before the total collapse or failure can occur in a particular masonry element. However, this requires that all other failure modes, such as shear failure and reinforcement rupture, be superseded. Finally, the large axial strains in RCMUs would help a structural masonry element to display higher ductility capacity, which is crucial for seismic regions. Furthermore, the large areas enclosed by the stress-strain loops (Fig. 15) indicate that RCMUs significantly increased the energy dissipation of the investigated masonry prisms compared to those prisms constructed using CMUs.

Effects of extreme environmental conditions

As mentioned previously, CMUs and RCMUs were placed into an environmental chamber and subjected to extreme weather cycles. Then, the compressive strengths of these specimens were determined. The compressive strengths of the conditioned RCMUs were higher than that of the conditioned CMUs (Fig. 18). As shown in the figure, the conditioned CMU displayed a compressive strength reduction of 4%. The rubber increased the compressive strength of the conditioned RCMUs by 1% to 20%; this increase, however, was not proportional to the rubber content. The compressive strength of the conditioned RCMU was controlled by contradicting parameters. Increasing the rubber content increased the entrapped air, which was filled with water during the weathering cycles. Under freezing conditions, the entrapped water volume increased imposing internal pressure on the RCMUs leading to microcracking and compressive strength reduction. Similar behavior was observed for CMUs. However, including crumb rubber in RCMUs acts as an internal spring that absorbs the increase in water volume. Furthermore, when rubber is exposed to low temperatures, the rubber particles crystallize, thereby increasing the rubber compressive strength and stiffness,[22] which increases the compressive strength of the unit. However, rubber crystallization decreases the spring effect of the crumb rubber particles inside the matrix, which decreases the ability of crumb rubber to release the internal stresses that result from entrapped water expansion. The amount of crystallinity is related to both the length and the temperature of exposure of RCMU. In the cases of having 20% rubber replacement, the positive factors dominated the performance of the RCMUs, meaning that the rubber hardening and internal spring action was significantly higher than the increase in the internal pressure due to water freezing. However, this was not the case for 10% and 37% rubber replacement.

Rapid freezing-and-thawing test

As explained previously, rapid freezing-and-thawing tests were conducted per ASTM C666 Procedure A. The behavior of RCMU after the rapid freezing-and-thawing test depends on the percentage of rubber content (Fig. 19 and 20). RCMUs having 10% rubber content behaved better than the conventional CMUs, with a gradual reduction in the measured dynamic modules of elasticity. However, RCMUs having 20% and 37% rubber content replacement, respectively, each behaved worse than the conventional CMUs, with rapid reduction in the dynamic modulus of elasticity. Similarly, the durability factor (DF) of RCMUs having 10% rubber content was 19% higher than that of CMUs, while the DFs of RCMUs having 20% and 37% rubber content were 21% and 29% lower than that of CMUs. This occurred, as explained previously, due to different contradicting factors, including the increase in entrapped water, rubber crystallization, and internal spring. This clarifies the vacillating behavior of the samples with a 37% rubber content replacement ratio. As a result, the strength of RCMU increased in the beginning of the low-temperature cycles when some of the rubber crystallized and the other part absorbed the internal stresses. When the entire amount of crumb rubber in the matrix crystallized, the flexibility of rubber decreased, which reduced its ability to absorb the internal stresses. Therefore, the strength started to decrease rapidly.

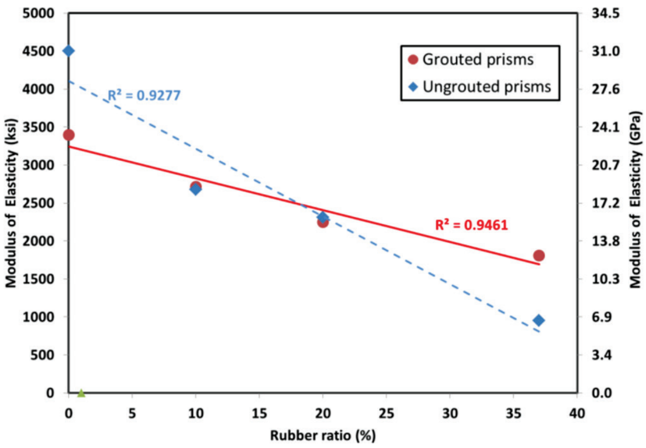


Fig. 17—Modulus of elasticity of masonry prisms with different rubber contents.

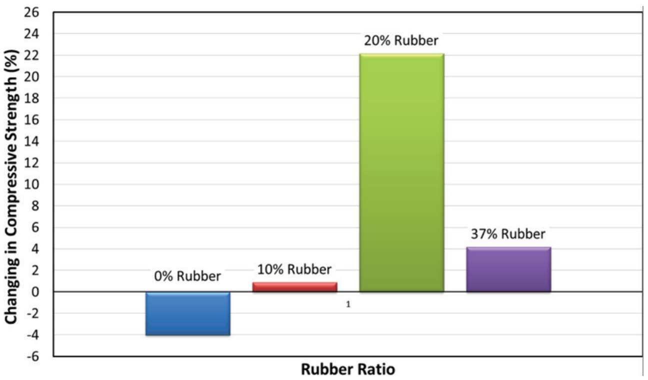


Fig. 18—Effect of extreme environmental conditions on compressive strength for different rubber replacement ratios.

Ultrasonic pulse velocity and sound insulation

Adding rubber particles to CMUs reduced the velocity of ultrasonic waves and had the same effect on the dynamic modulus of elasticity. Increasing the rubber content linearly decreased the velocity of ultrasonic waves (Fig. 21). There was a 36% reduction in the velocity of ultrasonic waves when

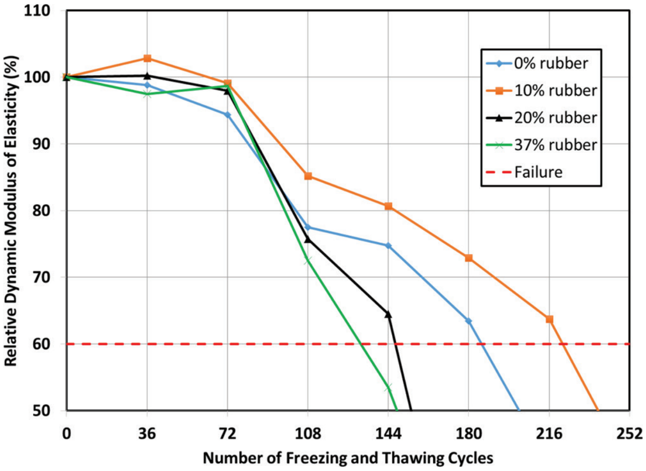


Fig. 19—Relative dynamic modulus of elasticity versus number of freezing-and-thawing cycles.

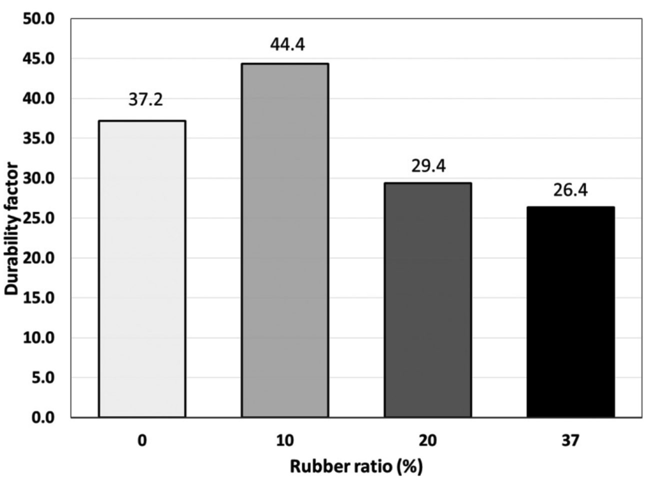


Fig. 20—Durability factor of masonry blocks with different rubber ratios.

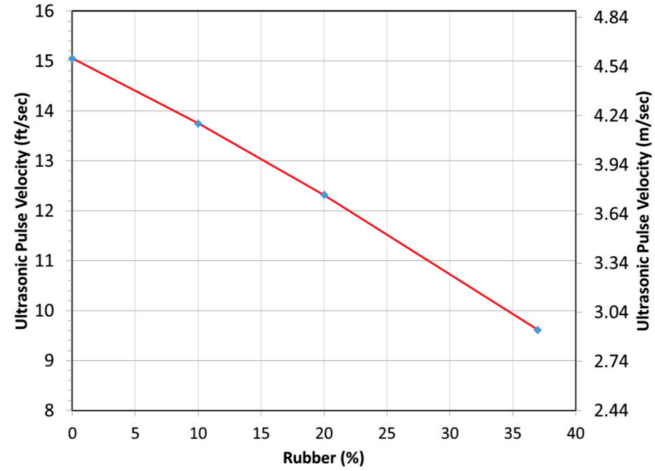


Fig. 21—Effect of rubber content on ultrasonic pulse velocity.

37% of the fine aggregate was replaced with crumb rubber. This reduction occurred due to the ability of rubber to absorb the waves. Moreover, the increase in the discontinuous air voids, which is related to the increase of crumb rubber in the matrix, impeded the ultrasonic waves and reduced the ultrasonic pulse velocity. This indicates that having crumb rubber in masonry blocks reduced the sound transmission, which is one of the aspects for the sound insulation. Similarly, Sukontasukkul proved that using crumb rubber in concrete increases sound absorption by increasing the sound absorption coefficient α and noise reduction coefficient (NRC).[15] Nehdi and Khan[23] stated that using rubber in concrete enhances the sound insulation compared to conventional concrete.

Scanning electron microscope (SEM) analysis

Figure 22 shows the results of the SEM analyses for CMUs and RCMUs. As shown in the figure, the RCMU samples (Fig. 22(b), 22(c), and 22(d)) had more air voids than the sample with no rubber (Fig 22(a)). The size of the air voids increased as the amount of rubber in the matrix increased.

To evaluate the interfacial bond between rubber particles and conventional aggregate from one side and the cement paste to the other side, the Ca/Si (C/S) criterion was used. This criterion considered the bond high if C/S < 1.5.[24] For the samples with no rubber, the element analysis of ITZ between the conventional aggregate and the cement paste showed a C/S of 0.483 (Fig. 23(a)). This number represents a very high bond between the aggregate and the cement paste. On the contrary, the C/S was 1.58 for the interfacial zone between the rubber particles and the cement paste (Fig. 23(b)). This ratio represents a relatively low bond relationship between the rubber particles and the cement paste.

The weak bond between the rubber particles and the cement paste was clear when the SEM analysis was conducted on the cracked samples. These samples were taken from RCMU that failed by compression test. As shown in Fig. 24, there was a gap between the rubber particles and cement paste after failure, which occurred due to the weak bond between them, which clarifies the systematic reduction in the compressive strength of the rubberized masonry blocks. The poor characteristic of the rubberized masonry blocks' ITZ was one of the main reasons for this reduction.

CONCLUSIONS

Concrete masonry units with four different ratios of crumb rubber were physically and mechanically examined. The results of compressive strength, peak strain, initial stiffness, water absorption, unit weight, durability, ultrasonic waves, and SEM analysis were reported in this paper. Based on the experimental investigation, the following conclusions can be drawn:

1. Producing RCMU in a typical masonry plant was undertaken successfully. Crumb rubber can be used up to 20% partial replacement for fine natural aggregate to produce a rubberized masonry block units (RCMUs) that meet the requirements of the ASTM C90.

2. The RCMUs have a lower unit weight; however, they have higher water absorption rate compared to those of CMUs.

3. Despite the reduction in the compressive strength of RCMUs with increasing the rubber content, using 20% rubber replacement in RCMU resulted in a reduction of 6% in compressive strength of four-unit-high masonry prism. However, significant reduction in the initial stiffness was observed, causing a 34% reduction in initial stiffness when 20% rubber replacement was used.

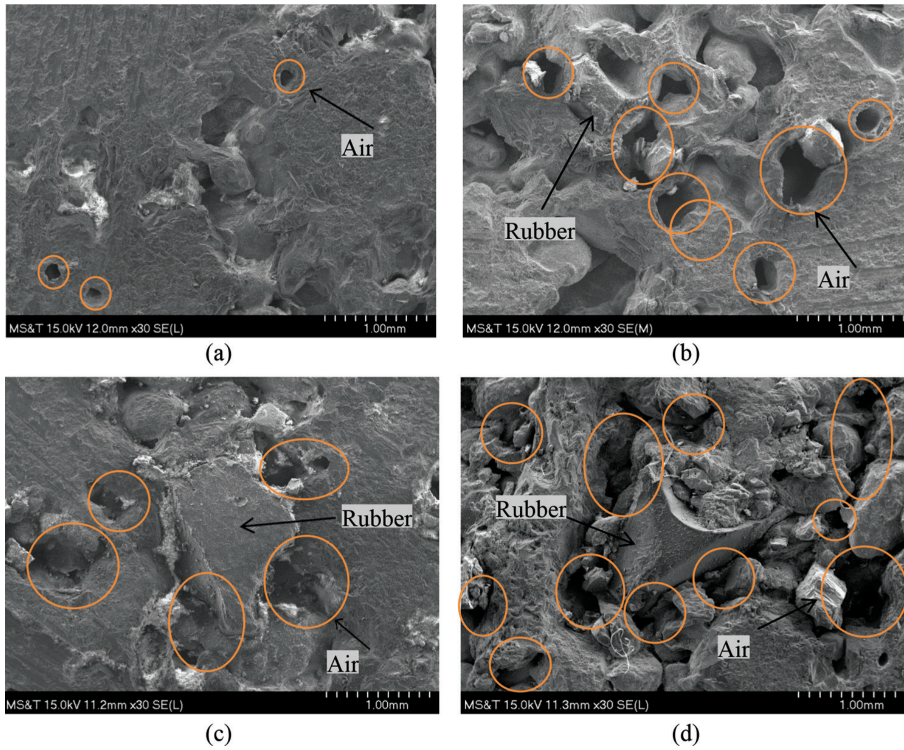


Fig. 22—Air voids for block units with different rubber content: (a) 0% rubber; (b) 10% rubber; (c) 20% rubber; and (d) 37% rubber.

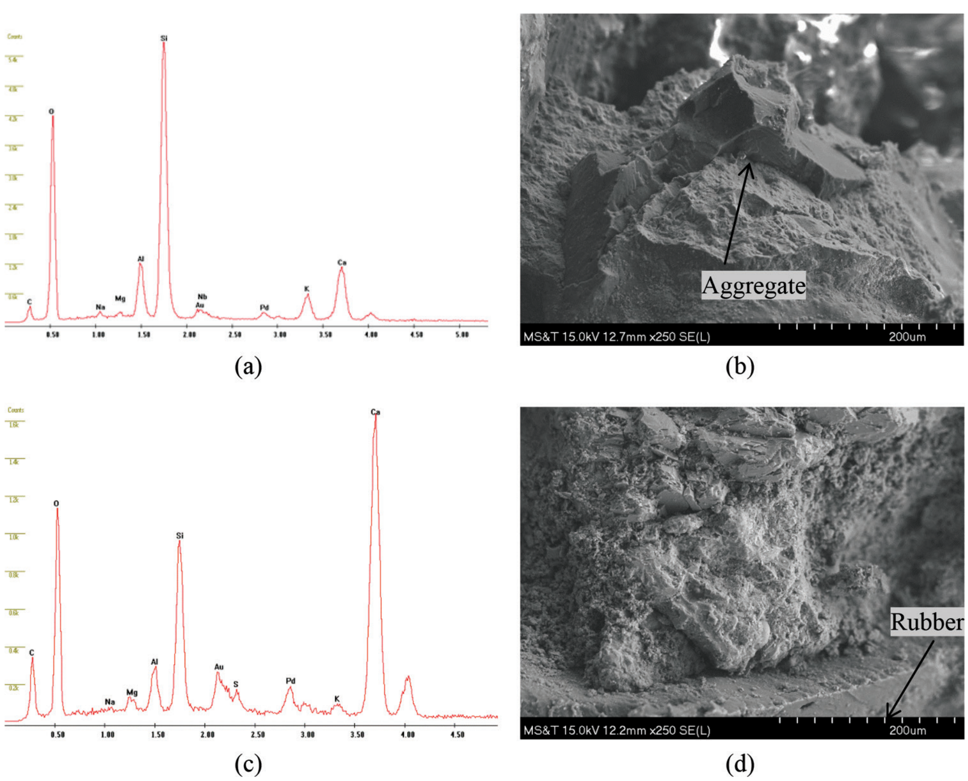


Fig. 23—(a) Chemical analysis for ITZ between natural aggregate and cement paste; (b) ITZ between natural aggregate and cement paste; (c) chemical analysis for ITZ between crumb rubber and cement paste; and (d) ITZ between rubber and cement paste.

4. RCMUs displayed significantly higher ultimate strain compared to those of CMUs.
5. The addition of 20% rubber as a partial replacement of fine aggregate improved the durability of the units by increasing the compressive strength after cycles of extreme environmental conditions.
6. Rubberized blocks displayed a reduction in the ultrasonic pulse velocity and sound transmission. However, further investigations are needed to study the impact of rubber on sound absorption, reflection, and energy reduction.
7. Scanning electron microscope (SEM) analysis of the interfacial transition zone (ITZ) showed that rubber parti-

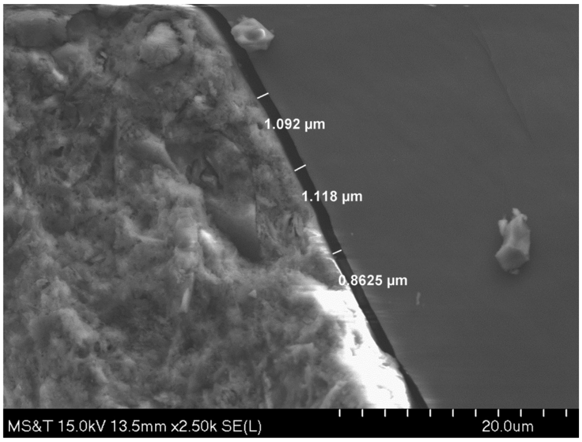


Fig. 24—A gap between rubber particle and cement paste after failure.

cles have a weaker bond with cement paste than natural aggregates, which explained the systematic reduction in the compressive strength of the rubberized masonry blocks.

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