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CYCLIC BEHAVIOR OF CONCRETE MASONRY UNITS MANUFACTURED WITH RECYCLED TIRES AS AN AGGREGATE

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ABSTRACT

Replacing mineral fine sand in concrete masonry units (CMUs) with a scrap rubber potentially can improve the sustainability, strain, and ductility of masonry. An experimental investigation was conducted to explore the effects of adding different ratios of scrape crumb tiers rubber as an aggregate replacement to concrete masonry units. Replacement ratios of 0%, 10%, 20%, and 37% were investigated. Both grouted and ungrouted masonry prisms were subjected to an axial cyclic load. Different types of capping were also used and compared to obtain accurate stress-strain curves. More than 60 masonry prisms were tested under cyclic compression loads. Two prism heights, namely, two-block and four-block high were used to capture the axial strain in the masonry prisms. Using rubber did not have a significant effect on compressive strength of grouted prisms while it had significant effects on ungrouted prisms. For grouted prisms, replacing 10%, 20%, and 37% of mineral sand with crumb rubber decreased the compressive strength by 27%, 6%, and 30%, respectively. Furthermore, the results indicated the rubber significantly influenced the masonry ultimate strain and initial stiffness. Blocks having high rubber content displayed larger ultimate axial strains. The ultimate strain increased by 4%, 46% and 630% for 10%, 20%, and 37% rubber replacement. The effect of rubber on the post-peak strength and descending branch of the stress-strain curve was significant. Specimens having rubber exhibited a significant ductility. Failure of conventional specimens was quite brittle while specimens having rubber content displayed a high ductility. The mechanical characterization of the rubberized block showed that the new rubberized masonry units met the ASTM requirements for load-bearing concrete masonry units.

KEYWORDS: *crumb rubber, cyclic, masonry, rubberized*

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INTRODUCTION

Concrete masonry unit (CMU) is an important construction material that is widely used around the world. Unfortunately, it is relatively brittle material. Hence, a pressing need exists to produce CMUs that are more ductile. The cement production industry is responsible for producing 5% of the oxygen dioxide emissions [1]. Thus, one more pressing need for masonry industry is to produce more sustainable CMUs. One approach toward achieving sustainability is the use of recycled materials.

Crumb rubber produced from scrap tires can be utilized as a replacement for aggregates in CMUs. The Rubber Manufacturer's Association stated that 233.34 million scrap tires were generated in 2013 in the U.S. The use of scrap tires has accelerated over the last 20 years, significantly alleviating historic tire dump issues and dropping the number of stockpiled tires from one billion in 1992 to 75 million tires in 2013. Scrap tires are considered harmful waste because they leach harmful toxic substances into the environment. Discarded tires serve as a home for mosquitoes, rats, and snakes. Furthermore, tires represent a tremendous fire hazard. For example, in 2005, 750,000 scrap tires blazed for several months in Polk County in the State of Missouri and nineteen area fire departments were not able to extinguish the fire for several months with black fumes visible from many miles. These fires will emit significant amounts of CO2 and dioxins into surrounding air and water. Many landfill operators do not accept whole scrap tires to be dumped in their landfill. Most states in the U.S. have enacted legislation that either restricts or even bans the disposal of tires in landfills.

Using recycled tires to produce CMUs would reduce the amount of scrap tires placed in landfills. Unfortunately, there has been no research on using crumb rubber in the production of CMUs. However, significant research was carried out to determine the effects of using scrap rubber as a partial replacement of fine and coarse mineral aggregate in concrete mixtures.

In 2001, the Arizona Department of Transportation used concrete including crumb rubber to build a section of the parking lot in its Phoenix Division. Cured samples of the pavement reached a compressive strength of 3,260 psi in one year [2]. The use of crumb rubber as a partial replacement for mineral aggregates reduced concrete compressive strength [3-8].

The dynamic modulus of elasticity decreased when crumb rubber was used in concrete. As a result, the damping properties significantly improved [9, 10]. Atahan and Yücel [11] performed dynamic drop-weight tests to assess the effect of rubber on energy dissipation. They determined that replacing 20-40% of aggregates with crumb rubber creates concrete mixtures that are useful for concrete safety barriers. Moustafa and ElGawady [8] conducted free vibration tests with an impact hammer on simply supported beams to investigate the effect of rubber replacement on concrete's dynamic properties. It was reported that both the viscous damping and the average hysteresis damping increased as the rubber replacement ratio increased. Youssef et al. [12, 13] investigated the seismic behavior of rubberized concrete columns confined using regular spiral rebar as well as fiber reinforced polymer tubes.

The effects of adding crumb rubber to masonry, brick, and paving units has also been studied. It is reported that the compressive strength decreased as the rubber replacement percentage increased. Rubberized masonry hollow units can, however, be produced for both load-bearing and non-load-bearing structures [14-16].

The mechanical characteristics of hollow concrete masonry units with four different ratios of crumb rubber replacing fine aggregate are presented in this paper. The compressive strength and ultimate strain under cyclic loads were investigated for two different heights of prisms.

MATERIALS AND EXPERIMENTAL PROGRAM

Four different ratios of rubber, namely, 0%, 10%, 20%, and 37% in relation to the volume of mineral sand were used as a replacement to manufacture rubberized concrete masonry units (RCUMs). A masonry plant in Jefferson City, Missouri used a conventional manufacturing process for manufacturing the blocks examined during this study.

Material

All the 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

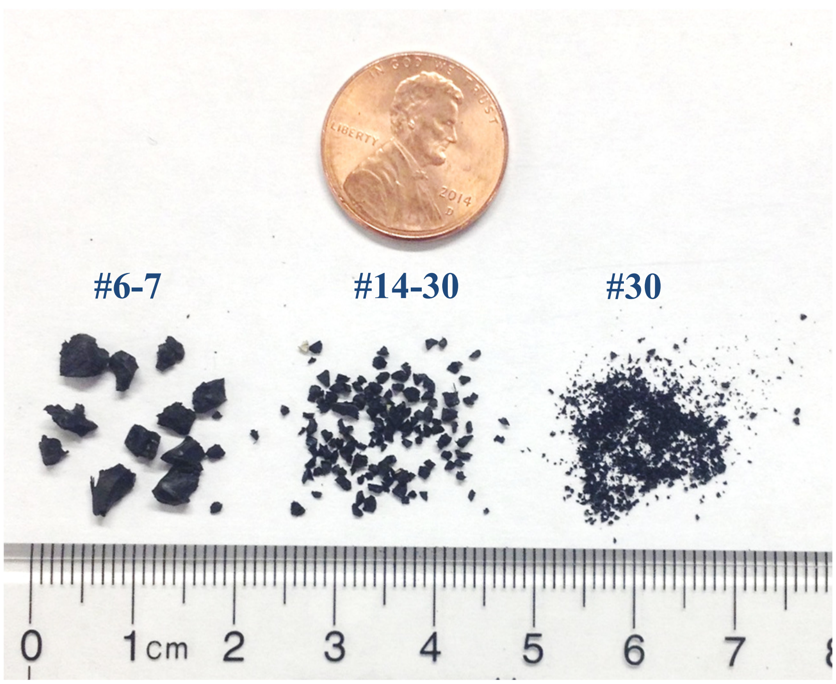


Figure 1: Different sizes of crumb rubber used in production of RCMUs

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
Masonry block prism	Compressive strength f'm ASTM C1314-12	see table 2	---------
Rubber	Unit weight	640 kg/m^3	---------

MECHANICAL CHARACTERIZATIONS OF RMCU MASONRY PRISMS

Sixty-four masonry prisms having two different heights were constructed and investigated to determine the RCMU's strength, E-modulus, and ultimate strain. Five fully-grouted and five ungrouted, two-course high prisms were tested for each rubber ratio, resulting in a total of forty tested prisms. Three fully-grouted and three ungrouted four-course prisms were also tested for each rubber ratio resulting in a total of twenty-four masonry prisms.

Professional masons constructed the masonry prisms according to ASTM C1314–12 in a stack bond using fully bedding Portland cement lime mortar type S. Both CMUs and RCMUs (each 200x200x400 mm) were used to construct the prisms. Each prism was constructed with one-block long and either two-course high or four-course high blocks. Grouting was completed immediately after the prisms were constructed. A rod vibrator was used to consolidate the grout in each cell immediately after the grout was poured into the prisms. The prisms were then cured in lab conditions until the day of testing.

Material samples were taken during the construction. Mortar cylinders measuring 100x50 mm and grout prisms measuring 100x100x200 mm were sampled according to ASTM C1019–11. The samples were tested at the same day when the prisms were tested and at 28 days to determine the mortar and grout compressive strengths.

Specimens Preparation

Three different capping procedures were used to test the specimens: sulfur-capping compound, gypsum cement, and a fibrous composite laminate (Fig. 2). The first two capping materials are permitted by ASTM C1552–12. Both the sulfur and gypsum capping were difficult to use due to the heavyweight of the masonry prisms. The third capping, however, is relatively new and thus it has not yet been permitted by the ASTM. The fibrous cap consisted of composite laminated to tough plastic sheeting. The fibrous caps provided an unbonded capping system and hence reduce the end plate effect during loading the prisms. The fibrous composite laminate was also more convenience than the other two capping procedures. Fibrous capping did not require retainers, melting, mixing, or cutting and hence eliminated the need to either move or handle the prisms.

(a) (b) (c)

Figure 2: Different capping types: (a) Sulfur capping layers, (b) Gypsum capping layers and (c) Fibrous composite laminated cap

Test Set-up, Loading, and Instrumentations

A displacement control compressive cyclic loading was used to test all of the specimens (Fig. 3). The cyclic compression consisted of full loading/unloading cycles. Each loading step was repeated for three times. According to ACI 374.2R-13, the loading increment's magnitude should be small enough to capture the main features in the experiment. Each set of cycles was run at 1.25 mm increments at a rate of 1.27 mm/min for each step.

Two linear variable displacement transducers (LVDTs) and two string potentiometers were used in each two-block high prisms to measure the vertical displacement in the middle third. Furthermore, an additional LVDT was attached to the top and bottom plates to measure the total axial displacement between the two plates (Fig.4a). Two LVDTs were fixed between the middle of the top and the bottom blocks in the four-block high prisms to measure the vertical displacement. These displacements were used to calculate masonry strains (Figs.4b).

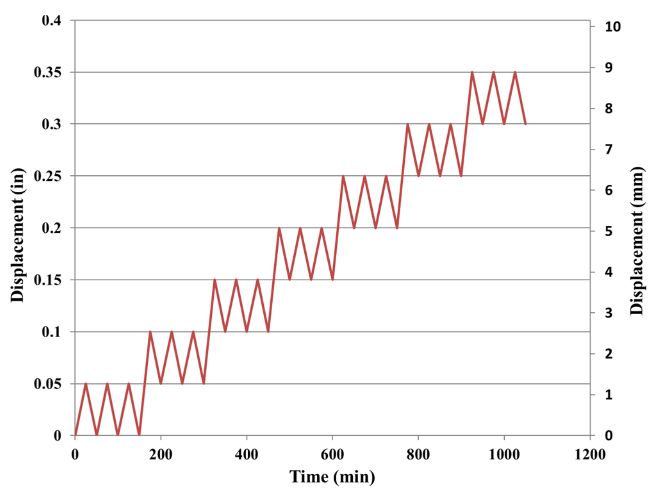


Figure 3: Loading protocol

(a) (b)

Figure 4. Displacement measurement instrumentations (a) Two-block high prisms, and (b) Four-block high prisms

RESULTS AND DISCUSSION

Two things significantly impact displacement reading accuracy during cyclic compression tests, namely, prism height and capping. The measured vertical displacement and associated strains were not accurate along the middle thirds of the Two-block high prisms. At the beginning of measurements, typically LVDTs read positive values indicating compression of the prisms. The LVDTs readings increased with increasing the applied load until approximately half of the displacement values corresponding to the peak loads. Beyond that, the measured displacements decreased because bulging took place in the face shells. This bulging accrued due to the horizontal expansion of grout under vertical loads. It then pushed the steel angles that were used as support to the LVTD's outward, causing them to rotate (Fig. 5). This rotation decreased the vertical measurements.

For the 4-block prism, the displacements were measured between the middle of the bottom block and the middle of the top block. Using this approach, the measured displacement represented the average displacement along the height of the prism without significant effect due to bulging as bulging occurred at mid-height of the prism.

Other LVDTs were used to measure the displacements between the two loading plates to calculate the prism displacement. Perhaps these displacements had two disadvantages. First, deformation in the capping layers contributed to the measured readings. This cap displacement was quite significant when it was compared to the displacements in the prisms themselves. Second, the friction between the loading plates and caps prevented the horizontal displacement of the prism at the top and bottom. This restraint increased the stiffness of the masonry prism compared to prisms having ideal pin-pin ends. As a result, the strain should be measured in the middle third of the prism's height or to significantly reduce the stiffness and friction of the capping material. As a suggestion, the stiffness and friction of the capping material should significantly be reduced.

As mentioned three different capping material including gypsum, sulfur, and fibrous were used during the course of this study. Both Gypsum and sulfur cappings worked very well with regard to compressive strength. The strain measurement, however, was inaccurate because of the cap's high compressibility. This type of capping created a significant amount of bonding between the prism's components. This bond, however, was still lower than that created by the sulfur capping.

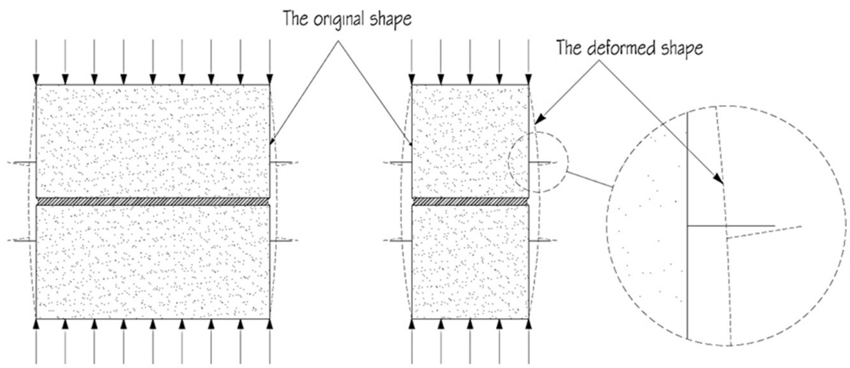


Figure 5. Effects of bulging on the points at which the strain was measured

The results gathered from testing four-block high prisms using fibrous capping are listed in Table 2. These results indicate that the mechanical characterizations of masonry units were impacted significantly when crumb rubber was used as a partial sand replacement.

As shown in Table 2, using rubber as a replacement of mineral sand in CMUs reduces the compressive strength and increases the ultimate strain. The effect of rubber on ungrouted prisms was more pronounced compared to that of the grouted prisms. Changing the rubber content from 0 to 37.5% decreased the strength from 24.08 MPa to 7.04 MPa corresponding to a reduction of 71% in the prism strength.

Table 2. Average tests result of four block height prisms

Specimen name	maximum stress (MPa)	MicroStrain at maximum stress (mm/mm)	Initial Stiffness (GPa)
0-G	22.88	960	23.44
10-G	16.64	1000	18.70
20-G	21.43	1400	15.51
37-G	15.91	7000	12.48
0-UG	24.08	700	31.03
10-UG	15.52	750	18.48
20-UG	15.52	750	15.94
37-UG	7.04	1200	6.58

A 630%, 46%, 4% increase in the peak strain with a 30%, 6% and 27% decrease in the compressive strength was recorded when rubber replacement ratios of 37%, 20%, and 10% respectively were used in the four-block height grouted prisms (Fig. 6a).

A 71%, 7%, and 7% strain increase were recorded with 37%, 20%, and 10% rubber replacement ratios, respectively in the ungrouted prisms (Fig. 6b). The f'$_m$ was lower in the CRMUs prisms. Thus, the peak strain (which was higher in the rubberized prisms) was achieved under relatively low stress, which is very advantageous; a high-energy dissipation can be achieved under low stress.

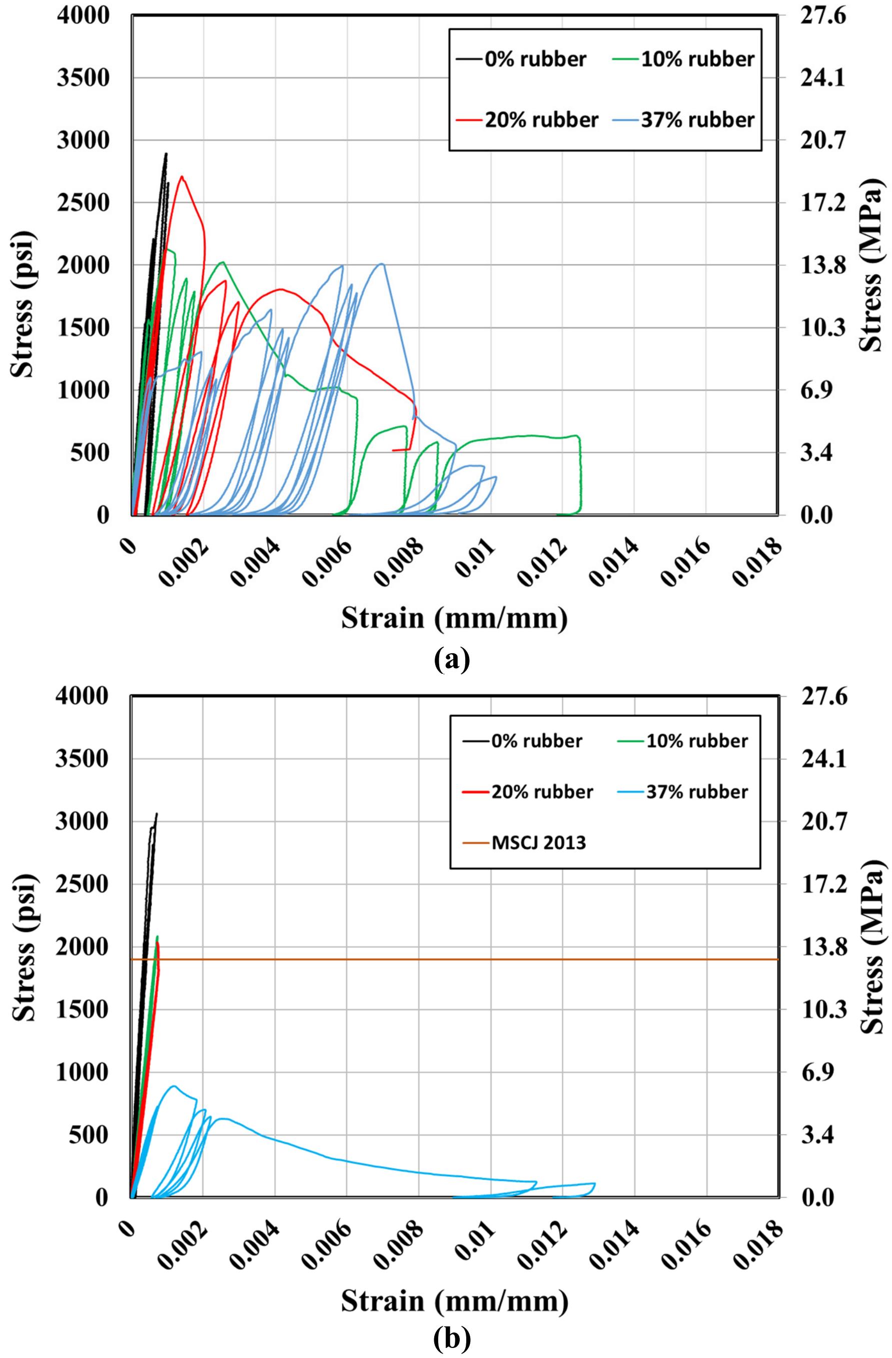


Figure 6: Stress vs. strain for four blocks height masonry prisms (a) grouted prisms (b) ungrouted prisms

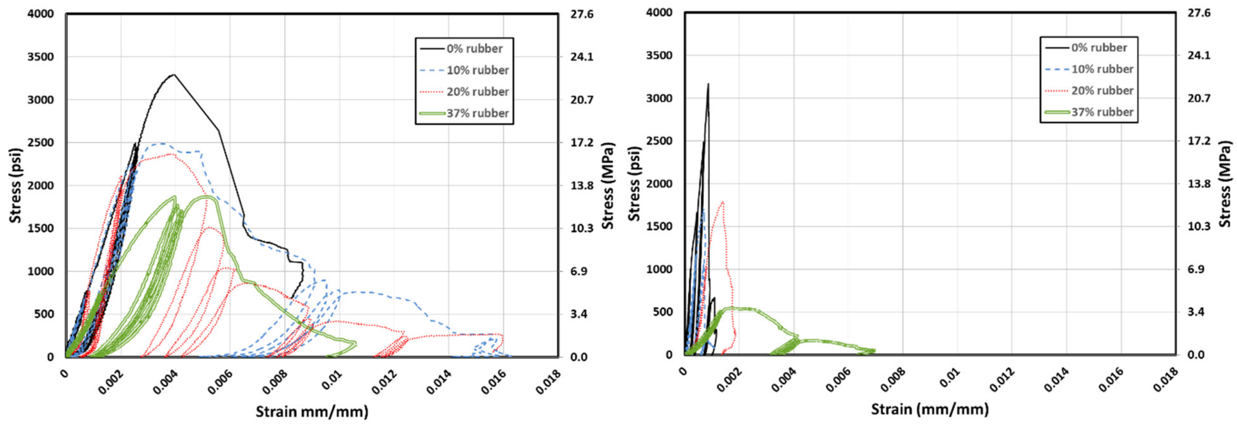
Another beneficial feature was recorded for the RCMUs prisms regarding the failure mechanism. Failure in the conventional CMU prisms was quite brittle and sudden. In contrast, RCMU prisms were able to sustain displacement cycles beyond the peak stress. For example, RCMUS having 20% rubber replacement ratio, exhibited gradual ductility and were able to resist three displacement cycles corresponding to a strain of 192% of its peak strain at a stress value of $0.67f'_m$ (Fig.6a).

RCMU prisms reached their maximum stress under a relatively high strain because the rubberized block had the ability to deform until the high strength grout reached its maximum strain. In contrast, the conventional CMUs collapsed early due to face shell spalling while the grout displayed no or micro-cracks (Fig. 7). This explains the limited effects of rubber content on the strength of the RCMU prisms.

(a) **(b)**

Figure 7: Failure mechanism for four blocks height prisms with no rubber added. (a) side view (b) front view

As shown in Figures 8a and 8b, the peak strain in each two-block high prism was higher than that measured in four-block high prisms with the same rubber content. As was stated by ASTM C1314–12 the compressive strength of two-block height prisms is higher than that of four-block height prisms.



(a) **(b)**

Figure 8: Stress vs. strain for two blocks height masonry prisms

(a) grouted prisms (b) ungrouted prisms

The initial stiffness of the investigated prisms was calculated and presented in table 2. The table shows the influence of crumb rubber content on prism stiffness. For the grouted prisms, increasing the rubber content from 0% to 37% decreased stiffness from 23.44 GPa to 12.48 GPa which represents a reduction of 47%. Regarding the ungrouted prisms, increasing the rubber content from 0% to 37% decreased stiffness from 31.03 GPa to 6.58 GPa which represents a reduction of 79%. The influence of rubber on stiffness was less in the grouted prisms because they all have the same type of conventional grout without any amount of rubber.

CONCLUSIONS

Four different ratios of crumb rubber, namely, 0%, 10%, 20%, and 37% were used as a replacement for mineral fine aggregate. RCMU prisms having two different heights (2 blocks and 4 blocks) were investigated. The prisms were subjected to a cyclic axial load in a displacement control. The compressive strength, peak strain, and initial stiffness of RCMU prisms were compared to those of CMU prisms. 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 rubberized masonry block units that meet the requirements of the ASTM C90.

• The use of rubber in masonry block units has a significant impact on increasing the peak strain.

• The use of rubber in masonry block units influences the initial stiffness and ductility for both grouted and ungrouted prisms.

• There is no significant loss in compressive strength when rubberized masonry units are used in fully grouted prisms.

• The capping type and prism height have a significant impact on strain measurements. Sulfur and gypsum capping apply extra confinement at the top an bottom ends of prism which influence the strain readings.

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