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IMPACT RESISTANCE ASSESSMENT OF INTERLOCKING COMPRESSED EARTH BRICKS (ICEB) INCORPORATING CRUMB RUBBER

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Graphical abstract

Abstract

Interlocking compressed earth bricks (ICEB) are a cleaner and sustainable alternative to conventional fired bricks and it has comparable strength to other masonry systems, making it feasible for both cladding and load-bearing purposes. However, it tends to be brittle and has poor performance under impact loading. Impact resistance of masonry walls are important as one of the main purposes of cladding is to protect its occupants from external projectiles. This study was commissioned to investigate the feasibility incorporating both crumb rubber (CR) and treated CR into ICEBs in place of sand to improve its impact resistance. The drop weight impact tests carried out concluded that ICEBs containing CR have better impact resistance and this was further improved with heat-treated CR. Heat-treated CR ICEBs also had less catastrophic failure compared to untreated CRs which had pieces of materials spalling off. Mechanical tests also show that this improvement in impact resistance comes at the expense of a minor loss in compressive and flexural strength at replacement levels higher than 7.5 %. Heat-treated CRs also showed higher losses of mechanical strength compared to untreated CRs.

Keywords: Interlocking compressed earth bricks, crumb rubber, treated crumb rubber, impact resistance, drop weight test

Abstrak

Interlocking compressed earth bricks (ICEB) ialah alternatif yang lebih bersih dan mampan daripada bata biasa dan ia mempunyai kekuatan yang setanding dengan sistem batu lain, menjadikannya sesuai untuk tujuan pelapisan dan penggalas beban. Walau bagaimanapun, ianya senang rapuh dan tidak sekuat dari segi rintangan beban impak. Rintangan hentaman adalah penting kerana ianya diugunakan untuk melindungi penghuni bangunan daripada peluru dari luar. Kajian ini bertujuan untuk menyiasat kebolehlaksanaan memasukkan getah remah (CR) serta CR yang terawat ke dalam ICEB sebagai bahan gantian pasir. ICEB yang mengandungi CR terawat juga berupaya mengurangkan keamatan mod kegagalan. Ujian hentaman mendapati bahawa ICEB yang mengandungi CR mempunyai rintangan hentaman yang lebih baik dan ini telah dipertingkatkan lagi dengan CR yang terawat. Namun, ia juga menyebabkan kehilangan kekuatan mampatan dan kelenturan jika tahap gantian melebihi 7.5 %. CR terawat juga kehilangan kekuatan mekanikal yang lebih tinggi berbanding CR biasa.

Kata kunci: Interlocking compressed earth bricks, getah remah, getah remah yang dirawat, rintangan hentaman, ujian hentaman

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1.0 INTRODUCTION

The world's population is expanding every year, which has a significant impact on the demand for products made of rubber and leads to a significant growth in rubber waste production. Rubber waste recovery is more challenging than recovering other wastes because of its complex composition. The main source of waste rubber is automobile and truck tyres. To ensure their durability and strength, tyres are made from a range of materials. The effort to stop waste rubber from ending up in landfills faces substantial obstacles because of these compositions. Tires for cars, trucks, and off-the-road (OTR) use materials such rubber, carbon black, metal, cloth, zinc oxide, sulphur, and additives. Rubber scraps can be difficult to recycle due to the presence of a three-dimensional network created during the vulcanization process, a wide range of compositions, and other factors.

Globally, the recovered waste rubber percentages are still fairly low, calling for comprehensive solutions. Every nation generates and recovers a different amount of waste rubber with Canada being the most effective nation, recovering nearly 100% in 2015. According to data from the Canadian Association of Tire Recycling Agencies (CATRA) Annual Report 2016, as cited by the World Business Council for Sustainable Development [1], strong public engagement, well-developed regulations, and a supportive government has helped Canada to maximize efficiency in waste tyre recovery. In Canada, used tyre recycling programmes sponsored by non-profit organisations serve as the primary means of provincial regulation for end of life tyres (ELTs). The low recovery rate was a result of the absence of a legal framework for ELT management in Argentina as well as the need for financial support during the course of therapy. Due to an increase in the number of motorised vehicles, insufficient operations, a lack of investment in generating and processing equipment, a lack of monitoring, and infrequent reporting, Saudi Arabia is unable to recover a significant amount of waste rubber.

Early intervention and practical solutions were therefore required to lessen the adverse effects on the ecology. In order to lessen the detrimental effects on the ecology, quick action and practical solutions were required. The major producer of rubber used to make tires is the transportation sector. Over billion tires are disposed of each year, with predictions that number will rise to 1.2 billion by 2030, according to earlier studies [2]. The annual tonnage of scrap tires in Peninsular Malaysia has increased year on year, as was the case from 2007 to 2010. The number of trash tires generated increased from 208,911 in 2007 to 245,087 in 2010. The amount of scrap tires increased by 17% between 2007 and 2010 [3]. An effective way to reduce the harmful effects of mass tire trash on the environment is to recycle and reuse tire waste into something useful, especially in the construction industry. One form of recycled tire waste used in the industry is as crumb rubber (CR). CRs are produced by running the scrap tires through a shredder initially to reduce it to smaller chips. These shredded tires are then mechanical ground to reduce its size even further whilst at the same time removing any steel and fibers contained within [4]. These recycled CRs are commonly used in sports surfaces, floor mats as well as rubberized asphalt in highways [5]. CR has also been adopted in building structure materials such as usage in high strength concrete [6] but overall it was less notable as rubber properties are seldom sought after as a structural material except where high dynamic modulus is required such as for impact or ballistic resistance applications.

In building structures, impact and ballistic protection are typically offered by the walls and cladding which are normally constructed from bricks. Common types of bricks used in the industry are fired clay bricks (FCB), concrete blocks as well as compressed earth bricks (CEB). However, conventional masonry systems tend to be brittle and have poor impact resistance. Masonry up to 90 mm thick has been shown to be able to resist up to 9 mm ammunition [7] but easily penetrated by higher velocity and heavier rounds such as the .223 Remington and .308 Winchester [8]. This meant standard masonry walls require additional strengtening or increase in thickness in order to provide any meaningful ballistic protection. In the past, however, some investigations have been successfully carried out looking at the prospect of using waste tyre rubber to enhance the ballistic properties of concrete panels [9].

Compressed earth bricks (CEB) are a novel type of engineering brick manufactured through hydraulic compaction of a mix of laterite clay, sand, cement and water [10]. The omission of the firing process makes CEB a clean alternative to the common FCBs [11]. Many CEBs also feature an interlocking design, allowing each unit to physically lock with subsequent upper and lower units to prevent shear movement. These CEBs are known as interlocking compressed earth bricks (ICEB) and typically measure around 250 mm long, 125 mm wide, and 100 mm tall. In addition to normal ICEB, two further ICEB variants, U-shape and half ICEB, are developed with the goal of reducing the use of reinforced concrete structural members [12]. Previous studies had emphasized how using soil as a readily accessible resource for building has facilitated the development of appropriate and sustainable built environment technology, as well as advantageous impacts across the economic spectrum and a wide range of social and technological advancements [13]. Interlocking compressed earth blocks (ICEBs) are a durable and economical building material that can be created using either hand-operated or motorized hydraulic machinery, and they have the potential to bring enduring housing options to low income nations worldwide [13]. In addition, ICEBs have demonstrated their viability as low carbon emission building materials. Compared to the ordinary burned clay brick (FCB), the ICEB produces carbon emissions at a rate that is 30 % lower [14].

In this study, the impact resistance of ICEB is investigated using the drop test method. Past research has shown that crumb rubber in concrete has shown potential for increased dynamic modulus of elasticity [15] which may translate to good energy absorbing abilty. Similar tests have been carried out using rubberized reinforced concrete with some success [16]. Thus, this research also looked into the possibly of replacing some of the sand in the ICEB mix with crumb rubber as well as heat-treated crumb rubber at rates of 5 %, 7.5 %, and 10 %, respectively. Even though it has been found that the compressive strength of masonry had very little influence on its impact resistance [8], compressive and flexural strengths were still important to the structural integrity of the wall and these properties may be affected by the inclusion of crumb rubber. Furthermore, past studies involving concrete specimens containing CR heated at 200 °C had shown slightly elevated impact resistance [17] but it is rather impractical to heat up entire blocks of concrete.

This study served to provide understanding into the effectiveness of incorporating CR into ICEBs in place of sand to enhance its impact resistance as well as investigate how the pre-heated CR influences these results. Additional investigation was also carried out into the crack propagation pattern of ICEBs resulting from the impact tests, as well as assessing the knock-on effect of the addition of CR on other mechanical properties such as the compressive and flexural strength. The crumb rubber samples were also characterized to understand its chemical composition, particle size distribution as well as the effects that the heat treatment has on its phase morphology.

Ultimately the study fills the gap where there is a current lack of study provides useful knowledge on the feasibility of ICEBs containing CR for use as impact and ballistic resistance cladding and identifies any additional beneficial or adverse effect it may also impart.

2.0 METHODOLOGY

Materials and Preparation

The main test material is crumb rubber (CR) which was sourced from a local business specializing in disposal and re-threading of used tyres. Visual inspection of the CR showed pre-dried black strips of cut rubber (Figure 1) from the tyres. The CR was supplied in large sealed polyethelene bags.

Figure 1 Crumb rubber as supplied

The control ICEBs were prepared using ordinary Portland cement (OPC) as stabilizer as well as river sand and laterite soil in a mix ratio of 1:2:3. The stabilizer used was Ordinary Portland Cement Grade CEM II with nominal strength of 32.5 MPa and conforming to BS EN 197-1. Sand used was washed river sand from Papar region in Sabah, Malaysia whilst the laterite soil was also locally sourced from the vicinity of Tuaran in Sabah as well. The final ingredient was water which was pulled from potable tap water source located at the Faculty of Engineering, Universiti Malaysia Sabah, which was also the location where the bulk of the testing were carried out. An X-Ray Fluorescence (XRF) analysis was conducted on all the materials used the CR sample to determine its chemical composition. A summary of the chemical composition of the materials above is presented in Table 1.

Table 1 Chemical composition of materials, % wt.

Material	Rubber hydrocarbons	Carbon black	Ash
Crumb rubber (CR)	52.1	12.2	18.0

Material	SO_3	SiO_2	Fe_2O_3	CaO	Al_2O_3
River sand (RS)	0.5	83.2	1.8	0.3	6.3
Laterite soil	0	65.7	8.2	0.1	21.1
OPC	4.0	14.2	3.8	72.2	3.9

It can be seen that CR mainly comprise of rubber hydrocarbons, carbon black and ash. This chemical composition was similar to those reported in earlier studies [18]. Rubber hydrocarbons at 52.1 % make up bulk of the content of CR. This was expected as high rubber hydrocarbon contents (> 42 %) are crucial for strong and durable tires [5]. This was followed by ash which accounts for about 18.0 % whilst the rest is made up of carbon black.[5].

On the other hand, RS which CR is replacing comprised mostly of SiO_2 which stood around 83.2 % followed by 6.3 % Al_2O_3 and 1.8 % Fe_2O_3 making up the rest.

A particle size analysis was also conducted on the CR and RS samples to gain an insight into their particle size distribution as well as corresponding specific surface area. The particle size distribution of both CR and RS are presented on Figure 2.

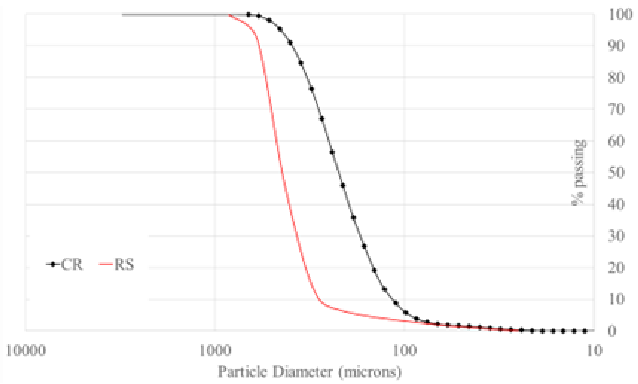

Figure 2 Particle size distribution of crumb rubber (CR) vs river sand (RS)

The particle size of CR tested ranged from 445 to 132 µm. Other papers, however, have reported size distribution as large as 9.5 to 0.5 mm [19], indicating that there could be great variability in CR particle sizes. The CR samples that were replacing the RS generally appeared finer with a mean particle size of 252.0 µm as opposed to the 443.0 µm for the RS samples as shown on Table 2. This again is in contradiction with past research where the sand samples were finer than the crumb rubber [17]. In fact, the d_{90} sizes of CR were very similar to the mean sizes of RS. Similar observations were also made for the 10th and 90th percentile sizes. As a result of its fine particles, the CR particles had more than twice the specific surface area at 27.6 m^2/kg compared to the 12.6 m^2/kg of the RS samples'.

Table 2 Specific surface area and particle sizes

Material	Specific surface area (m^2/kg)	Particle size (µm)		
		d_{10}	d_{50}	d_{90}
Crumb rubber (CR)	27.6	131.8	252.0	445.2
River sand (RS)	12.6	263.1	443.0	591.9

To produce the treated CR (RT) used in ICEB-RT units, the CR samples were thermally treated in a ventilated laboratory oven that allowed the smoke to be expelled safely into the environment. Each cycle of the thermal treatment consisted about 500g untreated CR being placed in the aluminium foil tray, spread out to ensure even heating rates for all specimens. The oven was then programmed to heat up from room temperature to the final target temperature of 200 °C and maintained for 60 minutes. After that, the CR samples were removed from the oven and allowed to cool back down to room temperature. Upon closer observation, the CR samples tend to agglomerate into larger particles after the thermal treatment. Thus, subsequent grinding using a planetary ball mill was done to return it to a finer particle size distribution.

An X-Ray Diffraction (XRD) analysis was carried out on the untreated crumb rubber (RU) as well as the treated crumb rubber (RT) sample to examine the changes that the thermal treatment had on the morphology and crystallinity of CR. This was done on a Rigaku Smartlabs X-Ray diffractometer operated at wavelength of k1 = 1.54059 and k2 = 1.54441, scanning mode of 2 theta from 3 to 90 °. The XRD results also allowed investigation into the change into the level of crystallinity resulting from the thermal treatment.

Mix Proportions

For the mechanical testing, two types of ICEB units prepared namely the control sample as well as the test ICEB-RU and ICEB-RT containing untreated and treated CR respectively to replace the RS content. The replacement percentages of treated and untreated CR investigated were 5, 7, and 10%. The mix proportions are presented on Table 3. It has previously been reported that any excessively high levels of replacement above 20 % would be detrimental to its mechanical properties [20].

Table 3 Mix proportion of ICEB unit specimens, % wt.

Mix	Fine aggregates (kg)			Stab. (kg)	Soil (kg)
	Sand	RU	RT	OPC	Laterite
CONTROL	33.3	-	-	17	50
ICEB-RU50	31.6	1.7	-	17	50
ICEB-RU75	30.8	2.5	-	17	50
ICEB-RU100	30.0	3.3	-	17	50
ICEB-RT50	31.6	-	1.7	17	50
ICEB-RT75	30.8	-	2.5	17	50
ICEB-RT100	30.0	-	3.3	17	50

Production of ICEB Units

All ICEB units were produced using a semi-automated production line which crushed the dried laterite soil before mechanically mixing it with the water, OPC, RS and RU/RT specimens. The mixture would then be transported via conveyor to be poured into a stainless steel ICEB mould to be hydraulically pressed into shape. The mould allowed casting of standardized ICEB units measuring 250 mm x 150 mm x 100 mm with two hollowed cylindrical cores on either side (Figure 3). The bottom face features a trough that acts as a shear key then interlocked with the protrusion its top surface when two units are laid onto of one another.

The cast ICEB units were then allowed to cure under cover for 28 days with intermittent wetting periods by subjecting them to light water spraying. On the testing day, the ICEB units were oven-dried for 24 hours at 115°C to remove all moisture present from the sample.

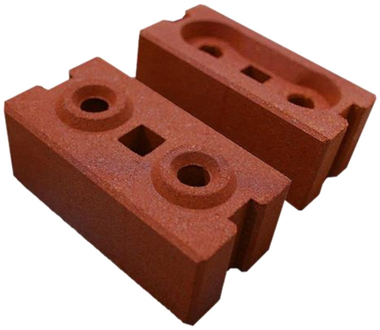

Figure 3 Interlocking compressed earth brick units (ICEB) units as produced

Testing of ICEB Units

The control and test ICEB specimens were subjected to three different types of mechanical testing to assess its structural performance. The first of these is the compressive strength test to determine the ICEB unit's load carrying capacity. Compressive strength tests have long been used as a yardstick in determining the structural performance of materials used in construction. The compressive strength test was done using a universal testing machine that subjected the ICEB unit to crushing loads by pressing it from the top and bottom simultaneously until failure and no further pressure could be applied.

The second type of mechanical test was the flexural strength test, which is essentially a combination of compressive and tensile stresses applied together to specimen until failure. For this research, the three-point bending test was used to assess the flexural strength of ICEB units.

Finally, to determine the impact resistance of ICEB units, drop weight tests were conducted. The drop weight impact tests allow assessment of the magnitude of impact energy the ICEB units can absorb. Similar test have been used in the past to investigate impact resistance of concrete [21]. The test setup is depicted in Figure 4. The setup is a variation of the drop test proposed in the past for testing polymer composites [22] and fiber reinforced concrete [23]. The apparatus consisted of a wooden frame, an electromagnetic release device, a 1 kg steel ball as the impactor and a white witness plate for the background for video recording. A rounded ball projectile was used as it would be similar to a bullet head. The ICEB units were laid on their side to simulate projectile impact onto the exposed side surface of the units when they are eventually used as wall units. To avoid the ICEB from coming into direct contact with the floor, which could affect the outcome of the impact test due to the support from the floor surface, a wooden frame was used. A magnet held the impactor in place at 0.45 m above the target surface until such a time when the weight is ready to be dropped. This allowed for a maximum impact velocity of nearly 3.0 m/s, corresponding to an impact energy of 4.4 J.

Figure 4 Drop impact test apparatus setup

In this investigation, the impactor weight was repeatedly dropped onto each ICEB surface. By counting the number of impactor blows required to achieve failure of the units, the impact resistance of the ICEB units could be estimated. The impact resistance energy from two types of failure were recorded; the initial failure when microcracks were first observed on the ICEB surface as well as the ultimate failure when the ICEB disintegrated, and no further impact could be sustained. For each test result, a set of three replicates were tested to obtain the average impact energy.

3.0 RESULTS AND DISCUSSION

This section discusses the results and observations from the characterization of untreated CR (RU) and treated CR (RT) as well as the tests of ICEB units containing partial replacement of sand with RU and RT.

Morphology of Untreated (RU) and Treated Crumb Rubber (RT)

Microscopic level inspection (Figure 5) of the RU sample showed particles that were mostly angular in nature and of varied sizes. The smaller particles appeared to have crumbled surfaces with many particles agglomerating together whilst the larger ones have smoother faces. Some of the smaller particles were also observed adhering onto the surfaces of the larger ones. After subjected to the 200 °C heat treatment and re-grinding, the RT particles had not appeared to change much visually but more agglomeration of the larger particles appeared to have taken place.

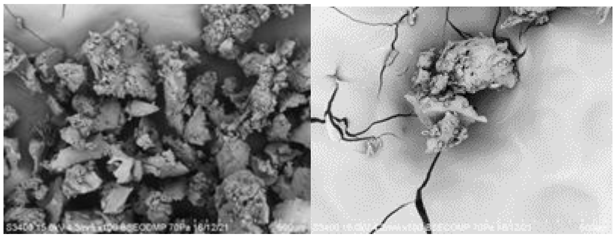

Figure 5 Magnified (x100) images of RU (left) and RT (right) particles

The XRD analysis of RU (Figure 6) detected mostly crystalline manganese zinc oxide (denoted by 'M'), with the highest intensity occurring at 2 theta of 36.24 °, followed by 31.79 ° and 34.43 °. The minor crystallinities were detected at 47.6 °, 56.56 °, 62.85 ° and 67.92 °. Overall crystallinity of the material was estimated to be about 32 %.

After being subjected to heat treatment, the RT samples reduced in overall crystallinity by about 6% to 26 %. This can be seen in the markedly reduced peaks on the diffractogram in Figure 5 for RT sample where the highest peak of 36.24 ° had gone down to an intensity of 1661 from 2770. This loss in crystallinity was expected as most research have indicated that heat treatment would tend to reduce crystallinity of materials and rendering it more amorphous [24].

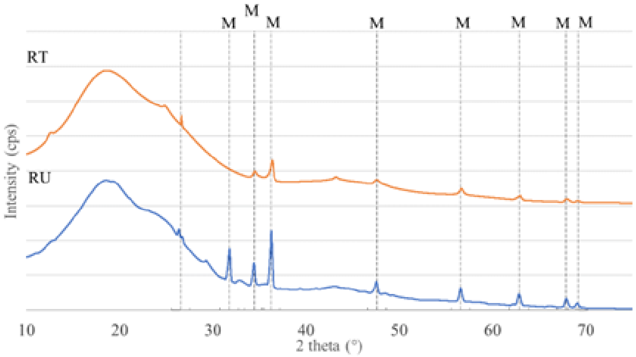

Figure 6 X-Ray Diffractogram (XRD) comparing RU and RT

Compressive Strength of ICEB Units

The control ICEB unit attained a compressive strength of 5.21 N/mm² which exceeded the stipulated compressive strength of 5.0 N/mm² for clay masonry units as specified by BS 3921. The incorporation of RU in ICEB (Figure 7) saw an increase in compressive strength to 6.9 N/mm² at 5 % replacement level but this reduced significantly as replacement levels increased further. For example, at 7.5 % replacement, the strength had gone down to 3.8 N/mm² whilst at 10 % replacement, it was even lower at only 4.1 N/mm², both of which were below the control ICEB's strength. This finding was consistent with past studies which also found that compressive strength of masonry blocks reduces proportionately with increasing percentages of crumb rubber [25]. Similarly past studies have shown that the inclusion of RU in other building materials such as concrete is typically associated with loss of compressive strength [26]. However, one contrasting observation that could be made here was how the ICEB-RU unit with 5 % replacement showed higher compressive strength than the control unit at 6.9 N/mm², hinting at the possibility that inclusion of RU at very low replacement levels may have a positive improvement to strength. However, levels of replacement of 7.5 % and beyond show a reduction in strength despite past research involving concrete claiming to be not the case [2].

The use of RT in place of RU saw degraded compressive strength performance where all the test ICEB units attained sub-par strength compared to the control units. Against units containing RU, ICEB-RT units with 5 % RT replacement saw reduced strength from 6.9 to 4.5 N/mm² whilst at 7.5 % replacement, a minor improvement from 3.8 to 5.0 N/mm² was observed. Finally at 10 % replacement, the strength reduced from 4.0 to 3.5 % in the RT units. Of noteworthy feature observed here was how the strength profile between ICEB-RU and ICEB-RT were inversed. It appeared here that the treatment of CR using heat did not improve its compressive strength properties, despite showing increased amorphousness earlier in XRD tests.

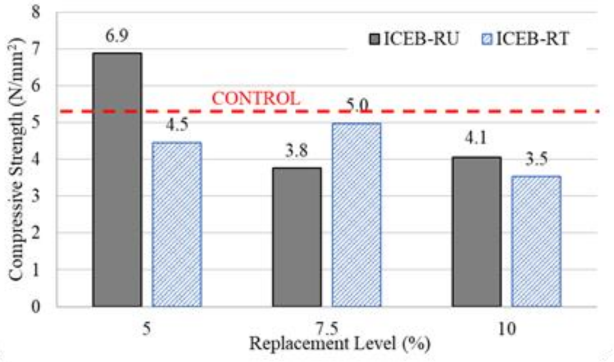

Figure 7 Compressive strength of ICEB containing partial replacement of RU and RT

Flexural Strength of ICEB Units

As seen in Figure 8, the control ICEB unit attained a flexural strength of 2.82 N/mm² which, as expected, was lower than the compressive strength. However this was higher than what was discovered in post research involving similarly sized ICEB unit [27]. ICEB-

RU demonstrated very slightly elevated flexural resistance for units with 5 and 10 % RU replacements at a strength of 3.2 and 2.9 N/mm² respectively. However, the ICEB-RU with 7.5 % replacement had slightly lower strength than the control unit.

It appeared that inclusion of RU in ICEBs had very minor effect on its flexural strength but the increase in flexural strength at 5 % replacement appeared to be similar to the observations made in the compressive strength tests. Past studies have shown that significant amounts of RU replacement (20 %) in masonry units have deleterious effect on its flexural strength [28].

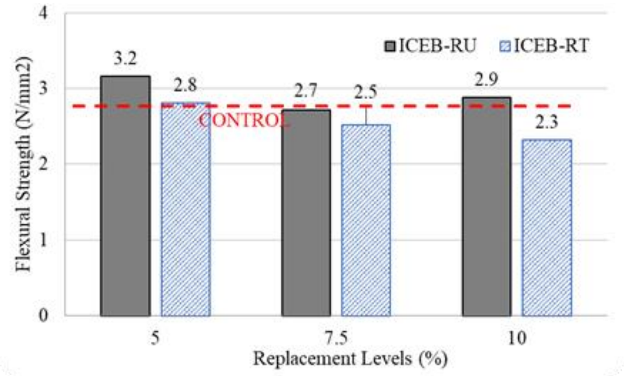

Figure 8 Flexural strength of ICEB containing partial replacement of RU and RT

Incorporating RT in ICEBs saw decline in flexural strength across all three levels of replacements investigated when compared against ICEB-RU. ICEB-RT with 5 % replacement was still able to generate sufficient flexural strength to surpass that of the control unit but at higher levels, the strength was consistently below that of the control unit.

The performance of ICEB-RTs here appeared very similar to the ones observed in the compressive strength tests where it generally all under-performed against ICEB-RUs. It would appear then that treatment of CR did not have any beneficial impact to the flexural strength of ICEBs. This has been well documented in past research where tensile strength of concrete degraded with the inclusion of CR [29].

Impact Resistance of ICEB Units

The energy absorbed by the ICEB units just prior to initial failure is shown on Figure 9. The control ICEB unit was able to absorb 7.36 J prior to development of first cracks. Partially replacing the sand contents with RU saw a very significant increase in the ability to absorb energy across all levels of replacement. The most significant of these was observed at 5 % replacement where the impact resistance increased to 20.6 J, which represented an increase in excess of 280 %. However, as replacement levels increased, the ability to absorb impact energy also decreased, as evident from the ICEB-RUs with 7.5 and 10 % replacement both absorbing 11.8 J at initial failure. Despite this, these were still markedly higher than the control unit in terms of impact resistance.

These results indicate that there is an 'optimal' replacement level in terms of energy absorption ability where excessively high replacement level would actually be counter-productive.

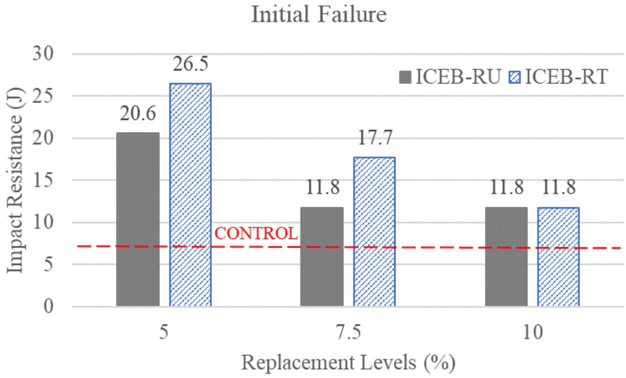

Figure 9 Impact resistance at initial failure

Replacing the RTs with RUs improved the ICEB units ability to absorb energy even further generally, exceeding the ICEB-RU energy absorption level across all levels of replacement. The ICEB-RT units with 5 % replacement yielded the highest energy absorbed at 26.5 J, followed by 17.7 J at 7.5 % replacement and finally 11.8 J at 10 %. As with the ICEB-RU units, as levels of replacement increase, the ability to absorb energy reduces.

Incorporating treated CRs in place of untreated ones clearly had a distinct benefit to ICEBs in terms of energy absorption ability, especially at the lower levels of replacement at 5 and 7.5 %. It can be said that in terms of impact resistance at initial crack, the lowest level of replacement of 5 % appeared to be the best performing for both ICEB-RU and RT units.

As expected, for ultimate failure to occur, the overall impact energy was clearly higher than those needed for initial cracking of the ICEB units. As seen in Figure 10, the control ICEB unit was able to absorb up to 11.8 J just prior to ultimate failure. With the incorporation of RU at 5 % replacement, the impact resistance improved to 26.5 J although subsequent increases in replacement levels reduced in efficacy. This is evident as 7.5 % replacement saw a drop in the resistance down to 17.7 J whilst at 10 % replacement it was also lower at 19.1 J.

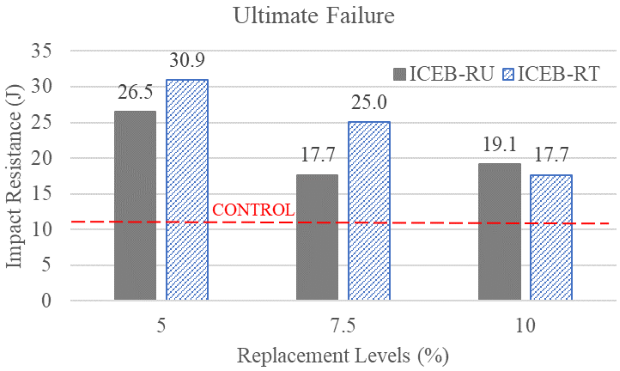

Figure 10 Impact resistance at ultimate failure

Incorporating RTs in place of RU saw increase in impact resistance at ultimate failure. The highest impact resistance was achieved by ICEB-RT unit with 5 % replacement at an energy of 30.9 J, whilst the unit with 7.5 % attained the second highest resistance at 25.0 J. The ICEB-RT unit with the lowest resistance was the one with the highest amount of replacement at 10 %, offering only 17.7 J of resistance which was even lower than that of its equivalent ICEB-RU strength. These results agree with past research where heated-treated blocks of concrete containing RU showed improved impact resistance[17].

A visual inspection of the ICEBs upon initial cracking showed hairline cracks less than 0.1 mm developing from the impact point at the top surface of the unit that propagated all the way down the to the bottom (Figure 12). Besides the expected minor abrasion caused by the dropped weight, there was no other noticeable spalling damage or denting to the impact surface of the unit.

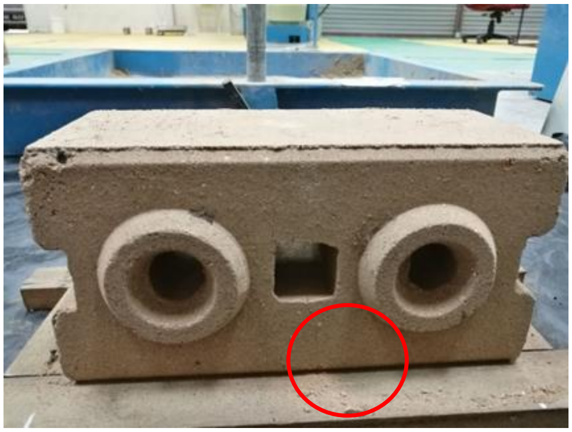

Figure 11 Crack pattern at initial failure

At ultimate failure, a full depth crack developed across the width of the surface of the ICEB-RU unit (Figure 11) where the impact occurred. This was expected as it presented the shorter path to the unrestrained edge of the unit as opposed to one that runs along the longitudinal length of the unit which would have presented a longer path to take. As it propagated down the unit, the crack path diverged and split into two which allowed a piece of the ICEB unit to fracture and become loose. More microcracks were also observed to have developed on the impact surface, spreading outward from the impact point in a spiderweb pattern.

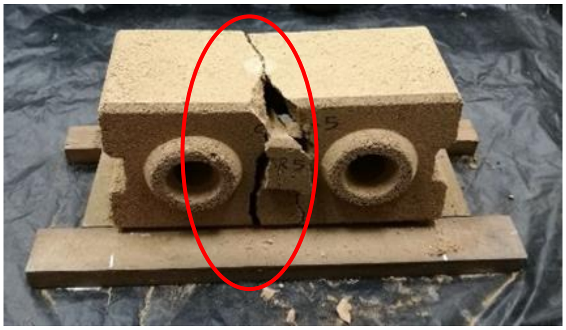

Figure 12 Crack pattern at ultimate failure, ICEB-RU

Similar observations could be made for ICEB-RTs (Figure 13) as well with fracture line developing across the width of the unit and extending downward to the bottom as well.

Figure 13 Crack pattern at ultimate failure, ICEB-RT

This observation signified that the cracks on the impact surface tend to develop in toward the closest unrestrained edges of the unit. This is very similar to how the flexural cracks develop in suspended slabs as well.

4.0 CONCLUSION

This study investigated the impact resistance offered by ICEBs containing crumb rubber as well as treated crumb rubber replacement by means of heating. Drop impact tests were carried out to assess this. At the same time, the effect of crumb rubber on the compressive and flexural strength of ICEB units were also investigated.

Untreated crumb rubber replacement in ICEBs was able to improve its impact resistance for the initial and ultimate failure stages very significantly, more than doubling it, especially at the optimum level of replacement of 5 %. Although higher replacement levels also saw reduced improvement to the overall impact resistance effectiveness.

Substituting the untreated crumb rubber with heat-treated ones saw even better impact resistance at both initial and ultimate modes of failure. Again, its impact resistance performance 5 % level of replacement was better than if it was higher.

Use of crumb rubber in ICEBs typically detrimental to both its compressive and flexural strength unless the level of replacement was limited to 5 %.

As with most materials, the low heat treatment applied to crumb rubber caused it to lose crystallinity and increase in amorphousness.

Despite this, the compressive strength of ICEBs was not improved by the reduction in crystallinity the heat-treated of crumb rubber. Similar observations could be made for the flexural strengths of ICEBs as well in terms of the use of treated crumb rubber.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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