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A review of the effect of waste tire rubber on the properties of ECC

Isyaka Abdulkadir [1, 2, *], Bashar S. Mohammed [1], M. S. Liew [1], Mohamed Mubarak Bin Abdul Wahab [1], Noor Amila Wan Abdullah Zawawi [1], Sholihin As'ad [3]

[1] *Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Malaysia*
[2] *Civil Engineering Department, Bayero University, Kano, Nigeria*
[3] *Department of Civil Engineering, Faculty of Engineering, Universitas Negeri Sebelas Maret Surakarta, Surakarta, Indonesia*

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ABSTRACT

Due to the growing concern over the adverse effect and threat posed by waste tire all over the world, researchers have over the last two decades focused attention on the use of rubber obtained from the waste tire in the form of crumb rubber (CR) or powdered rubber (PR) as a construction material by incorporating it in cementitious composites. Although there exists a lot of research on the use of CR/PR in cementitious composites, the only literature reviews available are on rubberized mortars and concrete but not on engineered cementitious composites (ECC). This paper aims at contributing towards filling this gap by reviewing relevant research works on the use of CR/PR in ECC. The effect of the tire rubber addition on the properties of the composite in fresh and hardened states have been comprehensively reported. The results revealed that the incorporation of tire rubber in ECC enhances the tensile ductility but negatively affects the compressive strength.

1. Introduction

The quest for a more ductile cementitious material capable of withstanding tensile stresses leads to the development of Engineered Cementitious Composite (ECC) (Mohammed et al., 2019; 2018a; Khed et al., 2020). ECC is a special type of High-Performance Fiber Reinforced Concrete (HPFRC) developed in the 90s (Ma et al., 2015; Kamal et al., 2016). Unlike other concretes, ECC has an exceptional ductility with a tensile strain capacity of 3-5% in contrast to 0.01% of conventional concrete and 0.5% of High performance fiber reinforced concrete (Mohammed et al., 2018b; 2017; Yu et al., 2015b; Khed et al., 2018a; Anwar et al., 2019). One of the amazing characteristics of ECC is its strain hardening ability under tensile stresses due to the formation of steady-state micro-cracks, as depicted in Fig. 1 (Wu and Li, 2017; Mohammed et al., 2014). These multiple tiny cracks have widths in the order of less than 100µm (Mohammed et al., 2018a; Lye et al., 2020). This ability, apart from making the ECC very ductile, also ensures its durability due to the reduced permeability as a result of the tightly packed micro-cracks (Zhang et al., 2015; Yu et al., 2015b). The compressive strength of ECC ranges from 35 to 100 MPa and a tensile strength of 2 to 7 MPa (Achara et al., 2019). Materials used for ECC are the same with those used for other concrete with the only exception being that coarse aggregate is completely omitted in the mix (Chethan et al., 2015). Also the fiber (usually Polyvinyl Alcohol Fiber) volume fraction is usually kept at or below 2% (Soe et al., 2013; Yu et al., 2015b; Mohammed et al., 2019; Kamal et al., 2016). The design and optimization of ECC to achieve its desired properties are done through the use of micromechanics principles. That ensures the tailoring of the fiber, the matrix, and the fiber-matrix interphase at the microscale level to achieve the desired ECC behaviors (Chethan et al., 2015).

Over the past two decades, a lot of research to improve the properties and behavior of ECC based on micromechanics theories and different materials have been and are still being carried out (Meng et al., 2017; Ma et al., 2015). Several researchers have investigated the properties of ECC in a fresh state (Yang et al., 2009; Mohammed et al., 2017) and at a hardened state (Li et al., 2001; Meng et al., 2017). Similarly, the durability performance of ECC has been investigated by numerous researchers (Mohammed et al., 2015; Liu et al., 2017) as well as its behavior at elevated temperatures (Mohammed

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* Corresponding Author.
Email Address: isyaka_18000638@utp.edu.my (I. Abdulkadir)
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Corresponding author's ORCID profile:
https://orcid.org/0000-0002-3620-5310

et al., 2018a; 2019). The use of waste tire rubber in ECC has also been investigated by numerous researchers (Khed et al., 2018a; Wang et al., 2019; Zhang et al., 2019; Mohammed and Azmi, 2014).

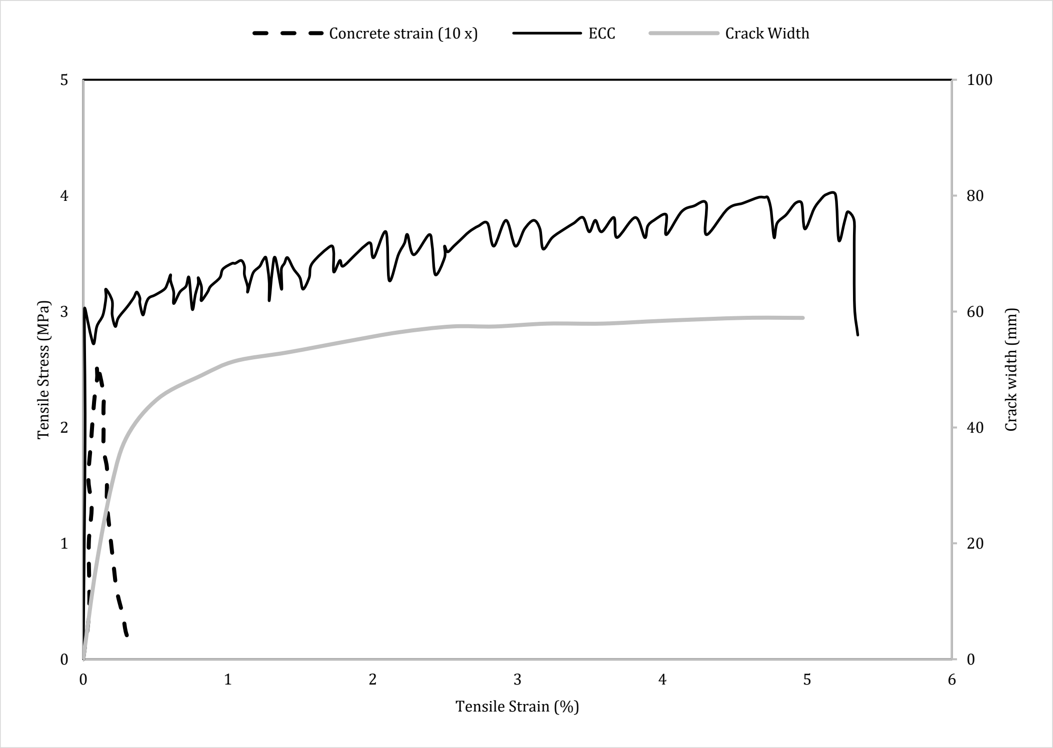


Fig. 1: Tensile stress-strain curve with tight crack width of a typical ECC (Van Mier et al., 2013)

Solid waste disposal has been one of the biggest global environmental problems for a very long time (Alaloul et al., 2018). The ever increasing global environmental challenge posed by the disposal of solid wastes particularly used and discarded tires has attracted the interest of researchers to focus on finding alternative ways of positively exploiting the menace (Chen and Lee, 2019; Sofi, 2018; Li et al., 2019; Al-Fakih et al., 2019; Mohammed et al., 2012; 2018c; 2018d; Al-Fakih et al., 2018). The use of crumb rubber (CR) obtained from waste tires as a sustainable construction material is among the feasible ways of safely getting rid of the problem (Mohammed, 2010; Mohammed and Adamu, 2018; Youssf et al., 2019; Hadzima-Nyarko et al., 2019). Discarded waste tires pose a threat to humans due to their potential to serve as a breeding place for mosquitoes and rodents that are vectors of numerous types of diseases (Mohammed et al., 2016). Some pieces of research on incorporating crumb rubber in concrete have been performed with interesting outcomes (Mohammed, 2010; Najim and Hall, 2012; Chen and Lee, 2019; Adamu et al., 2018). In conventional concrete, adding CR has been reported to significantly increase the concrete's toughness (Rashad, 2016), energy absorption capacity(Guo et al., 2014; Gerges et al., 2018), improved strain capacity (Najim and Hall, 2012), increased flexural strength (Gupta et al., 2014), enhanced durability behavior (Yung et al., 2013) better freeze and thawing behavior (Gonen, 2018) and application of Artificial Neural Networks to model the compressive strength behavior of CR concrete (Hadzima-Nyarko et al., 2019) amongst others. In the same vein, works on rubberized masonry bricks were also carried out (Al-Fakih et al., 2020; 2019; Mohammed et al., 2012). Also, a lot of works exist on the use of CR to produce roller compacting concrete with enhanced toughness and ductility characteristics (Mohammed et al., 2018c; 2018d; Mohammed and Adamu, 2018). Similarly, improvements in the behavior and properties of ECC were also recorded with the incorporation of CR. Likewise, there are several reviews on the properties of ECC, with none particularly focusing on rubberized ECC. This paper is aimed at reviewing the research carried out on rubberized ECC (RECC) with the view to explaining the effect of CR/PR on the properties of the composite in fresh and hardened states.

As stated earlier, for ECC to achieve the strain hardening behavior, the principle of micromechanics has to be followed (Yu et al., 2018; Mohammed et al., 2018a; 2017). This ensures that the materials are carefully tailored for all conditions of steady-state microcracks development to be satisfied (Yu et al., 2018; Mohammed et al., 2018b). This involves fine-tuning the properties and choice of the fiber, the matrix, and the fiber-matrix interface. Hence, to achieve the strain hardening behavior, two conditions have to be satisfied: The strength and the energy criteria (Eqs. 1 and 2) (Mohammed et al., 2019; Yu et al., 2018; Zhang and Zhang, 2018).

- Strength criterion:

$$J_{tip} \leq \sigma_0\delta_0 - \int_0^{\delta_0} \sigma(\delta)d\delta \equiv J_b' \qquad (1)$$

- Energy criterion:

$$\sigma_0 > \sigma_{CS} \quad (2)$$

where; J_{tip} is the crack tip toughness; J_b' is the complementary energy; σ_0 is maximum fiber bridging stress; σ_{CS} is the cracking strength of the matrix; δ_0 is the crack width corresponding to σ_0.

The nature of rubber particles having lower elastic modulus and specific gravity compared to the sand particles make it suitable for tailoring the composite to reduce the toughness and induce the strain hardening behavior. This justifies the use of the rubber particles in ECC, as will be seen in the subsequent sections.

2. Influence of CR/PR on properties of fresh RECC

Ismail et al. (2018) worked on the properties of Self-consolidating ECC (SCECC) modified with rubber. They concluded that up to 35% CR replacement of fine aggregate could yield a self-consolidating ECC with adequate flowability and passing ability for multiple applications. Similarly, a rubberized SCECC can be produced by up to 50% powdered rubber (PR) replacement of fine aggregate (Ismail et al., 2018). PR gives a better performance than CR at the same level of replacement. The reduction in the workability of the fresh rubberized SCECC with an increase in the rubber percentage was attributed to the increase in the inter-particle friction, which hindered the free flowability of the mixtures under their own weight (Ismail et al., 2018). Khed et al. (2018c) also investigated the effect of different CR sizes (No. 30 mesh and 1 to 3mm) on the flowability of hybrid fiber reinforced ECC. As the amount of the rubber increased, the dosage of the plasticizer needed to be reduced because of the repelling action of the rubber being hydrophobic. Consistent with the previous research discussed, the smaller sized (30 mesh) CR gave better flowability performance than the bigger sized CR. The amount of air content of the rubberized ECC in the fresh state has been found to increase with the increase in the rubber percentage. As determined by (Ismail et al., 2018), replacing 30% of the fine aggregate by CR led to an increase in the air content from 3.1% to 5.5%. It was discovered that at the same percentage replacement level (30%), PR had lower air content than CR. From the foregoing, it is evident that the inclusion of CR affects the properties of ECC in a fresh state. Bigger sized rubber particles tend to lower the flowability of the fresh ECC more than smaller sized CR particles.

3. Influence of CR/PR on properties of hardened rubberized ECC

3.1. Density

Zhang et al. (2015) determined that the density of ECC reduces with an increase in CR percentage replacement of fine aggregate. They offered two possible reasons behind this behavior. First is due to the lower specific gravity of the CR compared with the fine aggregate. The second is due to the air voids trapped on the surface of the CR during mixing. The reduction in density is more pronounced when smaller sized CR (No 80 mesh) was used as compared to the larger sized CR (No 40 mesh). After the inclusion of the CR, the density of the ECC was in the range of 1600 Kg/m^3–1710 Kg/m^3 which is classified as a lightweight concrete according to ACI 213 (1987) (Zhang et al., 2015).

Similarly, Ismail et al. (2018) concluded that the incorporation of CR and PR in ECC led to composites with lower density ranging from 1827 to 2001 kg/m3 that are classified as lightweight according to CSA A23.3-04

In the same vein, (Zhang et al., 2019), after partially replacing sand with CR, discovered that the density reduced from 2053 to 1960 Kg/m3 (4.5% reduction). However, the reduction in the density with CR substitution was less compared to the reduction observed when other materials such as fly ash-cenosphere and vermiculite were used as a replacement of the fine aggregate, which resulted in 12% and 15% density reduction respectively (Zhang et al., 2019). Similarly, Van Mier et al. (2013) also found out that the incorporation of CR in ECC leads to a reduction in the density of the composite, as shown in Table 1.

Table 1: Density of rubberized concrete (Kg/m3) (Van Mier et al., 2013)

Crumb Rubber	Mix ID	Sand Replacement (% Vol.) by CR	Density
0CR	M1	0	1830
80CR	M2	15	1660
80CR	M3	25	1600
40CR	M4	15	1710
40CR	M5	25	1640

This behavior of density reduction of RECC with rubber substitution for fine aggregate is consistent from the findings of all researchers with the main reason attributed to the lower specific gravity of CR compared with either silica sand, river sand, or iron ore tailings used as fine aggregates. Another reason behind the reduction in density of the matrix is the increased porosity due to the air bubbles trapped on the surface of the CR particles during mixing. When hardened, these trapped air bubbles become voids within the matrix, thereby reducing the density.

3.2. Compressive strength

High strength is a desirable property of concrete because of the advantages it offers, such as reduced member size and the consequent increase in safety margin (Yu et al., 2015a) and cost reduction in terms of time, materials needed for casting and formwork. This is not an exception for ECC (Zhang et al., 2019). However, common high strength concretes are very brittle and have low tensile capacities (Song and Hwang, 2004). The use of CR in normal and high strength concretes has been found to enhance the deformability and reduce the brittleness significantly but with a reduction in compressive strength (Youssf et al., 2016; Hadzima-Nyarko et al., 2019). Following are findings of research on the use of waste tire rubber (CR and PR) in ECC.

Noorvand et al. (2019) reported a decrease in the compressive strength of ECC with a 20% replacement of fine aggregate with CR. Their results indicated that when compared to normal ECC (without rubber), the rubberized ECC exhibited the highest loss of compressive strength as fly ash replacement level with cement was increased. All the rubberized ECC samples had strength less than normal concrete (30 MPa). The average compressive strength ranged between 15.1 MPa and 23.0 MPa. They attributed the loss in the strength to the lower elastic modulus of the CR particles, thereby acting as a defect within the hardened matrix. Furthermore, the increase in the porosity of the composite due to the CR incorporation was cited as another possible reason. In the same vein, (Ma et al., 2015) found that there was a gradual decrease in the compressive strength with an increase in the CR at percentages of 15, 25, and 35 of sand. They attributed the strength reduction to the poor bonding between the CR and the hydration products and also to the increased porosity due to the CR. Similarly, Zhang et al. (2015) reported a 35% decrease in compressive strength when two different sizes of CR (No 80 and No 40 sieves) were incorporated in ECC, as shown in Fig. 2. However, there was no significant difference in the compressive strengths between different CR sizes at the replacement ratios considered. The compressive strength loss was attributed to the porosity due to the CR and also as a result of the separation between the CR and the hydration products under compression.

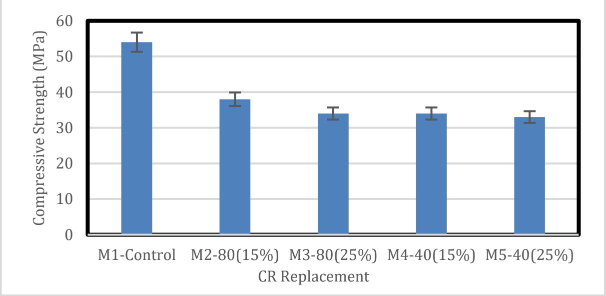
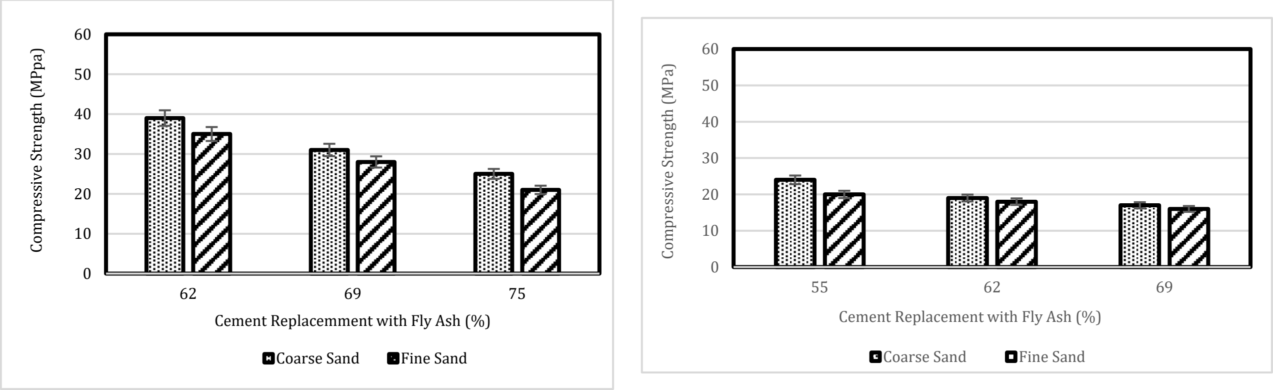


Fig. 2: Compressive strength of rubberized ECC samples (Zhang et al., 2015)

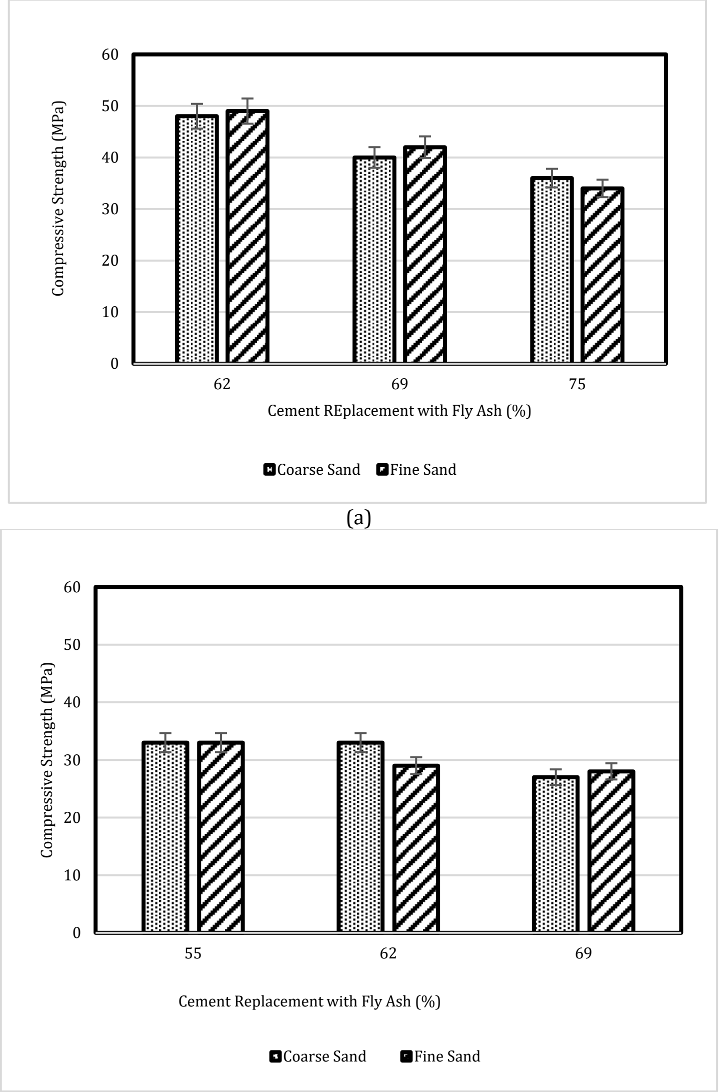
Amador et al. (2018) incorporated 20% CR replacement of fine aggregate in two different types of ECC (long PVA fiber ECC with coarse and with fine sand and short PVA fiber ECC with coarse and with fine sand respectively; both types having different percentage replacements of cement with fly ash). The result revealed that for both the long and short PVA fiber ECC, the compressive strengths at all the fly ash replacement levels decreased with incorporation of CR, as can be seen from Fig. 3 and Fig. 4. For the long fiber ECC, the incorporation of CR led to the compressive strengths for both types of sands to fall below normal strength concrete recommended by ACI (Fig. 3b). For the short PVA fiber ECC, only the ECC with 69% fly ash replacement of cement has compressive strength below the recommended value for normal concrete, as depicted in Fig. 4b. These results indicated that the inclusion of CR negatively affected the compressive strength of the ECC. This behavior is attributed to the lower stiffness of the CR as compared to the cement paste and the poor bonding between the CR and the cement hydration products (Amador et al., 2018).



(a) (b)

Fig. 3: Compressive strength of long Fiber-RECC (a) without CR (b) with CR (Amador et al., 2018)

The influence of CR and PR on the compressive strength of ECC has been investigated by Ismail et al. (2018). Results indicated that a 30% replacement of CR in ECC lead to 26.7% and 30.2% reduction in the 7 and 28 days compressive strengths, respectively. The reduction was 18.1% and 22.7% for 18 and 28 days compressive strengths respectively at 30% PR replacement; these values are lower compared to those of CR. Khed et al. (2018c), in similar research, investigated the influence of different CR sizes (30 mesh and 1 to 3 mm) on the flowability and compressive strength of ECC. Reported results indicated a reduction in the compressive strength with CR rubber replacement with the smaller sized CR (30 mesh) exhibiting lesser compressive strength reduction.



(a)

(b)

Fig 4: Compressive strength of short Fiber-RECC (a) without CR (b) with CR (Amador et al., 2018)

A correlation between the compressive strength and the pull out strength of hybrid fiber (PVA and tire wire) ECC was determined by Khed et al. (2018b) at an R2 value of 0.879, as shown in Fig. 5. In similar research by Khed et al. (2018a), a correlation of 93% (coefficient of determination, R^2 of 0.93) was established between the compressive strength of a hybrid fiber (PVA and tire wire) ECC and the modulus of elasticity as shown in Fig. 6. This indicated a strong relationship between the compressive strength and the modulus of elasticity.

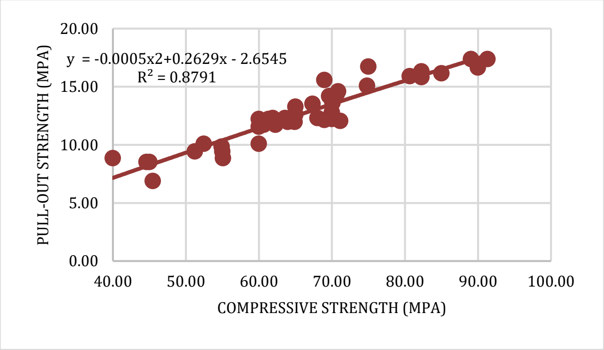


Fig. 5: Correlation between pull-out strength and compressive strength of CRECC (Khed et al., 2018b)

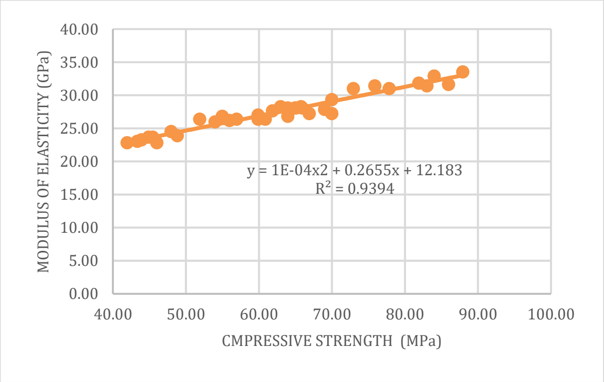


Fig. 6: Correlation between pull-out strength and compressive strength of CRECC (Khed et al., 2018a)

Wang et al. (2019) reported a decrease in compressive strength of rubberized ECC incorporating 40CR and 80CR (No 40 mesh and No 80 mesh) by 21.9% and 20.8% by increasing the CR dosage from 13% to 30% respectively. Better performance in terms of compressive strength was obtained using a finer CR (80CR), as can be observed in Fig. 7. The reduction in the strength was attributed to the increased porosity of the ECC as a result of CR by repelling water and trapping air bubbles on their surface, as shown in Fig. 8 (Zhang et al., 2015).

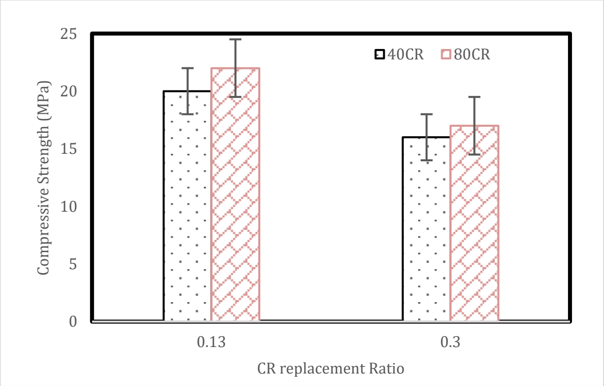


Fig. 7: Finer CR (80CR) shows a better performance in terms of compressive strength (Wang et al., 2019)

Zhang et al. (2019) recorded a general decrease in compressive strength with a 30% replacement of silica sand with CR. However, despite the decrease, the sample exhibited a compressive strength of about 75 MPa, which is classified as a high strength concrete. This is in sharp contrast to the findings of the previous researchers.

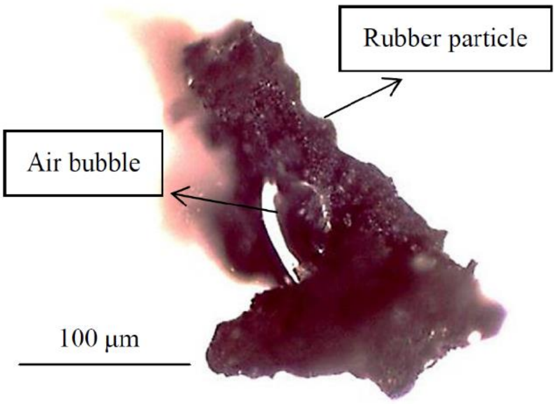


Fig. 8: Air bubble trapped on the surface of CR (Zhang et al., 2015)

3.3. Tensile behavior of rubberized ECC

The popularity of ECC is owed to its outstanding tensile strain capacity of up to 3-5%, which is 300 to 500 times that of normal concrete (Zhang et al., 2019; Şahmaran and Li, 2009). The effect of CR on the tensile behavior of ECC has been investigated by numerous researchers. This behavior of ECC is usually determined by conducting a uniaxial tensile test, as shown in Fig. 9.

A 181% and 434% improvement in the tensile ductility of ECC was reported for 20% CR replacement with fine and coarse sand, respectively (Noorvand et al., 2019). However, there was a significant decrease in the tensile strength with the CR replacement. For the coarse and fine sand, respectively, there was a 26% (4.6 to 3.39 MPa) and 21% (4.47 to 3.53 MPa) decrease in the tensile strength with CR replacement. Huang et al. (2013) reported that ECC samples with CR had a tensile capacity of 2–3%. The presence of tire rubber proves beneficial in terms of tensile ductility as the higher the content, the more ductile the ECC. As can be observed from Fig. 10, with an increase in rubber content, there is a reduction in the first cracking strength, which is attributed to the decrease in the matrix fracture toughness by about 50%. The dip in the matrix toughness is as a result of the increased porosity caused by the CR. Similar conclusions were drawn by Van Mier et al. (2013) and Zhang et al. (2015).

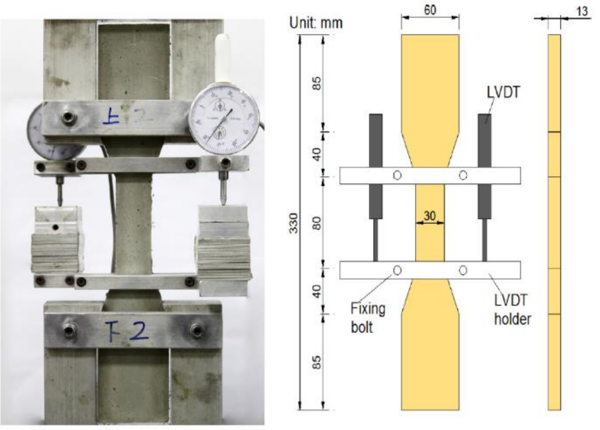


Fig. 9: Uniaxial tensile test set up (Ma et al., 2015)

The deformation capacity of the ECC increases with an increase in the CR content from 10 to 15% (Zhang and Qian, 2013). However, the toughness of the matrix decreases with an increase in CR, leading to a reduction in the first cracking strength of the samples. This is caused by the lower modulus of elasticity of the CR as compared to the cement paste (Zhang and Qian, 2013). Ma et al. (2015) reported that the tensile strain capacity increased to 7% with 35% silica sand replacement by CR. They concluded that the addition of CR significantly enhances the tensile ductility, although the ultimate strength is negatively affected.

As shown in Fig. 11a, Ma et al. (2015) recorded an increase in the tensile strain capacity of WW-ECC from 1.5% to 7% upon the incorporation of 35% CR as a replacement to silica sand when they experimented with ECC having two different types of locally made PVA fibers (WW and BHL). However, there was a reduction in the tensile strength of BHL-ECC from 5.5 MPa to 3.5 MPa with no change in the tensile strain capacity, as shown in Fig. 11b. This shows that the influence of fiber type is also significant on the tensile strain enhancement, not only the CR.

Amador et al. (2018) also found that among other factors, CR addition enhances the tensile ductility of ECC. The results indicated that for ECC having 62% cement replacement with fly ash, 434% and 181% increase in tensile strain was recorded by 20% CR replacement of coarse and fine sand, respectively.

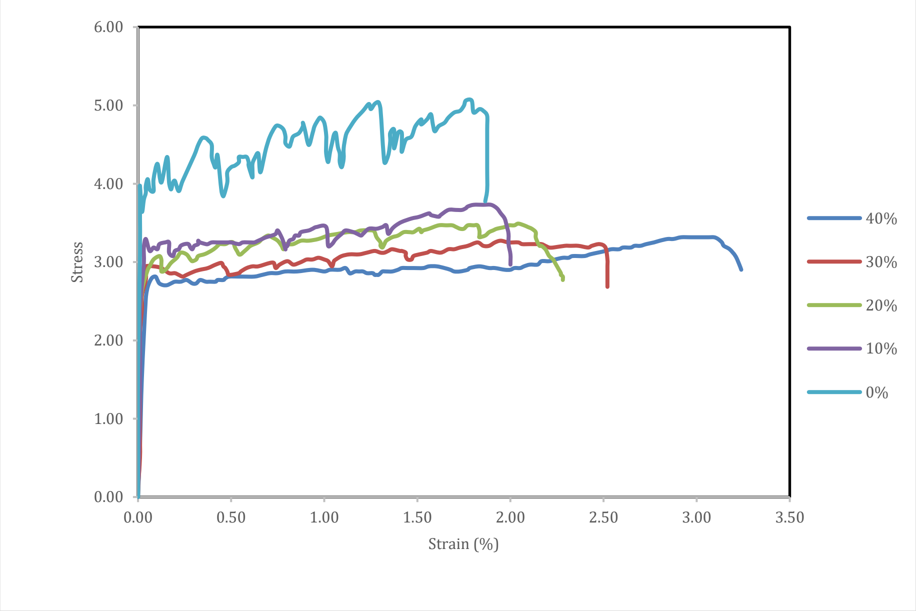
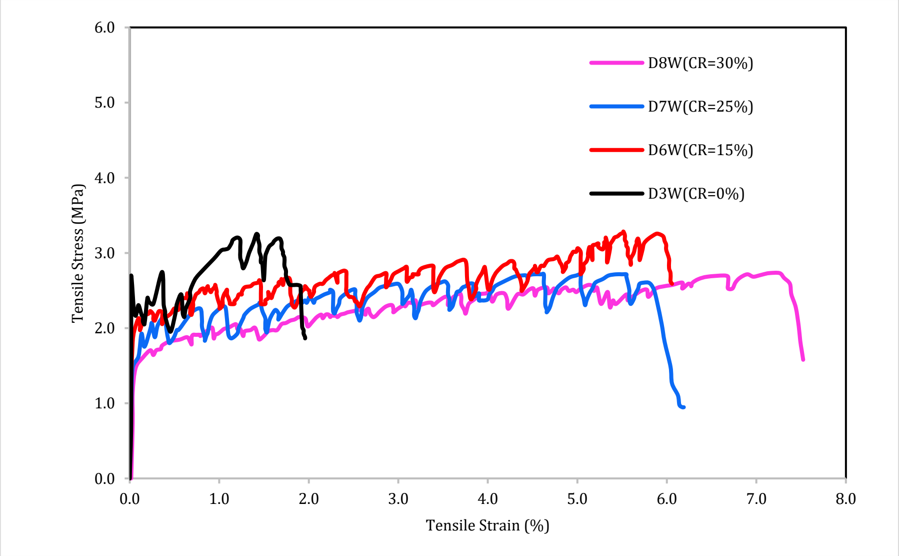


Fig. 10: Tensile stress-strain curves for different percentage replacements of sand with CR (Huang et al., 2013)

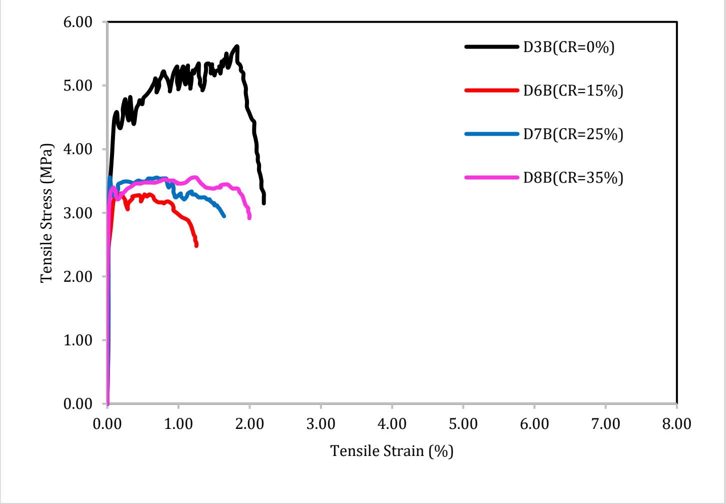
Similarly, for ECC with 69% fly ash replacement of cement, incorporation of 20% CR replacement with coarse and fine sand lead to 110% and 38% improvement in the tensile ductility, respectively. The authors attributed this behavior to the CR addition effect on the pseudo strain hardening (PSH) indicators, which are the strength (σ_0/σ_{cs}) and energy (J'_b/J_{tip}). The CR inclusion lead to a rise in the complimentary energy (J'_b) and the reduction in the crack tip toughness (J_{tip}) leading to improved ductility owing to the increase in the PHS energy (J'_b/J_{tip}) (Amador et al., 2018).

Wang et al. (2019), in an attempt to use green supplementary materials for a more ductile ECC, utilized CR as one of the materials. They observed that all the ECC incorporating CR and Recycled Powder (RP) from construction works exhibited a tensile capacity between 7-12% in contrast to the ECC without CR and RP, whose strain capacity was between 3-5%. The increased tensile strain was attributed to the microcracks propagation and tight crack widths development induced by the CR and the RP (Wang et al., 2019).

A similar conclusion was drawn by Zhang et al. (2019) when they described that the CR acted as a flaw within the matrix and also increases the porosity by trapping air voids due to its hydrophobicity and that led to decreased toughness of the composite. The reduced toughness caused the propagation of the multiple micro-cracks, as sown in Fig. 12 and thus, the strain hardening.



(a)



(b)

Fig. 11: Influence of CR on the ECC tensile strain capacity for (a) WW fiber type ECC (b) BHL fiber type ECC (Ma et al., 2015)

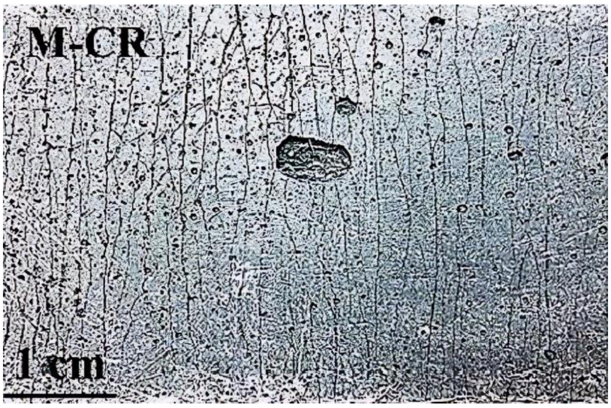


Fig. 12: Saturated micro-cracks of RECC (Zhang et al., 2019)

The elastic modulus (EM) of CR ECC was determined by Huang et al. (2013) using Eq. 3.

$$EM = 0.043d^{1.5}f^{0.5}EM \quad (3)$$

where, EM is the elastic modulus (MPa), d is the density (kg/m^3), and f is the compressive strength (MPa) at 28 days. The EM of the rubberized ECC at different percentage replacements of CR ranged between 7 to 11 GPa indicating a downward reduction with an increase in CR. This reduction was attributed to the lower modulus of CR as compared to the iron ore tailing (used as fine aggregates) and also to the increased porosity due to the incorporation of the air voids by the CR (Huang et al., 2013).

Ismail et al. (2018) followed a different approach in determining the tensile behavior of the REC by conducting a splitting tensile strength (STS) test. The results indicated that there was a 28.1% and 23.4% decrease in the 7 and 28 days splitting tensile strength, respectively, with an increase in the CR from 0 to 30%. Powdered rubber seemed to have a lesser negative effect on the STS than CR with 19.3% and 17.1% reduction in the 7 and 28 days strength, respectively, at 30% PR dosage, which is clearly less than in the case of CR. The reduction in the STS with an increase in the rubber was ascribed to the nature of the CR being softer than the surrounding cement paste behaving as a weak point within the matrix. Furthermore, the inclusion of CR increased the number of air voids in the mix leading to higher porosity and weakness under applied stresses.

3.4. Flexural behavior of RECC

A four-point bending test is mostly employed in the determination of the flexural behavior of ECC. The test set up is shown in Fig. 13. The first cracking strength, load-deflection behavior, and toughness of the composite can be determined using this test. The large deformation of the ECC in flexure due to the development of saturated microcracks at the tensile zone earned it the name bendable concrete (Li, 2008).

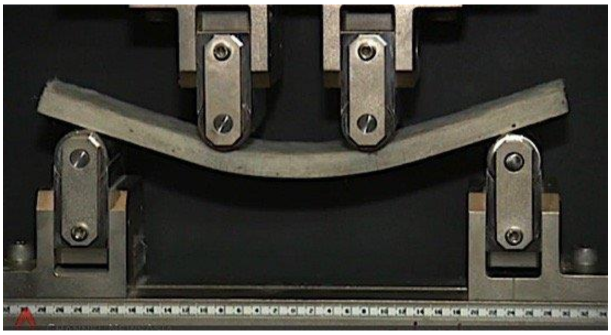


Fig. 13: An RECC four-point bending test set up (Zhang et al., 2015)

Using the third point bending test, (Noorvand et al., 2019) determined the influence of 20% fine and coarse sand replacement with CR in ECC having varying levels of cement replacement with fly ash. The results indicated a significant enhancement in the deflection capacity of the ECC with CR replacement. There was a 133% and 95% increase in deflection capacity for 62% and 69% cement replacement with fly ash, respectively, as compared with the same mix without CR. Similarly, 42% and 40% improvement in deflection capacity was noticed for fine and coarse sand ECC mixes, respectively, when 20% CR replacement of the sand was used as compared to the same mixes without the CR. This behavior of increased deflection capacity due to the CR was explained to be caused by the increase in the strain hardening behavior of the composite as a result of the enhanced energy criterion (J_b'/J_{tip}).

Van Mier et al. (2013) conducted a four-point test on 300 mm long ECC samples having different CR sizes (80CR and 40CR) at a loading rate of 0.75 mm/min. Results indicated that an increase in the CR leads to a lower first cracking strength due to reduced matrix toughness. This behavior is attributed to the weaker bonding between the CR with the matrix as compared to the replaced silica sand. However, there was a significant improvement (1.5 to 2.9 times) in the deformation capacity of the ECC with the addition of the CR. The deformation capacity was noticed to be higher for 80CR.

In the same vein, Zhang and Qian (2013) also performed a four-point bending test to investigate the flexural behavior of ECC containing different sized CR (450µm and 200µm in average). It was observed that the first cracking strength of the ECC reduces with an increase in the CR due to the weaker bonding between the CR and the matrix. An increase in the deformability with the addition of CR was explained to result from the rubber particles acting as small flaws leading to the development of microcracks and increased deformability of the composite (Van Mier et al., 2013; Zhang and Qian, 2013).

In a separate paper, Zhang et al. (2015) determined the flexural properties of ECC having different sized CR using a four-point bending test at 60 days of curing. It was observed that the first cracking strength decreased with an increase in the CR content. On the contrary, the deflection capacity increases with an increase in the CR and also with a decrease in the CR size. The reduced flexural strength observed is explained to be caused by the increase in the CR content, which reduced the fiber bridging capacity (Zhang et al., 2015).

Amador et al. (2018) found out that the incorporation of CR in ECC negatively affected the flexural strength like other mechanical strength. But in line with the findings of other researchers, there was a remarkable improvement in the tensile ductility and the deflection capacity of the composite. Following a similar trend, (Ismail et al., 2018) carried out a four-point bending test on rubberized ECC samples to determine the flexural strength. Results showed that the addition of CR negatively affected the flexural strength (FS). The severity of the FS reduction increased with increasing rubber dosage. However, the deformability of the RECC is significantly increased with increased rubber percentage due to the propagation of multiple saturated cracks leading to the noticed strain hardening behavior.

4. Conclusion

The use of waste tire rubber in the form of CR or PR in ECC is a relatively new area of research with very few literature available. This is so when compared with the available kinds of literature on rubberized mortar and concrete. The first available literature discussing the results of incorporating tire rubber in ECC was published in 2013. This is in contrast to works on the use of tire rubber in concrete and mortar that have been carried out for over two decades.

Interestingly, from the available research works reviewed, incorporation of tire rubber has negative as well as beneficial effects on the properties of ECC. The fresh properties are negatively affected, so is the density. Similarly, the compressive and the flexural strengths experience a significant loss with an increase in the CR or PR substitution of fine aggregate. The severity in the loss of mechanical properties is lesser for finer CR (PR) than that experienced with larger sized CR.

The use of tire rubber has a positive influence on the ductility of ECC. There is a consistent outcome from all the researchers regarding the increase in the tensile capacity of ECC with tire rubber percentage. In the same vein, the ECC exhibits a better strain-hardening behavior due to the matrix fracture toughness lowering effect of the rubber leading to propagation of saturated micro-cracks.

Based on the works of literature covered, an improvement in the ductility properties of the ECC of up to 434% with CR/PR incorporation was reported. Similarly, the deflection capacity enhancement of 133% was also recorded. On the other hand, a reduction or loss of compressive strength to the order of 35% has been reported. In the same vein, reduction in matrix toughness by 50% due to rubber replacement has also been observed.

In summary, the use of CR/PR in ECC is found to be beneficial in ECC due to the enhancement of the strain-hardening property that the ECC is known for. But that comes at the cost of the mechanical strength of the composite. The authors are presently working on research aimed at recovering the mechanical strength loss using a nano-material.

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Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

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