Case Studies in Construction Materials 17 (2022) e01336

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Uniaxial compressive stress-strain relationship for rubberized concrete with coarse aggregate replacement up to 100%

Abbas Abdulalim Abbara [a], Abdelrahman Abdelhalim [a], Mohammed Al-Ajamee [a,b,*], Omer Ahmed [a], Suman Kumar Adhikary [c], Mohamedelmustafa Ahmed [a]

[a] *Department of Civil Engineering, Faculty of Engineering, University of Khartoum, Khartoum, Sudan*
[b] *Department of Civil Engineering, Indian Institute of Technology, Guwahati, Guwahati 781039, Assam, India*
[c] *Faculty of Civil Engineering and Architecture, Kaunas University of Technology, Kaunas LT - 44249, Lithuania*

A R T I C L E I N F O

Keywords:
Rubberized concrete
Coarse aggregate replacement
Compressive strength
Elastic modulus
Peak strain
Compressive stress-strain relationship

A B S T R A C T

Rubberized concrete (RuC) is a green and environmentally friendly concrete that can be a sustainable production material by replaced mineral aggregate by rubber particles. Rubber particles used for replacing mineral aggregate classified by two types: shredded or chipped rubber as coarse aggregate and crumb rubber as fine aggregate. Mechanical properties and stress-strain curve of rubberized concrete change as mineral aggregate replaced by rubber particles. However, present constitutive stress-strain models for conventional concrete are not valid for rubberized concrete. Also, proposed modified models for rubberized concrete have been done based on limited experimental tests or low volume replacement ratio for coarse aggregate replacement. Therefore, this paper presents an investigation on the mechanical properties of rubberized concrete with volume replacement of coarse aggregate by rubber particles with size larger than 4 mm up to 100%, which represent about 60–65% from total aggregate, after analyzing published experimental tests in the literature for 98 concrete mixes. New equations were proposed to predict the compressive strength, modulus of elasticity, peak strain and compressive stress-strain relationship with taken the volume replacement of coarse aggregate from total aggregate into account. The proposed equations showed reliable prediction of the mechanical properties and compressive stress-strain relationship of the published experimental tests and improved accuracy over existing models.

1. Introduction

Concrete is one of the most widely used materials in the world, concrete production consumes significant natural resources every year. Sources of these natural resources are gradually depleting, which is a big rising concern for the concrete industry. Extraction of natural aggregates from lakes, river beds and other water bodies for prolonged period of time have resulted in enormous environmental problems in some parts of the world [3,28]. This led researchers attempted to use different recycled materials in concrete during the last few decades. On the other hand, the disposal of waste tires represents a major issue in the solid waste dilemma; accumulations of discarded tires potentiality create fire and health. Therefore, a great importance has been attached to the recycling and reuse of rubber tire waste materials to replace the mineral aggregate in conventional concrete to save resource of mineral aggregate

* Corresponding author at: Department of Civil Engineering, Faculty of Engineering, University of Khartoum, Khartoum, Sudan.
E-mail address: mohammedalajamee@gmail.com (M. Al-Ajamee).

https://doi.org/10.1016/j.cscm.2022.e01336
Received 21 March 2022; Received in revised form 16 July 2022; Accepted 20 July 2022
Available online 26 July 2022
2214-5095/

and to limit the discarded tires last 20 years [10,11,19,24,40,41]. This approach complies with international agenda to move the economic strategy from linear approach to circular one that respects the environment. Such approach might significantly improve the management of non-renewable natural resources and might lead to reductions in waste storage in public landfills, environmental pollution as well as the decrease of construction cost [43]. Rubber particles used for replacing mineral aggregate can be classified by two types: shredded or chipped rubber with size larger than 4 mm used as coarse aggregate and crumb rubber with size between 4 mm and 0.075 mm used as fine aggregate [14,37]. Using of rubber particles results in reduction of compressive strength, elastic modulus, tensile strength and density of concrete, but higher toughness index, plastic energy capacity, fracture energy and damping ratio were observed as compared to conventional concrete [11,15,24,46,49]. The main parameters governing the mechanical properties of rubberized concrete are the volumetric replacement ratio, the size of replaced aggregate and characteristics of rubber particles [35,4,

Table 1
Experimental tests in the literature with coarse aggregate replacement.

Reference	W/C	Cement type	Coarse aggregate CA (mm)	Fine aggregate FA (mm)	Tire chips (mm)	Rep. of course aggregate (%)
[19]	0.48	Type I, portland cement	Brazos River (4–25 mm)	Brazos River (0–4 mm)	CA (10–50 mm)	0–100
[17]	0.39	Type I, portland cement	Crushed natural aggregate (2.36–12.5 mm)	Crushed natural aggregate (0.15–4.75 mm)	CA (2.36–12.5 mm)	0–20
[5]	0.4 0.6	Ordinary portland cement (OPC)	Crushed stone gravel (4–20 mm)	Natural sand (0.1–4 mm)	CA (4–25 mm)	0–100
[41]	0.5	Type II, portland cement	Crushed stone gravel (4–19 mm)	Natural sand (0.1–4.76 mm)	CA (4–12.7 mm)	0–100
[12]	0.4	CEM I 42.5 R, Portland cement	Crushed limestone (4–25 mm)	Crushed limestone sand (0.1–4 mm)	CA (10–40 mm)	0–30
[36]	0.57	Ordinary portland cement (OPC)	Crushed stone gravel (4–20 mm)	Natural siliceous sand (0.1–4.75 mm)	CA (5–20 mm)	0–100
[10]	0.48	Type I, portland cement	Mineral aggregate (4–20 mm)	Natural sand (0.1–4.75 mm)	CA (4–30 mm)	0–100
[1]	0.55	Ordinary portland cement (OPC)	Mineral aggregate (4–20 mm)	Natural sand (0.1–4 mm)	CA (4–20 mm)	0–51.23
[9]	0.33	Ordinary portland cement (OPC)	Mineral aggregate (4.75–19 mm)	Masonary sand (0.15–4.75 mm)	CA (4.75–25.4 mm)	0–100
[49]	0.45	Type I, portland cement	Crushed stone (4.75–30 mm)	River sand (0.1–5 mm)	CA (15–40 mm)	0–45
[42]	0.45	Cement CEM II A-L 42.5 R	Crushed limestone (4–25 mm)	Rolled limestone sand (0.1–4 mm)	CA (4–25.4 mm)	0–25.9
[35]	0.35	CEM II-52.5 N, Portland Limestone Cement	Round river washed gravel from Trent Valley (UK) (4–20 mm)	River washed sand from Shardlow, Derbyshire (UK) (0–5 mm)	CA (5–20 mm)	0–100
[18]	0.53	Ordinary portland cement (OPC)	Gravel (14 mm, 20 mm)	Natural riverand manufactured sand (0–5 mm)	CA (15 mm)	0–9.7
[44]	0.48	P. II52.5 R, Ordinary Portland cement (OPC)	Crushed granite (5–20 mm)	River sand (0.1–5 mm)	CA (5–20 mm)	0–100
[2]	0.52 0.6	Ordinary portland cement (OPC)	Mineral aggregate (10–20 mm)	Natural sand (0.1–4 mm)	CA (8–20 mm)	0–47.05 0–28.1

Reference	Rep. of Total aggregate Pvr (%)	density (Kg/m3)	Size and shape of specimens	fc test (Mpa)	fc 150 × 300 (Mpa)	Ec (Gpa)	εo %(mm/mm)
[19]	0–56.76	2390–1740	Cylinder (150 ×300 mm)	37.5–3	37.5–3	–	–
[17]	0–10.25	2323–2210	Cylinder (150 ×300 mm)	35.26–22	35.26–22	–	–
[5]	0–62.2	2260–1640 2250–1625	Cylinder (150 ×300 mm)	62–15.9 38.5–11.4	62–15.9 38.5–11.4	38–16.5 34–10.5	– –
[41]	0–60	–	Cylinder (100 ×200 mm)	31.9–7.5	30.94–7.28	–	–
[12]	0–15.87	–	Cube (150×150×150 mm)	53.69–27.91	51.4–21.43	40.9–24.8	–
[36]	0–64.8	2400–1870	Cylinder (150 ×300 mm)	27–5.94	27–5.9	–	–
[10]	0–64	–	Cylinder (150 ×300 mm)	34–6	34–6	–	–
[1]	0–31	–	Cylinder (150 ×300 mm)	29–5.77	29–5.77	16.8–5.89	0.219–0.1350
[9]	0–63	2552–2014	Cylinder (150 ×300 mm)	65.7–14.4	65.7–14.4	39.2–11.8	0.205–0.391
[49]	0–28.8	2399–2050	Cylinder (150 ×300 mm)	38.8–18.1	38.8–18.1	31.8–16.5	–
[42]	0–15	–	Cylinder (150 ×300 mm)	55.5–28.5	55.5–28.5	40.6–30.9	–
[35]	0–55	–	Cylinder (100 ×200 mm)	61.7–8.7	59.8–8.4	39.4–14	0.218–0.108
[18])	0–5.7	–	Cylinder (100 ×200 mm)	41.3–29.26	40.06–28.38	31–22.9	0.16–0.1817
[44]	0–48.3	–	Cylinder (150 ×300 mm)	31–4	31–4	29–1	0.2–0.44
[2]	0–18.8 0–11.23	2372–2163 2310–2117	Cube (150×150×150 mm)	45.8–17.4 27.11–17.06	42.2–9.23 20.5–8.8	– –	– –

6].

One of early studies on rubberized concrete have been conducted by Eldin and Senouci [10], the study investigated the effect of crumb and shipped rubber particles on the mechanical properties of conventional concrete, compressive strength was reduced by 85% when coarse aggregate fully replaced by shipped rubber particles, while 65% reduction was observed when fine aggregate fully replaced by crumb rubber particles. Also, rubberized concrete did not show brittle failure as compared to conventional concrete. Similar results have been concluded by Topçu [40]. However, Toutanji [41] investigated the behavior of rubberized concrete between 0% and 100% of coarse aggregate replacement, specimens with rubber particles showed greater toughness as compared to the control specimens up to 50% replacement, while toughness was constant for coarse aggregate replacement between 50% and 100%. An experimental program has developed by Khatib and Bayomy [19] to study the effect of fine aggregate, coarse aggregate and both fine and coarse aggregate replacement on conventional concrete, three reasons of strength reduction in rubberized concrete have been hypothesized. First, because the rubber particles are much softer than the surrounding cement paste, so higher stress concentration around rubber particles leading to early failure of concrete. Secondly, due to the lack of adhesion between rubber particles and the paste. Thus, rubber maybe treated as voids in the concrete mix. The third possible reason is that concrete compressive strength is dependent greatly on the coarse aggregate, density, size and hardness. Therefore, the reduction in strength is anticipated as aggregates are partially replaced by rubber. Based on the previous reasons, several researchers investigated the potential enhancing of the mechanical properties of rubberized concrete by pre-treatment or pre-coating of rubber particles [24,29,31], or by adding supplementary materials such silica fume [13,20], other studies reported that steel fibers can improve the mechanical properties of rubberized concrete [22,30,45]. Also, Improving the physicochemical property of rubber particles by irradiation may enhance the compressive strength and splitting tensile strength of rubberized concrete in some cases [16,26]. However, Confine the concrete by fiber reinforced polymers FRP is one of the solutions to overcome the reduction of the compressive strength of rubberized concrete [7,48].

As known, the compressive stress-strain relationship is very important for designing of structural elements, present constitutive stress-strain models for conventional concrete are not valid for rubberized concrete [4,6]. Accordingly, a few attempts have been done to develop compressive stress-strain relationship for rubberized concrete with respect to volume replacement ratio and type of replaced aggregate by rubber particles, such as fine aggregate [18,21,23,39,4,6] coarse aggregate [1,18,4,6], and both fine and coarse aggregate replacement [4,6]. However, the models developed for coarse aggregate replacement were based on limited experimental tests or for low replacement ratio. Therefore, the aim of this study is to develop compressive stress-strain relationship for rubberized concrete with coarse aggregate replaced by rubber with size larger than 4 mm and wide range of volume replacement up to 100% of coarse aggregate, which represent 60–65% of total aggregate after analyzing published experimental results in the literature.

2. Experimental tests database

Based on extensive inspection of the experimental tests in the literature, the papers clearly including information for the mechanical properties of concrete mixes and mixing proportions for both conventional and rubberized concrete, with coarse aggregate replaced by tire rubber with size larger than 4 mm only considered, any concrete mix with steel fiber, pre-treatment or pre-coating of the rubber particles was excluded. Therefore, 98 concrete mixes from 15 studies [1,10,18,19,34,36,41,42,49] and [12,17,2,44,5] were used to predict the concrete compressive strength, elastic modulus, peak strain and compressive stress-strain relationship for rubberized concrete, with considering the volume replacement (P_{vr}) of coarse aggregate from total aggregate up to 65%. Experimental results database for the properties shown in Table 1 and for more details, the reader can refer to the Appendix 1.

It should be noted that concrete compressive tests were conducted on specimens with different shape and size. Thus, the

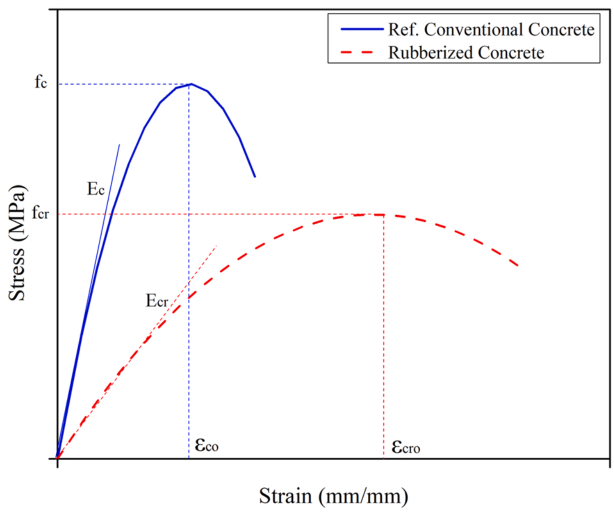

Fig. 1. Stress-strain curve of rubberized concrete with respect to reference conventional concrete with same mix proportions.

compressive strength of concrete changes as the shape and size change [32]. However, most of experimental tests were on cylinders with size 150×300mm. Therefore, to limit the effect of previous factors, the compressive concrete strength of 100×200mm cylinders were converted to 150×300mm cylinders by reduction factor 0.97. In addition, the compressive concrete strength of 150×150×150mm cubes were converted to 150×300mm cylinders by Eq. (1) proposed by Yi et al. [47], where fc in (MPa).

$$f_{c(cyl150x300mm)} = 1.16 \quad f_{c(cube150x150x150mm)} - 11 \tag{1}$$

In the following sections, the mechanical properties and compressive stress-strain relationship equations for rubberized concrete were proposed after analyzing the published experimental results with considering the volumetric replacement of coarse aggregate by chipped rubber particles only up to 65% of volume of total aggregate.

3. Prediction of mechanical properties for rubberized concrete

Fig. 1 shows the compressive stress-strain curve of rubberized concrete with respect to reference conventional concrete curve with same mix proportions, the only parameter considered is the volumetric replacement ratio of coarse aggregate by chipped rubber particles. As can be seen concrete compressive strength, elastic modulus, peak strain, ascending and descending branches of rubberized concrete are different as compared to reference conventional concrete. Therefore, successful stress-strain relationship should predict the mechanical properties of rubberized concrete accurately.

3.1. Compressive strength fcr

Fig. 2. illustrates the relationship between the compressive strength degradation of published experimental results as a function of rubber replacement p_{vr}. On the vertical axis, the rubberized concrete strength fcr is normalized against the reference strength of the conventional concrete fc, whereas on the horizontal axis, the rubber content is reported as volumetric ratio p_{vr}. As can be seen, the compressive strength of rubberized concrete decreases as the volume replacement (P_{vr}) increases. The compressive strength reduction factor was 57%, 42% and 32% for 10%, 20% and 30% volume replacement, while it was 26%, 21% and 17% for 40%, 50% and 60% volume replacement. However, the rate of change of compressive strength decreases as volume replacement increases, this trend has been reported by several researchers [1,10,4,9]. however, this might be due to that the rubber particles act as large pores, and the compressive strength decreases in an exponential trend [10]. Proposed relationship between compressive strength of rubberized concrete and reference conventional concrete given by Eq. (2), with average ($f_{cr,\ predicted}$/ $f_{cr,\ test}$) of 0.992 and COV of 19.2%.

$$f_{cr} = e^{\alpha_1 (p_{vr})^{\beta_1}} \quad f_c; \alpha_1 = -0.126 \text{and} \beta_1 = 0.643 \tag{2}$$

Where f_{cr} is the compressive strength of rubberized concrete, p_{vr} is volume replacement of coarse aggregate by rubber particles from total aggregate, f_c is the compressive strength of reference conventional concrete, α_1 and β_1 are coefficients for the fitting curve.

3.2. Modulus of elasticity E_{cr}

Fig. 3. illustrates the relationship between the Elastic modulus degradation of published experimental results as a function of rubber replacement p_{vr}. On the vertical axis, the modulus of elasticity Ecr is normalized against the modulus of elasticity of reference conventional concrete Ec, whereas on the horizontal axis, the rubber content is reported as volumetric ratio p_{vr}. Modulus of elasticity of rubberized concrete decreases as the volume replacement increases as shown in Fig. 3. However, the reduction of modulus of elasticity is less than compressive strength; the modulus of elasticity reduction factor was 77%, 63% and 53% for 10%, 20% and 30% volume

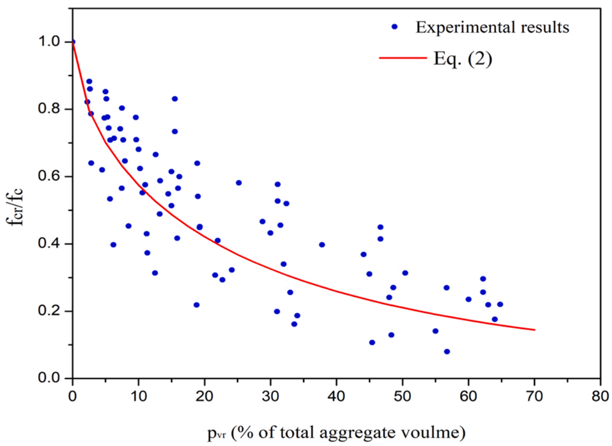

Fig. 2. Relationship between compressive strength of rubberized concrete and reference concrete.

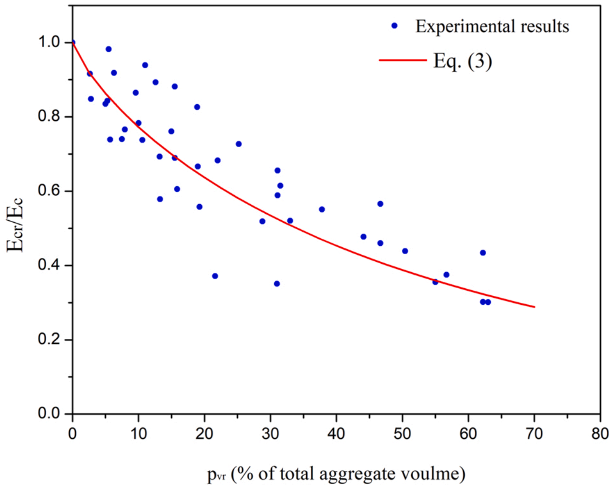

Fig. 3. Relationship between modulus of elasticity of rubberized concrete and reference concrete.

replacement, while it was 45%, 38% and 33% for 40%, 50% and 60% volume replacement. Proposed relationship between the modulus of elasticity of rubberized concrete and reference conventional concrete given by Eq. (3), with average ($E_{cr, predicted}/E_{cr, test}$) of 0.986 and COV of 13.1%.

$$E_{cr} = e^{\alpha_2 (p_{vr})^{\beta_2}} E_c ; \alpha_2 = -0.04 \text{ and } \beta_2 = 0.809 \quad (3)$$

Where E_{cr} is the modulus of elasticity of rubberized concrete, p_{vr} is volume replacement of coarse aggregate by rubber particles from total aggregate, E_c is the modulus of elasticity of reference conventional concrete, α_2 and β_2 are coefficients for the fitting curve.

3.3. Peak strain ε_{cro}

Peak strain of rubberized concrete showed contrary results as compared to reference conventional concrete, some studies reported that the peak strain increases as volume replacement increases [41,44,9]. However, others studies reported that the peak strain decreases as volume replacement increases [1,35]. also, Mendis et al. [27] reported that the behavior of rubberized concrete is approximately same as conventional concrete with same strength. Accordingly, the peak strains of rubberized concrete and normal concrete with same strength are equal.

[25] reported that the peak strain of lightweight concrete is higher than peak strain of conventional concrete with same strength. The density of rubberized concrete decreases as volume replacement ratio increases as compared to reference conventional concrete [10,11,19,24,41]. Therefore, it expected to behave similarly to lightweight concrete. Indeed, parametric study have been done on rubberized concrete specimens with same strength approximately (23–28) MPa showed that peak strain of rubberized concrete increases as volume replacement increases as shown in Fig. 4. Eq. (4) has been proposed for the relationship between peak strain and

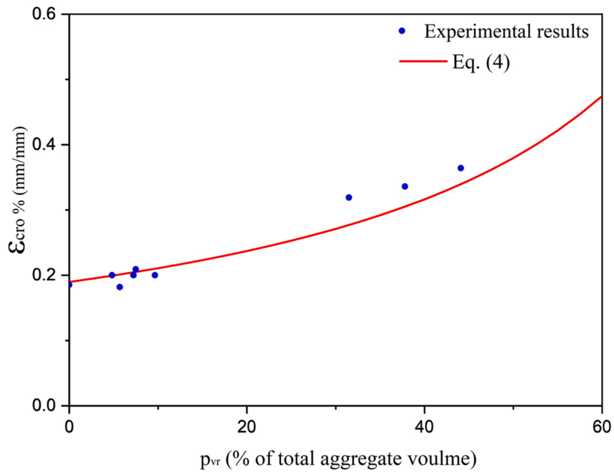

Fig. 4. Relationship between peak strain and compressive strength of rubberized concrete with strength between 23 and 28 MPa.

compressive strength of rubberized concrete, with average ($\varepsilon_{cro,predicted}$/ $\varepsilon_{cro,test}$) of 1.045 and COV of 10.0%.

$$\varepsilon_{cro} = \frac{\alpha_3 \quad (f_{cr})^{\beta_3}}{\lambda \quad - p_{vr}}; \alpha_3 = 0.07, \quad \beta_3 = 0.31 \text{and} \quad \lambda = 100 \tag{4}$$

Where ε_{cro} is the peak strain of rubberized concrete in (mm/mm), p_{vr} is volume replacement of coarse aggregate by rubber particles from total aggregate, f_{cr} is the compressive strength of rubberized concrete in (MPa), α_3, β_3 and λ are coefficients for the fitting curve.

4. proposed compressive stress-strain relationship

The prediction of pre-peak stage (ascending branch) and post-peak stage (descending branch) is essential to accurately represent the uniaxial compressive stress-strain relationship for conventional and rubberized concrete. Popovic's [33] Equation one of the most widely expression used for compressive stress-strain relationship. However, Collins and Mitchell [8] found a relationship describing the behavior of conventional concrete under compressive strength and peak strain [9]. Recently, Lim and Ozbakkaloglu [25] developed simple new expression to describe the stress-strain relationship in the post-peak stage for both normal and lightweight concrete. In the following sections, 4 equations were proposed to predict the stress-strain relationship for rubberized concrete with coarse aggregate replacement.

4.1. Pre-peak stage (ascending branch)

Popovic's [33] Equation one of the most widely expression used for compressive stress-strain relationship. Therefore, in this study Popovics equation, Eq. (5) is adopted to represent the pre-peak stage of the stress-strain relationship. However, a new expression has been proposed using nonlinear regression analysis to predict parameter ρ_m based on investigated published experimental results by Eq. (6).

$$\frac{\sigma_{cr}}{f_{cr}} = \frac{\rho_m \left(\frac{\varepsilon_{cr}}{\varepsilon_{cro}}\right)}{\rho_m - 1 + \left(\frac{\varepsilon_{cr}}{\varepsilon_{cro}}\right)^{\rho_m}} \text{if} 0 \leq \varepsilon_{cr} \leq \varepsilon_{cro} \tag{5}$$

Where:

$$\rho_m = \left(0.66 - 0.3 \left(\frac{E_p}{E_{cr}}\right)\right)^{-1.9} \tag{6}$$

$$E_P = \frac{f_{cr}}{\varepsilon_{cro}} \tag{7}$$

Where ε_{cro} is the peak strain of rubberized concrete in (mm/mm), f_{cr} is the compressive strength of rubberized concrete in (MPa), σ_{cr} is the compressive stress of rubberized concrete in (MPa), ε_{cr} is the strain of rubberized concrete in (mm/mm), E_{cr} and E_p are the Elastic and Secant modulus respectively in (GPa).

4.2. Post-peak stage (descending branch)

The strain-localization of concrete specimens effect the shape of the descending branch. However, strain localization depends on the size and aspect ratio of the concrete specimens, since all the specimens taken in to account in this study are with L/D = 2, and diameter of 100 and 150 mm, and due to limited experimental results in the literature, the strain localization due to the size of specimens has been neglected since the difference between the compressive fracture energy of concrete of specimens with diameter 100 and 150 mm is very small [38]. Accordingly,

The descending branch of the compressive stress-strain relationship is to be predicted using an expression developed by Lim and Ozbakkaloglu [25] for normal and lightweight concrete by Eq. (8). However, the parameter $\varepsilon_{cr,i}$ has modified to fit the experimental results as function of the volume replacement of coarse aggregate from total aggregate (p_{vr}) using nonlinear regression analysis. A new expression for $\varepsilon_{cr,i}$ developed in this study by Eq. (9).

$$\frac{\sigma_{cr}}{f_{cr}} = 1 - \frac{1}{1 + \left(\frac{\varepsilon_{cr} \quad - \varepsilon_{cro}}{\varepsilon_{cr,i} \quad - \varepsilon_{cro}}\right)^{-2}} \text{if} \varepsilon_{cr} \geq \varepsilon_{cro} \tag{8}$$

$$\varepsilon_{cr,i} = 3.9 \quad \varepsilon_{cro} \quad f_{cr}^{-0.188} \quad \left(1 - 0.38 \quad \left(\frac{p_{vr}}{100}\right)\right)^{1.15} \tag{9}$$

4.3. Comparison the proposed stress-strain relationship with experimental results

The proposed compressive stress-strain relationship was validated via published experimental results, as shown in Figs. 5 and 6, the proposed relationship predicts experimental tests with wide range of concrete compressive strength and volume replacement of coarse aggregate from total aggregate. However, to complete the comparison, the proposed compressive stress-strain relationship was also compared with Bompa et al. [6] model for rubberized concrete. The results of this comparison are shown in Error! Reference source not found., which illustrate the improved accuracy of the proposed compressive stress-strain relationship in prediction of the behavior of rubberized concrete with wide range of concrete compressive strength and volume replacement of coarse aggregate from total aggregate. Fig. 7.

5. Case study

To clarify the effect of chipped rubber particles on the mechanical properties and compressive stress-strain relationship of reference conventional concrete, two case studies has been done based on proposed equations, Eq. (2) to Eq. (9), on two reference conventional concrete with concrete strength of (60 and 30 MPa) with volume replacement ratio by 5%, 10%, 20%, 40% and 60% as in Fig. 8**.** In addition, the effect of rubber particles on stress-strain relationship for conventional and rubberized concrete with same strength and equal to (20 MPa) in Fig. 9.

As can be seen in Fig. 8, compressive strength, elastic modulus, slopes of ascending and descending branches of rubberized concrete decrease as volume replacement increase. However, the peak strain of rubberized concrete decreases slightly as volume replacement ratio increase up to 40% but it increases for volume replacement ratio of 60% as compared to reference conventional concrete. This in agreement with published experimental results by Wu et al. [44] and Abbasii and Ahmad [1].

For rubberized and conventional concrete with same strength as shown in Fig. 9, the elastic modulus decreases as volume replacement increases. In the contrary, the peak strain increases as volume replacement increases, while the slop of descending branches for all stress-strain curves are approximately equal. Therefore, the rubber particles have slight effect on the shape of descending branch of rubberized concrete. However, there not any study in the literature investigated the effect of rubber particles on the strain localization of rubberized concrete.

6. Conclusions

The present study investigated the behavior of rubberized concrete with coarse aggregate replacement by rubber particles up to

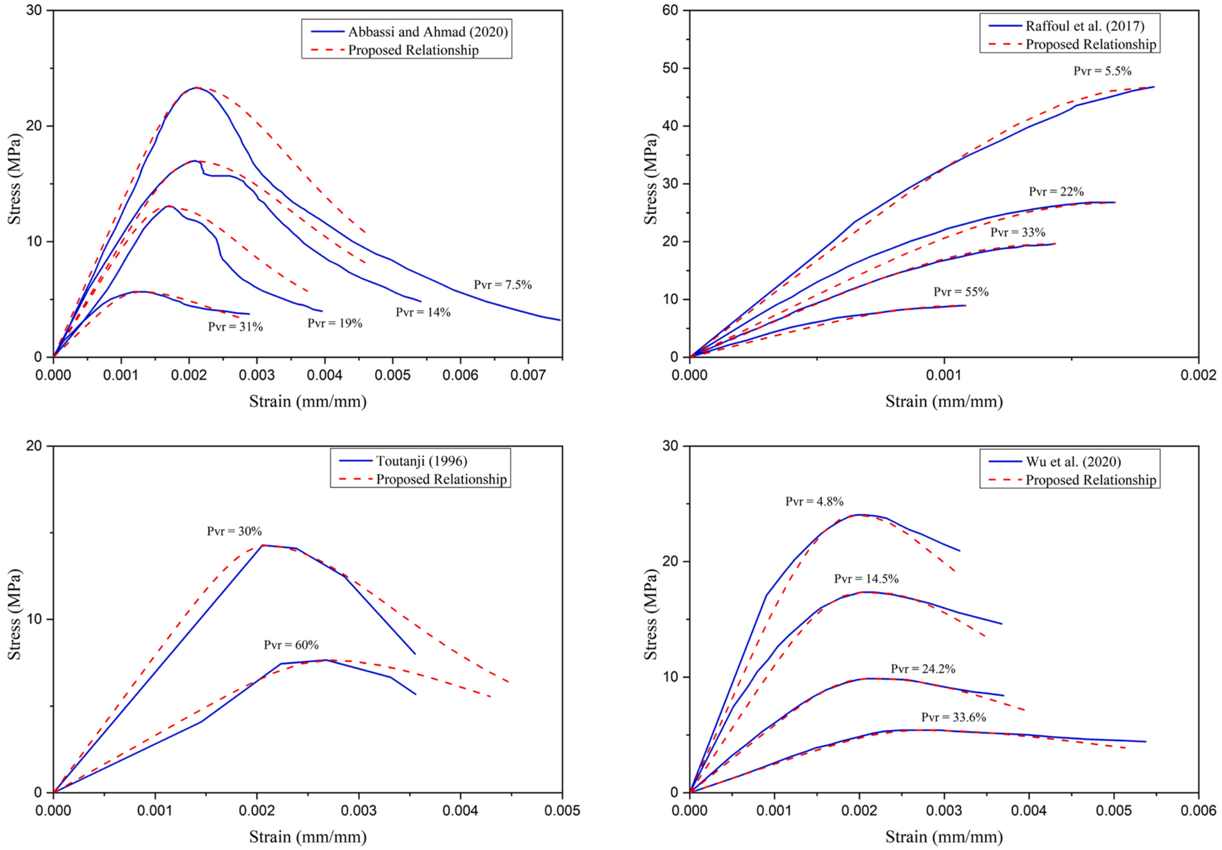

Fig. 5. Comparison the proposed stress-strain relationship with experimental results.

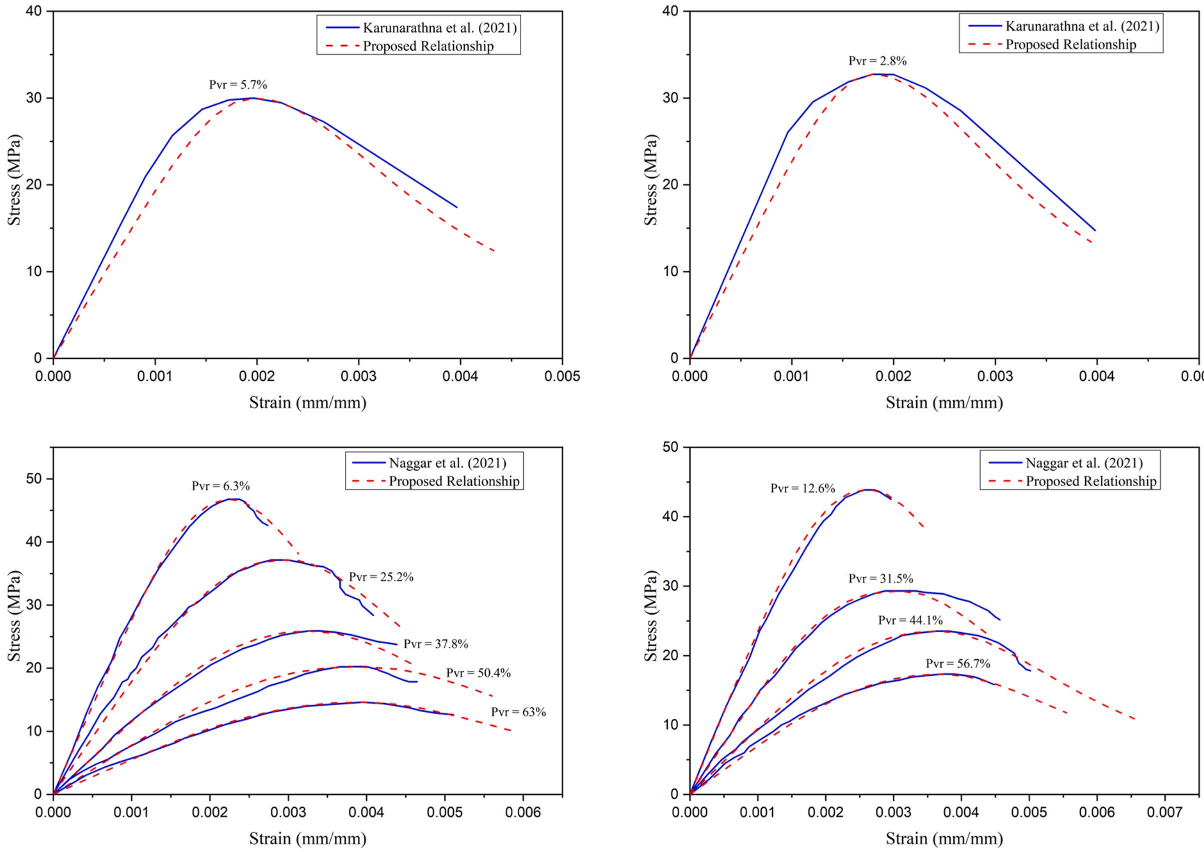

Fig. 6. Comparison the proposed stress-strain relationship with experimental results.

100% of coarse aggregate volume, which represents between (60–65%) of total aggregate volume, after analyzing the published experimental results for 98 concrete mixes in the literature. New equations for compressive strength, elastic modulus, peak strain and compressive stress-strain relationship were proposed. However, amongst the analytical investigation of experimental tests in the literature, these observations can be highlighted from this study:

- The proposed compressive stress-strain relationship showed reliable prediction of experimental tests in the literature with wide range of concrete strength and volume replacement of coarse aggregate from total aggregate (p_{vr}).
- The proposed compressive stress-strain relationship showed improving of accuracy of available models for rubberized concrete in the literature.
- The proposed compressive stress-strain relationship is based on 3 parameters only, namely the rubberized concrete compressive strength, peak strain and volume of coarse aggregate replacement from total aggregate (p_{vr}). Therefore, using of this relationship is simple and suitable for modeling of reinforced rubberized concrete members.
- The mechanical properties of rubberized concrete can be related to reference conventional concrete as function of volume replacement of coarse aggregates from total aggregate (p_{vr}).
- Based on parametric study, relationship between peak strain and compressive strength of rubberized concrete was proposed.
- Relationship of compressive strength and modulus of elasticity of rubberized concrete regarding volume replacement ratio of coarse aggregate from total aggregate were proposed.
- The proposed relationships for compressive strength, modulus of elasticity and peak strain agree with experimental tests.
- Rubber particles have slight effect on the shape of descending branch of rubberized concrete. however, study the effect of rubber particles on strain localization is recommended.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

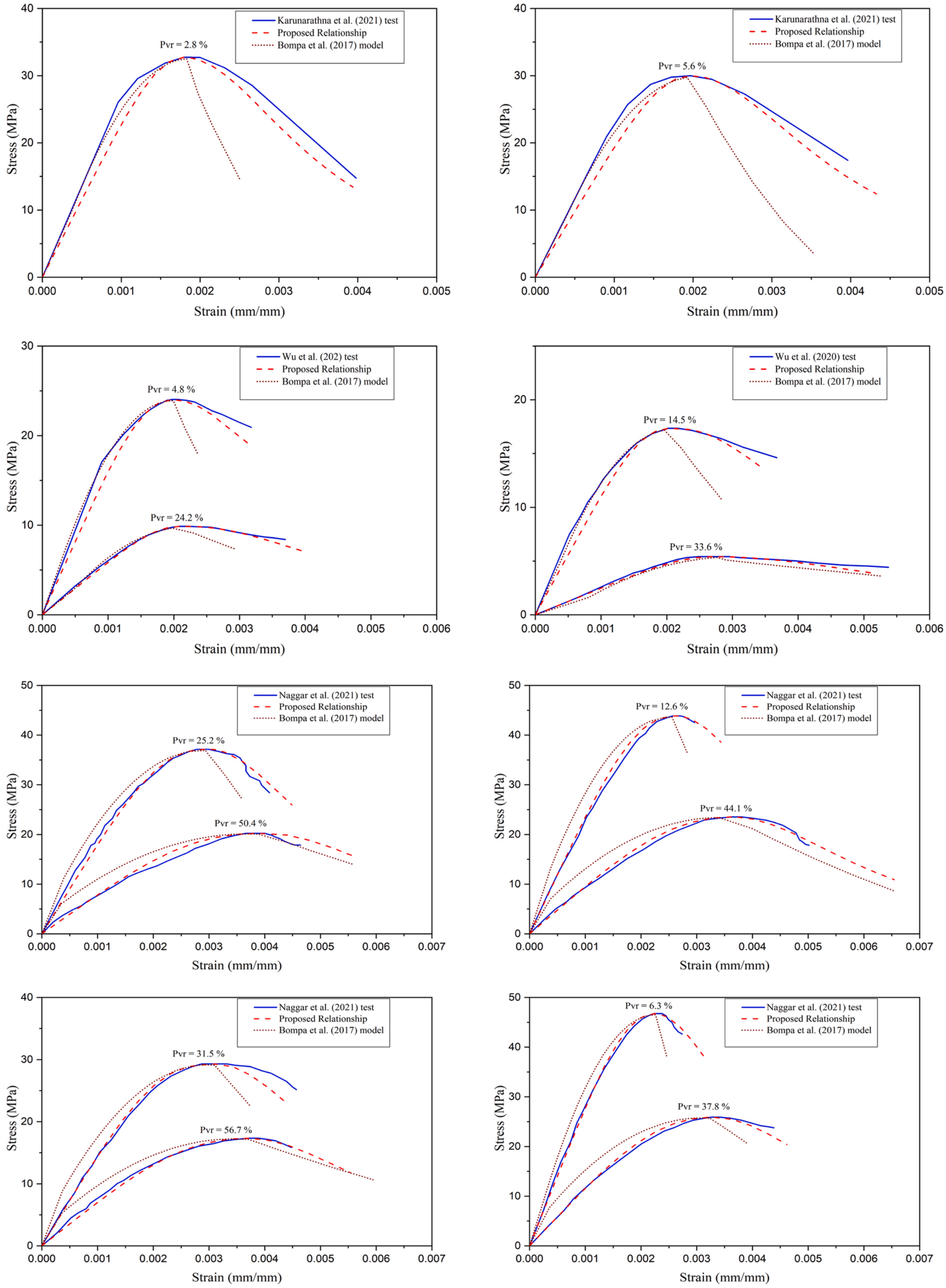

Fig. 7. Comparison the proposed stress-strain relationship with Bompa et al. [6]model.

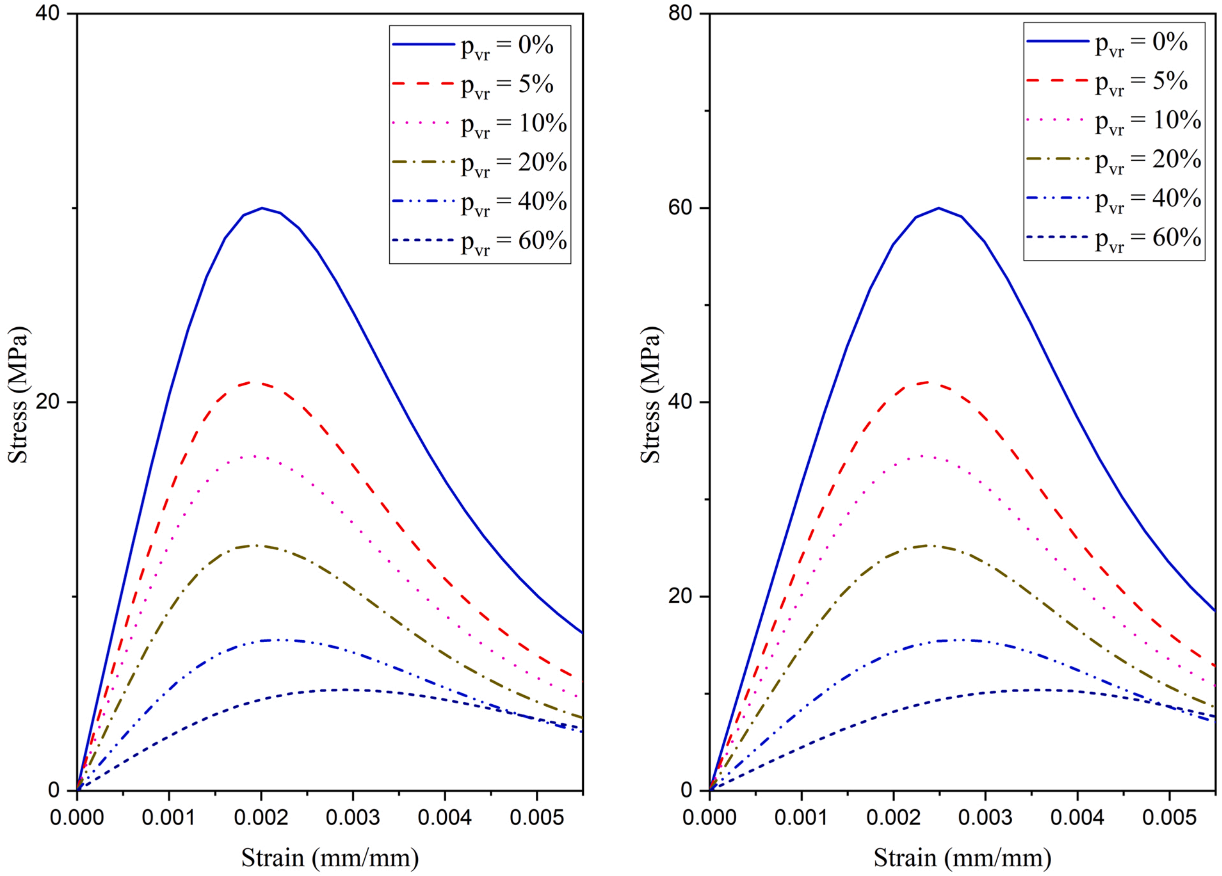

Fig. 8. Effect of rubber particles on the stress-strain curves for rubberized concrete with respect to reference conventional concrete with compressive strength of 30 and 60 MPa.

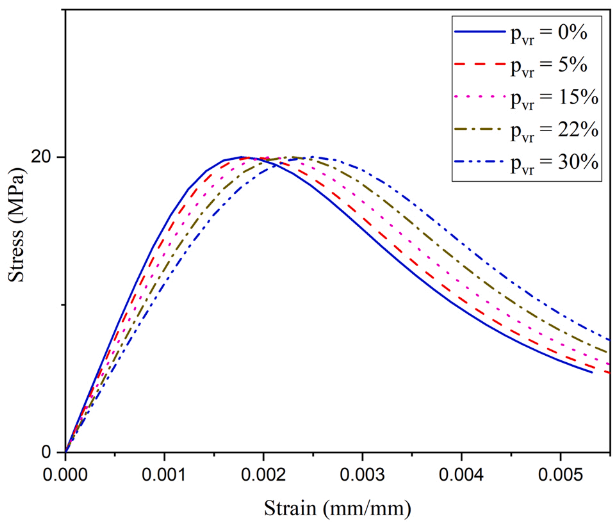

Fig. 9. Effect of p_{vr} on the shape of stress-strain curve for conventional and rubberized concrete with same strength.

Data availability

Data will be made available on request.

Appendix 1. Experimental database properties with coarse aggregate replacement, used in this study

Reference	W/C	Cement type	Coarse aggregate CA (mm)	Fine aggregate FA (mm)	Tire chips (mm)	Rep. of coarse aggregate (%)
[19]	0.48	Type I, portland cement	Brazos River (4–25 mm)	Brazos River (0–4 mm)	CA (10–50 mm)	0.00
						5.00
						10.00
						15.00
						20.00
						40.00
						60.00
						80.00
						100.00
[17]	0.39	Type I, portland cement	Crushed natural aggregate (2.36–12.5 mm)	Crushed natural aggregate (0.15–4.75 mm)	CA (2.36–12.5 mm)	0.00
						5.00
						10.00
						15.00
						20.00
[5]	0.4	Ordinary portland cement (OPC)	Crushed stone gravel (4–20 mm)	Natural sand (0.1–4 mm)	CA (4–25 mm)	0.00
						25.00
						50.00
						75.00
						100.00
	0.6					0.00
						25.00
						50.00
						75.00
						100.00
[41]	0.5	Type II, portland cement	Crushed stone gravel (4–19 mm)	Natural sand (0.1–4.76 mm)	CA (4–12.7 mm)	0.00
						25.00
						50.00
						75.00
						100.00
[12]	0.4	CEM I 42.5 R, Portland cement	Crushed limestone (4–25 mm)	Crushed limestone sand (0.1–4 mm)	CA (10–40 mm)	0.00
						5.00
						10.00
						15.00
						20.00
						25.00
						30.00
[36]	0.57	Ordinary portland cement (OPC)	Crushed stone gravel (4–20 mm)	Natural siliceous sand (0.1–4.75 mm)	CA (5–20 mm)	0.00
						25.00
						50.00
						75.00
						100.00
[10]	0.48	Type I, portland cement	Mineral aggregate (4–20 mm)	Natural sand (0.1–4.75 mm)	CA (4–30 mm)	0.00
						25.00
						50.00
						75.00
						100.00
[1]	0.55	Ordinary portland cement (OPC)	Mineral aggregate (4–20 mm)	Natural sand (0.1–4 mm)	CA (4–20 mm)	0.00
						12.30
						21.91
						31.78
						35.60
						51.23
[9]	0.33	Ordinary portland cement (OPC)	Mineral aggregate (4.75–19 mm)	Masonary sand (0.15–4.75 mm)	CA (4.75–25.4 mm)	0.00
						10.00
						20.00
						30.00
						40.00
						50.00
						60.00
						70.00
						80.00
						90.00

(continued on next page)

(*continued*)

Reference	W/C	Cement type	Coarse aggregate CA (mm)	Fine aggregate FA (mm)	Tire chips (mm)	Rep. of coarse aggregate (%)
						100.00
[49]	0.45	Type I, portland cement	Crushed stone (4.75–30 mm)	River sand (0.1–5 mm)	CA (15–40 mm)	0.00
						15.00
						30.00
						45.00
[42]	0.45	Cement CEM II A-L 42.5 R	Crushed limestone (4–25 mm)	Rolled limestone sand (0.1–4 mm)	CA (4–25.4 mm)	0.00
						8.50
						17.15
						25.94
[35]	0.35	CEM II-52.5 N Portland Limestone Cement	Round river washed gravel from Trent Valley (UK)(4–20 mm)	River washed sand from Shardlow, Derbyshire (UK) (0–5 mm)	CA (5–20 mm)	0.00
						10.00
						20.00
						40.00
						60.00
						100.00
[18]	0.53	Ordinary portland cement (OPC)	Gravel (14 mm, 20 mm)	Natural riverand manufactured sand (0–5 mm)	CA (15 mm)	0.00
						4.80
						9.70
[44]	0.48	type P. II52.5 R, Ordinary Portland cement	Crushed granite (5–20 mm)	River sand (0.1–5 mm)	CA (5–20 mm)	0.00
						10.00
						15.00
						20.00
						30.00
						40.00
						50.00
						80.00
						100.00
[2]	0.52	Ordinary portland cement (OPC)	Mineral aggregate (10–20 mm)	Natural sand (0.1–4 mm)	CA (8–20 mm)	0
						15.45
						31.2
						47.05
	0.6					0
						5.6
						11.3
						18.7
						28.1

Reference	Rep. of Total aggregate (%)	density (Kg/m3)	Size & shape of specimens	fc test (Mpa)	fc 150×300 (Mpa)	Ec (Gpa)	εo % (mm/mm)
[19]	0.00	2390.00	Cylinder (150 ×300 mm)	37.50	37.50	–	–
	2.84	2360.00		24.00	24.00	–	–
	5.68	2340.00		20.00	20.00	–	–
	8.50	2310.00		17.00	17.00	–	–
	11.35	2290.00		14.00	14.00	–	–
	22.70	2160.00		11.00	11.00	–	–
	34.05	2000.00		7.00	7.00	–	–
	45.41	1880.00		4.00	4.00	–	–
	56.76	1740.00		3.00	3.00	–	–
[17]	0.00	2323.00	Cylinder (150 ×300 mm)	35.26	35.26	–	–
	2.56	2294.82		31.13	31.13	–	–
	5.12	2266.65		29.29	29.29	–	–
	7.69	2238.42		25.00	25.00	–	–
	10.25	2210.30		22.00	22.00	–	–
[5]	0.00	2260.00	Cylinder (150 ×300 mm)	62.00	62.00	38.00	–
	15.50	2125.00		45.50	45.50	33.50	–
	31.10	2000.00		32.70	32.70	24.90	–
	46.67	1730.00		25.70	25.70	21.50	–
	62.20	1640.00		15.90	15.90	16.50	–
	0.00	2250.00		38.50	38.50	34.80	–
	15.50	2120.00		32.00	32.00	24.00	–
	31.10	1980.00		22.20	22.20	20.50	–
	46.67	1690.00		17.30	17.30	16.00	–
	62.20	1625.00		11.40	11.40	10.50	–
[41]	0.00	–	Cylinder (100 ×200 mm)	31.90	30.94	–	–
	15.00	–		19.60	19.01	–	–
	30.00	–		13.80	13.39	–	0.21
	45.00	–		9.90	9.60	–	–

(*continued on next page*)

(*continued*)

Reference	Rep. of Total aggregate (%)	density (Kg/ m3)	Size & shape of specimens	fc test (Mpa)	fc 150×300 (Mpa)	Ec (Gpa)	εo % (mm/mm)
	60.00	–		7.50	7.28	–	0.27
[12]	0.00	–	Cube (150×150×150 mm)	53.69	51.41	40.92	–
	2.65	–		47.51	44.22	37.50	–
	5.29	–		43.83	39.94	34.50	–
	7.94	–		38.05	33.22	31.36	–
	10.58	–		33.89	28.38	30.20	–
	13.23	–		31.10	25.14	28.36	–
	15.87	–		27.91	21.43	24.79	–
[36]	0.00	2400.00	Cylinder (150 ×300 mm)	27.00	27.00	–	–
	16.20	2190.00		16.20	16.20	–	–
	32.40	2095.00		14.04	14.04	–	–
	48.60	1900.00		7.29	7.29	–	–
	64.80	1870.00		5.94	5.94	–	–
[10]	0.00	–	Cylinder (150 ×300 mm)	34.00	34.00	–	–
	16.00	–		19.20	19.20	–	–
	32.00	–		11.60	11.60	–	–
	48.00	–		8.20	8.20	–	–
	64.00	–		6.00	6.00	–	–
[1]	0.00	–	Cylinder (150 ×300 mm)	29.00	29.00	16.80	0.219000
	7.50	–		23.30	23.30	12.43	0.209000
	13.27	–		17.04	17.04	9.72	0.206000
	19.25	–		13.00	13.00	9.37	0.169000
	21.60	–		8.90	8.90	6.24	0.150000
	31.00	–		5.77	5.77	5.89	0.135000
[9]	0.00	2552	Cylinder (150 ×300 mm)	65.70	65.70	39.20	0.205000
	6.30	2473		46.90	46.90	36.00	0.228000
	12.60	2433		43.70	43.70	35.00	0.258000
	18.90	2374		42.00	42.00	32.40	0.281000
	25.20	2321		38.20	38.20	28.50	0.290000
	31.50	2263		29.90	29.90	24.10	0.319000
	37.80	2213		26.10	26.10	21.60	0.336000
	44.10	2180		24.20	24.20	18.70	0.364000
	50.40	2118		20.60	20.60	17.20	0.376000
	56.70	2048		17.70	17.70	14.70	0.387000
	63.00	2014		14.40	14.40	11.80	0.391000
[49]	0.00	2399.00	Cylinder (150 ×300 mm)	38.80	38.80	31.80	–
	9.60	2245.00		30.10	30.10	27.50	–
	19.00	2130.00		21.00	21.00	21.20	–
	28.80	2050.00		18.10	18.10	16.50	–
[42]	0.00	–	Cylinder (150 ×300 mm)	55.50	55.50	40.60	–
	5.00	–		47.30	47.30	33.90	–
	10.00	–		37.80	37.80	31.80	–
	15.00	–		28.50	28.50	30.90	–
[35]	0.00	–	Cylinder (100 ×200 mm)	61.70	59.85	39.40	0.218000
	5.50	–		45.90	44.52	38.70	0.183000
	11.00	–		35.50	34.44	37.00	0.159000
	22.00	–		25.30	24.54	26.90	0.167000
	33.00	–		15.80	15.33	20.50	0.143000
	55.00	–		8.70	8.44	14.00	0.108000
[18]	0.00	–	Cylinder (100 ×200 mm)	41.30	40.06	31.00	0.160000
	2.80	–		32.48	31.51	26.30	0.166400
	5.70	–		29.26	28.38	22.90	0.181700
[44]	0.00	–	Cylinder (150 ×300 mm)	31.00	31.00	29.00	0.200000
	4.83	–		24.00	24.00	21.00	0.200000
	7.24	–		23.00	23.00	19.00	0.200000
	9.66	–		22.00	22.00	16.00	0.200000
	14.50	–		17.00	17.00	13.00	0.200000
	19.30	–		14.00	14.00	10.00	0.210000
	24.15	–		10.00	10.00	6.00	0.210000
	33.60	–		5.00	5.00	2.00	0.260000
	48.30	–		4.00	4.00	1.00	0.440000
[2]	0	2372	Cube (150×150×150 mm)	45.8	42.23	–	–
	6.2	2304		23.9	16.77	–	–
	12.5	2234		20.87	13.24	–	–
	18.8	2163		17.42	9.23	–	–
	0	2310		27.11	20.50	–	–
	2.25	2254		23.97	16.85	–	–
	4.5	2195		20.41	12.71	–	–
	7.47	2170		19.45	11.59	–	–
	11.23	2117		17.06	8.81	–	–

References

[1] F. Abbassi, F. Ahmad, Behavior analysis of concrete with recycled tire rubber as aggregate using 3D-digital image correlation, J. Clean. Prod. 274 (2020), 123074, https://doi.org/10.1016/j.jclepro.2020.123074.
[2] M.A. Aiello, F. Leuzzi, Waste tyre rubberized concrete: properties at fresh and hardened state, Waste Manag. 30 (8–9) (2010) 1696–1704, https://doi.org/10.1016/j.wasman.2010.02.005.
[3] T.A. Ako, U.S. Onoduku, S.A. Oke, B.I. Essien, F.N. Idris, A.N. Umar, A.A. Ahmed, "Environmental effects of sand and gravel mining on land and soil in Luku, Minna, Niger State, North Central Nigeria, J. Geosci. Geomat. 2 (2) (2014) 42–49.
[4] F. Aslani, Mechanical properties of waste tire rubber concrete, J. Mater. Civ. Eng. 28 (3) (2016) 04015152, https://doi.org/10.1061/(ASCE)MT.1943-5533.0001429.
[5] C. Bing, L. Ning, Experimental research on properties of fresh and hardened rubberized concrete, J. Mater. Civ. Eng. 26 (8) (2014) 04014040, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000923.
[6] D.V. Bompa, A.Y. Elghazouli, B. Xu, P.J. Stafford, A.M. Ruiz-Teran, Experimental assessment and constitutive modelling of rubberised concrete materials, Constr. Build. Mater. 137 (2017) 246–260, https://doi.org/10.1016/j.conbuildmat.2017.01.086.
[7] C.W. Chan, T. Yu, S.S. Zhang, Q.F. Xu, Compressive behaviour of FRP-confined rubber concrete, Constr. Build. Mater. (2019) 416–426, https://doi.org/10.1016/j.conbuildmat.2019.03.211.
[8] Collins, M.P. and Mitchell, D. 1997. Prestressed concrete structures. Response Publications, Canada 9.
[9] A. El Naggar, H. El Naggar, P. Sadeghian, Simplified material model for concrete containing high-content of tire-derived coarse aggregate under compression loading, Can. J. Civ. Eng. 48 (8) (2021) 912–924.
[10] Neil N. Eldin, B.Senouci Ahmed, Rubber-tire particles as concrete aggregate, J. Mater. Civ. Eng. 5 (4) (1993) 478–496, https://doi.org/10.1061/(ASCE)0899-1561(1993)5:4(478).
[11] N.I. Fattuhi, L.A. Clark, Cement-based materials containing shredded scrap truck tyre rubber, Constr. Build. Mater. 10 (4) (1996) 229–236, https://doi.org/10.1016/0950-0618(96)00004-9.
[12] M. Gesoglu, E. Güneyisi, O. Hansu, S. İpek, D.S. Asaad, Influence of waste rubber utilization on the fracture and steel–concrete bond strength properties of concrete, Constr. Build. Mater. 101 (2015) 1113–1121, https://doi.org/10.1016/j.conbuildmat.2015.10.030.
[13] E. Güneyisi, M. Gesoğlu, T. Özturan, Properties of rubberized concretes containing silica fume, Cem. Concr. Res. 34 (12) (2004) 2309–2317, https://doi.org/10.1016/j.cemconres.2004.04.005.
[14] A. Hamdi, G. Abdelaziz, K.Z. Farhan, Scope of reusing waste shredded tires in concrete and cementitious composite materials: a review, J. Build. Eng. 35 (2021), 102014, https://doi.org/10.1016/j.jobe.2020.102014.
[15] R. Hassanli, O. Youssf, J.E. Mills, Experimental investigations of reinforced rubberized concrete structural members, J. Build. Eng. 10 (2017) 149–165, https://doi.org/10.1016/j.jobe.2017.03.006.
[16] E.S. Herrera-Sosa, G. Martínez-Barrera, C. Barrera-Díaz, E. Cruz-Zaragoza, Waste tire particles and gamma radiation as modifiers of the mechanical properties of concrete, Adv. Mater. Sci. Eng. (2014), https://doi.org/10.1155/2014/327856.
[17] A.A. Kadhim, H.M. Al-Mutairee, An experimental study on behavior of sustainable rubberized concrete mixes, Civ. Eng. J. 6 (2020) 1273–1285, https://doi.org/10.28991/cej-2020-03091547.
[18] S. Karunarathna, S. Linforth, A. Kashani, X. Liu, T. Ngo, Effect of recycled rubber aggregate size on fracture and other mechanical properties of structural concrete, J. Clean. Prod. 314 (2021), 128230, https://doi.org/10.1016/j.jclepro.2021.128230.
[19] Z.K. Khatib, F.M. Bayomy, Rubberized Portland cement concrete, J. Mater. Civ. Eng. 3 (11) (1999) 206–213, https://doi.org/10.1061/(ASCE)0899-1561(1999)11:3(206).
[20] H.L. Li, Y. Xu, P.Y. Chen, J.J. Ge, F. Wu, Impact energy consumption of high-volume rubber concrete with silica fume, Adv. Civ. Eng. (2019), https://doi.org/10.1155/2019/1728762.
[21] D. Li, Y. Zhuge, R. Gravina, J.E. Mills, Compressive stress strain behavior of crumb rubber concrete (CRC) and application in reinforced CRC slab, Constr. Build. Mater. 188 (2018) 745–759, https://doi.org/10.1016/j.conbuildmat.2018.01.142.
[22] G. Li, M.A. Stubblefield, G. Garrick, J. Eggers, C. Abadie, B. Huang, Development of waste tire modified concrete, Cem. Concr. Res. 34 (12) (2004) 2283–2289, https://doi.org/10.1016/j.cemconres.2004.04.013.
[23] L. Li, S. Ruan, L. Zeng, Mechanical properties and constitutive equations of concrete containing a low volume of tire rubber particles, Constr. Build. Mater. 70 (2014) 291–308, https://doi.org/10.1016/j.conbuildmat.2014.07.105.
[24] Zongjin Li, Li Faming, Li Jim SL, Properties of concrete incorporating rubber tyre particles, Mag. Concr. Res. 50 (4) (1998) 297–304, https://doi.org/10.1680/macr.1998.50.4.297.
[25] J.C. Lim, T. Ozbakkaloglu, Stress–strain model for normal-and light-weight concretes under uniaxial and triaxial compression, Constr. Build. Mater. 71 (2014) 492–509, https://doi.org/10.1016/j.conbuildmat.2014.08.050.
[26] G. Martínez-Barrera, J.J. del Coz-Díaz, F.P. Álvarez-Rabanal, F.L. Gayarre, M. Martínez-López, J. Cruz-Olivares, Waste tire rubber particles modified by gamma radiation and their use as modifiers of concrete, Case Stud. Constr. Mater. (2020), https://doi.org/10.1016/j.cscm.2019.e00321.
[27] A.S. Mendis, S. Al-Deen, M. Ashraf, Behaviour of similar strength crumbed rubber concrete (CRC) mixes with different mix proportions, Constr. Build. Mater. 137 (2017) 354–366, https://doi.org/10.1016/j.conbuildmat.2017.01.125.
[28] Mohamed, Abubaker Ahmed Mohamed Salih, Mohammed Al-Ajamee, Ayman Kobbail, Haytham Dahab, Mohammed Mohammed Abdo, Husam-Eldein Alhassan, A study on soil stabilization for some tropical soils, Mater. Today.: Proc. (2021), https://doi.org/10.1016/j.matpr.2021.12.260.
[29] Iman Mohammadi, Hadi Khabbaz, Kirk Vessalas, Enhancing mechanical performance of rubberised concrete pavements with sodium hydroxide treatment, Mater. Struct. 49 (2016) 813–827, https://doi.org/10.1617/s11527-015-0540-7.
[30] G. Murali, L. Poka, K. Parthiban, M.K. Haridharan, A. Siva, Impact response of novel fibre-reinforced grouted aggregate rubberized concrete, Arab. J. Sci. Eng. 10 (44) (2019) 8451–8463, https://doi.org/10.1007/s13369-019-03819-5.
[31] K.B. Najim, M.R. Hall, Crumb rubber aggregate coatings/pre-treatments and their effects on interfacial bonding, air entrapment and fracture toughness in self-compacting rubberised concrete (SCRC, Mater. Struct. 46 (2013) 2029–2043, https://doi.org/10.1617/s11527-013-0034-4.
[32] A.M. Neville. Properties of concrete, 4th ed..,, Longman,, London (UK), 1993.
[33] S. Popovics, A numerical approach to the complete stress-strain curve of concrete, Cem. Concr. Res. 3 (5) (1973) 583–599, https://doi.org/10.1016/0008-8846(73)90096-3.
[34] S. Raffoul, R. Garcia, D. Escolano-Margarit, M. Guadagnini, I. Hajirasouliha, K. Pilakoutas, Behaviour of unconfined and FRP-confined rubberised concrete in axial compression, Constr. Build. Mater. 147 (2017) 388–397, https://doi.org/10.1016/j.conbuildmat.2017.04.175.
[35] S. Raffoul, R. Garcia, K. Pilakoutas, M. Guadagnini, N.F. Medina, Optimisation of rubberised concrete with high rubber content: an experimental investigation, Constr. Build. Mater. 124 (2016) 391–404, https://doi.org/10.1016/j.conbuildmat.2016.07.054.
[36] M.M. Reda Taha, A.S. El-Dieb, M.A. Abd El-Wahab, M.E. Abdel-Hameed, Mechanical, fracture, and microstructural investigations of rubber concrete, J. Mater. Civ. Eng. 10 (20) (2008) 640–649, https://doi.org/10.1061/(ASCE)0899-1561(2008)20:10(640).
[37] R. Roychand, R.J. Gravina, Y. Zhuge, X. Ma, O. Youssf, J.E. Mills, A comprehensive review on the mechanical properties of waste tire rubber concrete, Constr. Build. Mater. 237 (2020), 117651, https://doi.org/10.1016/j.conbuildmat.2019.117651.
[38] A.K. Samani, M.M. Attard, A stress–strain model for uniaxial and confined concrete under compression, Eng. Struct. 41 (2012) (2012) 335–349, https://doi.org/10.1016/j.engstruct.2012.03.027.
[39] K. Strukar, T. Kalman Šipoš, T. Dokšanović, H. Rodrigues, Experimental study of rubberized concrete stress-strain behavior for improving constitutive models, Materials 11 (11) (2018) 2245, https://doi.org/10.3390/ma11112245.
[40] Ilker Bekir Topcu, The properties of rubberized concretes, Cem. Concr. Res. 25 (2) (1995) 304–310, https://doi.org/10.1016/0008-8846(95)00014-3.

[41] H.A. Toutanji, The use of rubber tire particles in concrete to replace mineral aggregates, Cem. Concr. Compos. 2 (18) (1996) 135–139, https://doi.org/10.1016/0958-9465(95)00010-0.
[42] F. Valadares, M. Bravo, J. de Brito, Concrete with used tire rubber aggregates: mechanical performance, Acids Mater. J. -Am. Concr. Inst. 109 (3) (2012) 283.
[43] A.P. Velenturf, S.A. Archer, H.I. Gomes, B. Christgen, A.J. Lag-Brotons, P. Purnell, Circular economy and the matter of integrated resources, Sci. Total Environ. 689 (2019) 963–969, https://doi.org/10.1016/j.scitotenv.2019.06.449.
[44] Y.F. Wu, S.M.S. Kazmi, M.J. Munir, Y. Zhou, F. Xing, Effect of compression casting method on the compressive strength, elastic modulus and microstructure of rubber concrete, J. Clean. Prod. 264 (2020), 121746, https://doi.org/10.1016/j.jclepro.2020.121746.
[45] J. Xie, Y. Zheng, Y. Guo, R. Ou, Z. Xie, L. Huang, Effects of crumb rubber aggregate on the static and fatigue performance of reinforced concrete slabs, Compos. Struct. 228 (2019), 111371, https://doi.org/10.1016/j.compstruct.2019.111371.
[46] Z. Xiong, Z. Fang, W. Feng, F. Liu, F. Yang, L. Li, Review of dynamic behaviour of rubberised concrete at material and member levels, J. Build. Eng. 38 (2021), 102237, https://doi.org/10.1016/j.jobe.2021.102237.
[47] S.T. Yi, E.I. Yang, J.C. Choi, Effect of specimen sizes, specimen shapes, and placement directions on compressive strength of concrete, Nucl. Eng. Des. 236 (2) (2006) 115–127, https://doi.org/10.1016/j.nucengdes.2005.08.004.
[48] O. Youssf, R. Hassanli, J.E. Mills, Mechanical performance of FRP-confined and unconfined crumb rubber concrete containing high rubber content, J. Build. Eng. (2017) 115–126, https://doi.org/10.1016/j.jobe.2017.04.011.
[49] L. Zheng, X.S. Huo, Y. Yuan, Experimental investigation on dynamic properties of rubberized concrete, Constr. Build. Mater. 22 (5) (2008) 939–947, https://doi.org/10.1016/j.conbuildmat.2007.03.005.