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RESEARCH PAPER

Mechanical Properties of Self-Compacting Rubberised Concrete (SCRC) Containing Polyethylene Terephthalate (PET) Fibres

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Abstract

This study focuses on the development and assessment of greener and sustainable mix of self-compacting rubberised concrete (SCRC) utilising commonly available waste materials such as fly ash, worn tires, and polyethylene terephthalate (PET) drinking bottles as fibres. Ten mixes containing ground tire rubber and PET fibres were investigated under compression, split tension, and flexure. In 05 out of 10 mixes, SCRC contained 35% fly ash by mass substitution of cement and ground tire rubber to substitute 0, 5, 10, 15, and 20% masses of fine aggregates. The remaining 05 mixes of SCRC contained a fixed 2% volume fraction of PET fibres measured by the volume of concrete. The compression, split tension, and flexure tests were performed at 28 days to assess the effects of ground tire rubber and PET fibres on the strengths, compressive stress–strain behaviour, and load–deformation behaviour. The results indicated that the replacement of 15% mass of fine aggregates with ground tire rubber is optimum without impairing the strengths of concrete. The PET fibres played a role in stabilising and improving the post-peak response in the compression and the flexure. Overall, the use of ground tire rubber as fine aggregates and PET fibres as reinforcement in concrete improved the response of concrete in compression and flexure.

Keywords Self-compacting rubberised concrete · Fly ash · Ground tire rubber · PET fibres · Mechanical properties

1 Introduction

The recent trend in the construction industry is to develop and use "green building materials" (or environment-friendly materials) to build sustainable structures. The term "green building material" refers to the one, which affects less to the environment during its production until placing and maintenance. Concrete, which is an irreplaceable material so far being cheaper, releases tons of greenhouse gases (e.g. carbon dioxide (CO_2)) into the environment and is one of the contributing and responsible factors to climate change. With this emphasis, substantial studies are conducted across the globe to investigate the compressive behaviour of concrete by experimenting with a variety of waste materials. One of the most investigated waste materials in concrete is scrap tires, which have well explored to replace fine aggregates partially (AbdelAleem and Hassan 2018; Ismail and Hassan 2016; Khan et al. 2017; Moustafa and ElGawady 2015; Sofi 2018; Yung et al. 2013). Self-compacting concrete (SCC) by incorporating ground rubber as partial substitution of fine aggregate, commonly known as self-compacting rubberised concrete (SCRC) was investigated (AbdelAleem and Hassan 2018; Ismail and Hassan 2016; Khan et al. 2017; Moustafa and ElGawady 2015; Sofi 2018; Yung et al. 2013). The reported investigations aimed to utilise the growing volume of scrap tires in ground form, which presently is a significant ecological and environmental issue. It is worth mentioning that SCC is a preferable concrete type rather than traditional vibrated concrete (Murthy et al. 2016) in severe concreting conditions especially and is economical in terms of placement, vibration, and results in well-finished surfaces (Murthy et al. 2016). When ground rubber is added, SCC contributes to higher ductility, improves energy dissipation characteristics, and resists impact (Elghazouli et al. 2018), and most importantly, SCC employs numerous applications,

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for example, road barriers, sidewalks, and pavement (Jedidi et al. 2014; Moustafa and ElGawady 2015; Si et al. 2018). The use of SCRC is recommended in non-structural applications, e.g. sports courts, sidewalks, and traffic noise barriers on highways (Murugan et al. 2017) and also recommended in structures subjected to dynamic loading due to ductility and enhance impact resistance (Moustafa and ElGawady 2015).

In SCRC, the use of ground rubber as a partial substitution of the fine aggregate reduces flowability, passing ability, and resistance against segregation; however, viscosity and porosity increase with an increase in the amount of rubber (Bušić et al. 2018). In the literature, the partial substitution of fine aggregates with ground rubber is in the range of 5–40% (Bušić et al. 2018), whereas the decrement in the compressive strength at 40% replacement is in the range of 40 to 67% (Aslani et al. 2018; Ismail and Hassan 2016; Khalil et al. 2015). At 5% replacement of fine aggregates, the strength reduction was less than 15% due to the rubber acted as voided element (AbdelAleem et al. 2018; Ganesan et al. 2013; Güneyisi et al. 2016; Hilal 2017; Ismail et al. 2015; Ismail and Hassan 2017; Yung et al. 2013). Hilal (Hilal 2017). Some researchers (AbdelAleem and Hassan 2018; Aslani et al. 2018) related the compressive strength reduction to the deprived adhesion, bond strength between rubber elements and cement paste, as well as the low elastic modulus of rubber if compared to the ordinary aggregates. While few researchers (Eldin and Senouci 1993; Sofi 2018) reported that the compressive strength of SCRC reduces due to lower compressive strength of crumbed rubber, a higher content of air entrapped between rubber elements and cement paste along with the soft characteristics of rubber particles as compared to the sand particles. Also, this lessening effect is independent of rubber replacement level, or replacement type (as fine or coarse aggregate) (Sofi 2018). Overall, there is agreement among researchers that the reduction in the compressive strength is significant at higher replacement level of fine aggregates with ground rubber, and the variation depends on the particle size of the rubber.

To overcome the reduction in compressive strength, some researchers used supplementary cementitious materials (SCMs) and recommended a 25% replacement of fine aggregates with crumb rubber as an optimised percentage in SCRC using silica fume (AbdelAleem and Hassan 2018); however, the use of metakaolin exhibited the best behaviour (Ismail and Hassan 2016). They (Ismail and Hassan 2016) recommended the use of up to 40% replacement of fine aggregates with crumb rubber in SCRC with metakaolin. The durability of SCRC by replacing fine aggregates up to 20% with ground tire rubber was investigated (Yung et al. 2013) and recommended the 5% ground tire rubber in concrete for enhanced durability. According to them (Yung et al. 2013), the use of 5% ground tire rubber increases the resistance against sulphate corrosion and electricity as compared to the ordinary concrete. It is also reported that the static and dynamic elastic modulus of SCRC is reduced with the increasing amount of rubber as an aggregate apart from compressive strength (Sofi 2018). In SCRC, four designated substitutions of crumb rubber as 0, 5, 15, and 25% by volume of fine aggregate and four fly ash contents as 0, 20, 40, and 60% were used to assess the rheological properties (Güneyisi 2010). The results of rheological properties indicated that the combined use of ground rubber and fly ash significantly enhanced the fresh properties of SCRC. Other than the compressive strength, various researchers reported the reduction in the splitting tensile strength (Sofi 2018) and flexural strength (Sofi 2018; Yilmaz and Degirmenci 2009) with the increasing amount of rubber aggregate in SCRC regardless of rubber particle size, aggregate replacement level, and SCMs (Sofi 2018; Yilmaz and Degirmenci 2009).

To improve the tensile and flexural properties of SCRC, several researchers (AbdelAleem et al. 2018; Ali and Hasan 2020; Aslani and Gedeon 2019) used fibres; however, the investigation on the behaviour of SCRC with fibres is limited in the literature. The use of steel fibres in SCRC significantly boosted the mechanical properties, particularly splitting tensile, and flexural strengths and suggested the use of long fibres to obtain higher splitting tensile strength (AbdelAleem and Hassan 2018). The flexural behaviour of SCRC beams using steel fibres was investigated, and it was found that the flexural response of steel fibre-reinforced SCRC beams was acceptable as compared to SCC with and without steel fibres depending on the load-carrying capacity (Ali and Hasan 2020). Furthermore, the addition of steel fibres along with the use of scrap tire rubber decreased the width of the cracks. In another study (Aslani and Gedeon 2019), 20% content of rubber as fine aggregate and 0.25% volumes of polypropylene (PP) and 1% volume of steel fibres were used in SCRC. It was found that the rheological properties of SCRC were affected by the use of higher fibre volume. The reduction in compressive strength of SCRC was observed with the increasing volume percentage of PP fibres, whereas the splitting tensile strength was not affected. Steel fibres, on the other hand, positively contributed to the compressive and splitting tensile strengths. Besides, the behaviour of SCRC using steel fibres against elevated temperatures and impact (Ismail et al. 2018; Khalil et al. 2015) is also studied.

This overview identifies that the use of a low volume fraction of ground tire rubber as a partial substitution of fine aggregate is suitable in structural applications and the use of SCMs can control the reduction of compressive strength. Among fibre types used in SCRC, steel fibre is the most commonly used fibre in SCRC, and there is an opportunity to investigate other fibres type. The current study aims at to investigate the SCRC in most sustainable and economically manner by utilising 35% volume of fly ash and the ground rubber replacing 0, 5, 10, 15, and 20% volume of fine aggregates. In this study, the use of fly ash is to enrich the rheological properties of SCRC, which is suggested elsewhere (Güneyisi 2010). The assessment of the effect of fibre addition on the fresh and hardened state properties was carried out using polyethylene terephthalate (PET) fibres. In the literature, the use of PET fibres in concrete is explored by quite a few researchers (Dinesh and Rao 2017; Fraternali et al. 2011; Irwan et al. 2013), whereas the use of PET fibres in SCRC has yet to explore. The volume percentage of PET fibre used in this study is 2%, as suggested in the literature (Fraternali et al. 2011; Irwan et al. 2013), and others have used up to 1.5% volume fraction of PET fibres in concrete (Dinesh and Rao 2017). The inclusion of rubber and PET fibres in concrete is significant to explore as both are waste materials, and utilisation of these materials is good from an environmental perspective. Secondly, the use of these two flexible materials may lead to the concrete better in ductility. The obtained results indicated that the combination of SCRC and PET fibres is suitable for structural application due to added ductility with marginally compromising strength.

2 Materials and Method of Specimen Casting

2.1 Material Properties

The materials used in the present study were ordinary Portland cement (OPC) (ASTM 2012a), class F fly ash, ground rubber, river sand (as the fine aggregate) and natural coarse aggregates. The specific gravity of cement was 3.05, and the density of fine aggregates was 2350 kg/m^3. Ground rubber used up to 20% substitution of sand. The natural coarse aggregates of the size 10 mm and 12 mm were used with a density of 2590 kg/m^3. It had been earlier mentioned that fly ash is an SCM that replaces the highest content of cement among all SCM types. Thomas recommended up to 50% content of fly ash for most elements if the early-age strength is not required (Thomas 2007). Therefore, a 35% content of cement is replaced with fly ash as a partial substitution in this study. The use of 15% ground tire rubber to acquire higher compressive strength is recommended (Güneyisi et al. 2004), but ground rubber up to 20% as partial replacement of fine aggregates was used in the present study to verify the recommended 15% replacement. A 2% fixed volume of PET fibres is used to improve the compressive and flexural tensile behaviour and ductility of concrete.

The physical and chemical properties of fly ash used in current investigation are given in Khan and Ayub (2020), while Table 1 shows the physical and chemical properties of ground rubber. The view of ground tire rubber is shown in Fig. 1a. The authors of this paper explained the cutting and testing detail of PET fibres to determine the elongation at the verge of failure (Khan and Ayub 2020). The typical width and length of PET fibres were 5 mm and 25 mm, respectively, as shown in Fig. 1b and c. The fibres were sprinkled gradually on the mix, while the mixer was running to ensure the dispersion of fibres. In this way, fibres remain randomly oriented in the concrete. The random orientation of fibres is important to achieve a large homogenous volume of concrete. The viscosity-modifying agent (VMA) was used in the range of 1–1.2% by weight of binder in the mixes depending upon the addition of rubber and polyethylene terephthalate (PET) fibres. Table 2 shows the physical and chemical characteristics of PET fibres.

Table 1 Physical and chemical characteristics of rubber tire

Properties	Rubber tire
Bulk specific gravity (g/cm^3)	0.5
Size	80 µm–1.6 mm
Surface area (m^2/g)	0.47–0.81
Porosity	0.14–0.17
Elongation at break (%)	Minimum 245
Presence of steel fibres (%)	0
Natural rubber (% by mass)	70
Polybutadiene rubber (% by mass)	30
Carbon black (% by mass)	48.5–53
Ash content (%)	4

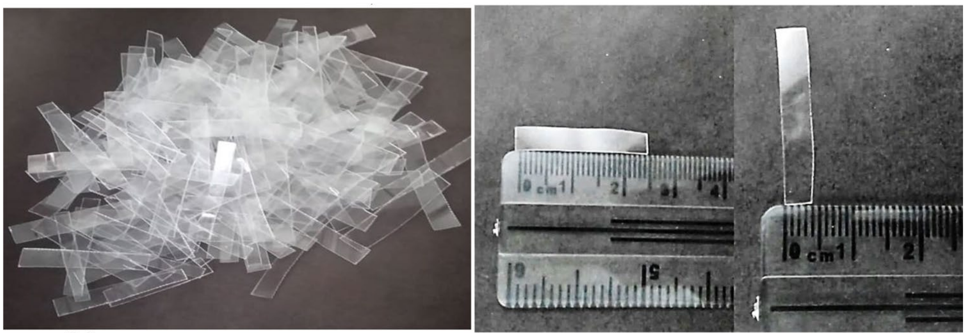
Note: The properties determined through thermogravimetric analysis (TGA) and scanning electron microscope (SEM) results

2.2 Mixing and Casting Detail

The mix design of SCC used in this study was referred from Reddy et al. (2013) with slight modification and is given in Table 3. In the following table, the mix ID R0 refers to the SCC mix (without ground tire rubber), and this mix served as a control mix for SCRC without PET fibres. The SCRC mixes were containing 5, 10, 15, and 20% content of ground tire rubber as a partial substitution of fine aggregates and named R5, R10, R15, and R20. As given in Table 3, SCC mix P-R0 contained 2% volume of PET fibres (without rubber), and the SCRC mix was containing 2% volume fraction of PET fibres is named P-R5, P-R10, P-R15, and P-R20. This experimental program aimed to assess the compressive and flexural tensile behaviour of a 2% volume of PET fibres in SCC (without ground tire rubber) by comparing mix R0 and P-R0. Series "R" (with and without ground tire rubber) is to assess the contribution of ground tire rubber, whereas series "P-R" (with and without ground tire rubber and 2% fixed volume of PET fibres).

Fig. 1 Ground tire rubber and PET fibres with dimensions

(a) View of Ground tire rubber



(b) PET fibres extracted from PET strips

(c) PET fibre dimensions

Table 2 Characteristics of PET fibre

Property	PET fibre
Specific gravity	1.34
Cross-section shape	Rectangular (Flat)
Texture	Straight embossed
Width (mm)	5
Thickness (mm)	0.8
Length (mm)	25
Tensile strength (MPa)	260.00
Elongation (%)	20

Table 4 lists the tests for the mechanical properties with the sample sizes and testing standards. All materials were mixed in a pan mixer of 100 l's capacity, whereas the total concrete volume of each mix for the specimens listed in Table 4 was 0.03 m^3. The mixing procedure of SCC was referred from the European Guidelines for Self-compacting Concrete Specification, Production and Use (EFNARC) (BIBM and EFNARC 2005).

Table 3 Mix proportion and quantities (kg/m^3)

Mix ID	Cement	Fly ash	Coarse aggregate	Fine aggregate	Ground tire rubber (%)	Water/binder (w/b) ratio	Viscosity modifying agent (VMA) (g, %)	PET fibre (%)	Remarks
R0	290	155	810	960	0	0.48	133.5, 1%	0	Control mix (without rubber powder and fibres)
R5*	290	155	810	912	48 (5%)	0.48	133.5, 1%	0	Mixes with variable dosages of rubber powder only
R10	290	155	810	864	96 (10%)	0.48	133.5, 1%	0	
R15	290	155	810	816	144 (15%)	0.48	133.5, 1%	0	
R20	290	155	810	768	192 (20%)	0.48	133.5, 1%	0	
P-R0	290	155	810	960	0	0.48	133.5, 1%	2%	Mix with PET fibres only
**P-R5	290	155	810	912	48 (5%)	0.48	160, 1.2%	2%	Mixes with variable dosages of rubber powder and 2% fixed volume of PET Fibres
P-R10	290	155	810	864	96 (10%)	0.48	160, 1.2%	2%	
P-R15	290	155	810	816	144 (15%)	0.48	160, 1.2%	2%	
P-R20	290	155	810	768	192 (20%)	0.48	160, 1.2%	2%	

* In the following mix design, the letter "R" represents "rubber" and number "5" represents percentage substitute of sand with ground rubber

** Letters "P" abbreviated from "PET Fibre", "R" represents "rubber", and number "5" represents percentage replacement of sand with ground rubber

Table 4 Tests for mechanical properties

Mechanical properties test			
Test	Sample size (mm)	No. of samples	Test standard
Compression	100 dia. × 200 Height	03	ASTM C39 (ASTM 2012b)
Splitting tensile strength	100 dia. × 200 Height	03	ASTM C496 (ASTM 2011)
Flexural strength	100 × 100 × 500	03	ASTM standard C78 (ASTM 2010)

3 Testing of Specimens and Results

3.1 Rheological Properties

According to EFNARC (BIBM and EFNARC 2005), the filling ability and stability of SCC after mixing are well defined by four key characteristics, which can be addressed by one or more test methods mentioned in Table 5. After mixing, the tests for "Flowability", "Passing ability", and "Viscosity “of concrete were performed. Table 5 shows the characteristics, tests performed along with the recommended value ranges for SCC (BIBM and EFNARC 2005). The slump flow test was carried out for *flowability* according to EFNARC guidelines (BIBM and EFNARC 2005) to note time T500. V-funnel test was performed by following the same guidelines (BIBM and EFNARC 2005) to assess the filling ability of SCC and SCRC mixes. This test determines the ease in the concrete flow through reinforcements. The flow spread calculated using Eq. (1):

$$S = \frac{d_{\max} + d_{\min}}{2} \tag{1}$$

In Eq. (1), "S" represents flow spread, "$d_{\max}$" is the maximum spread diameter, and "$d_{\min}$" is the diameter measured perpendicular to the $d_{\max}$. The time T500 and average flow spread (S) are reported in Table 6.

For passing ability, L-box was used to check the flow of SCC through narrow openings and without segregation or blocking between reinforcing bars. L-box test can be performed with two bars and three bars. The three bars test is used in the situation of more crowded reinforcement (BIBM and EFNARC 2005). In calculating the passing ability ratio (PA) or blocking ratio (BL), the following relationships were used:

$$PA = \frac{H}{H_{\max}} \tag{2}$$

$$BL = 1 - \frac{H}{H_{\max}} \tag{3}$$

In Eqs. (2) and (3), ’PA’ is the passing ratio, "BL" is the blocking ratio, and "H" is measured as the height of concrete at the end of the horizontal portion of the L-Box. "$H_{\max}$" was measured as the height when the vertical hopper contains exactly 12.7 l of SCC and complete levels in the test. The measured value of "$H_{\max}$" was 91 mm. Table 6 shows the results of rheological properties of SCC and SCRC mixes. The results are similar, as reported in the literature (Aslani et al. 2018; Bušić et al. 2018; Güneyisi 2010). According to the presented results, the use of rubber in SCRC mix results in reduced flowability and passing ability. At the same time, the viscosity is increased with the increasing amount of ground rubber in SCRC.

3.2 Compression Test

The deformation controlled compression test was performed according to ASTM C39 (ASTM 2012b) procedure by testing three specimens using a Universal Testing Machine (UTM) shown in Fig. 2.

Figure 3 represents the compressive strength of all mixes in the bar chart. The samples with partial substitution of sand with ground tire rubber showed a decrease in the compressive strength. The average compressive strength of the SCC control mix "R0" was obtained as 30.83 MPa.

Table 5 Characteristics, test methods and value ranges for different tests for SCC (BIBM and EFNARC 2005)

Characteristic	Test method(s)	Test result obtain	Unit	Range of values	
				Minimum	Maximum
Flowability	Slump-flow (SF) test	785	mm	650	800
Viscosity (a measure of the speed of flow and assessed by the rate of flow), VS or VF	T_{500} Slump-flow test or V-funnel test	3.9	Sec	2	5
Passing ability ratio (PA)	L-box test	0.887	–	0.75	1

Table 6 Fresh state properties test with allowable limits as per EFNARC (BIBM and EFNARC 2005)

Mix IDs	Flowability test results					Passing ability test results						Remarks
	T_{500} (s)	Time limits (s)	d_{max} (mm)	d_{min} (mm)	Average flow spread (mm) (S)	Δh (mm)	$H = 150 - \Delta h$ (mm)	H_{max} (mm)	Passing ratio (PA)	Blocking ratio (BL)	Limits as per EFNARC (BIBM and EFNARC 2005)	
R0	3.53	2 to 5 s (refer to Table 5)	870	850	860	67	83	91	0.91	0.09	$0.75 \leq PA \leq 1.0$ $0 \leq BL \leq 0.25$	All mixes qualified for the minimum slump flow requirements as well as good passing ability
R5*	3.67		850	840	845	71	79	91	0.87	0.13		
R10	4.84		790	790	790	78	77	91	0.85	0.15		
R15	4.88		770	760	765	78	72	91	0.79	0.21		
R20	4.89		750	760	755	81	69	91	0.76	0.24		
P-R0	3.99		810	800	805	71	79	91	0.87	0.13		
P-R5	3.98		810	790	800	73	77	91	0.85	0.15		
P-R10	3.87		790	800	795	70	80	91	0.88	0.12		
P-R15	4.67		780	760	770	81	69	91	0.76	0.24		
P-R20	4.78		770	750	760	83	67	91	0.74	0.26		

Fig. 2 Setup of compressive strength test

The compressive strengths for SCRC mixes "R5", "R10", "R15", and "R20" were 28.68 MPa, 26.28 MPa, 26.23 MPa, and 24.36 MPa, respectively. In the following mixes, the decrease in the compressive strengths as compared to the control mix "R0" is found to be 6.99%, 14.78%, 14.92%, and 21%, respectively. By comparing the obtained results with the one reported in the literature (Bušić et al. 2018), it is found that the reduction in the compressive strength is 6.99% at 5% substitution of fine aggregates with ground tire rubber in this study, while it was reported in the range of 5% to 40% in the literature (Bušić et al. 2018). The compressive strength results at 10% and 15% were closed to each other. Thus, 15% can be a suitable substitution, as also suggested by (Güneyisi et al. 2004) that 15% substitution appropriate to acquire higher compressive strength. Several researchers (Ganesan et al. 2013; Mishra and Panda 2015; Yung et al. 2013; Zaoiai et al. 2016) reported the decrease in the compressive strength as 40%, 47%, 13%, and 36%, respectively, at 20% substitution of fine aggregates with ground rubber, whereas in this study, 21% decrease was observed at the use of 20% content of ground tire rubber.

In mix P-R0 (with a 2% volume of PET fibre and without rubber), the compressive strength was 28.72 MPa, which is 6.85% less than the compressive strength of control mix R0 (without PET fibres and rubber). The compressive strength comparison of mixes containing only rubber (i.e. mixes R5, R10, R15, and R20) with the mixes containing rubber and PET fibres (i.e. mixes P-R5, P-R10, P-R15, and P-R20) showed that the reduction in the compressive strength is 5–7% due to the addition of 2% PET fibres volume. It shows that the addition of PET fibres reduces the

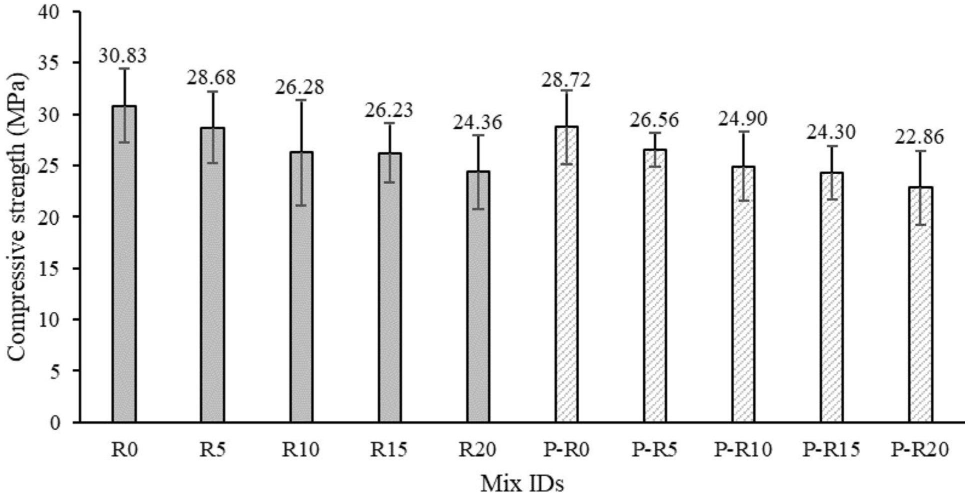


Fig. 3 Compressive strength with and without PET fibres

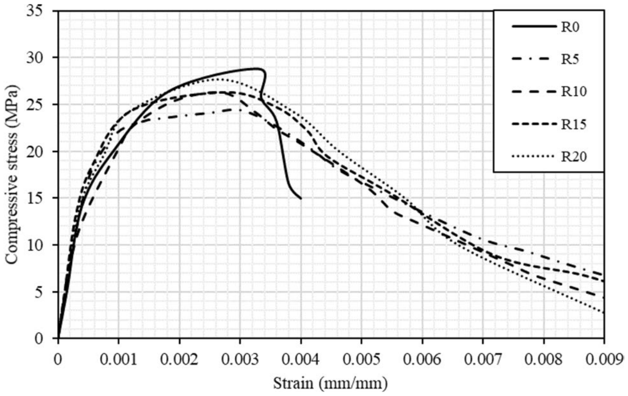


Fig. 4 Compressive stress–strain behaviour without PET fibres

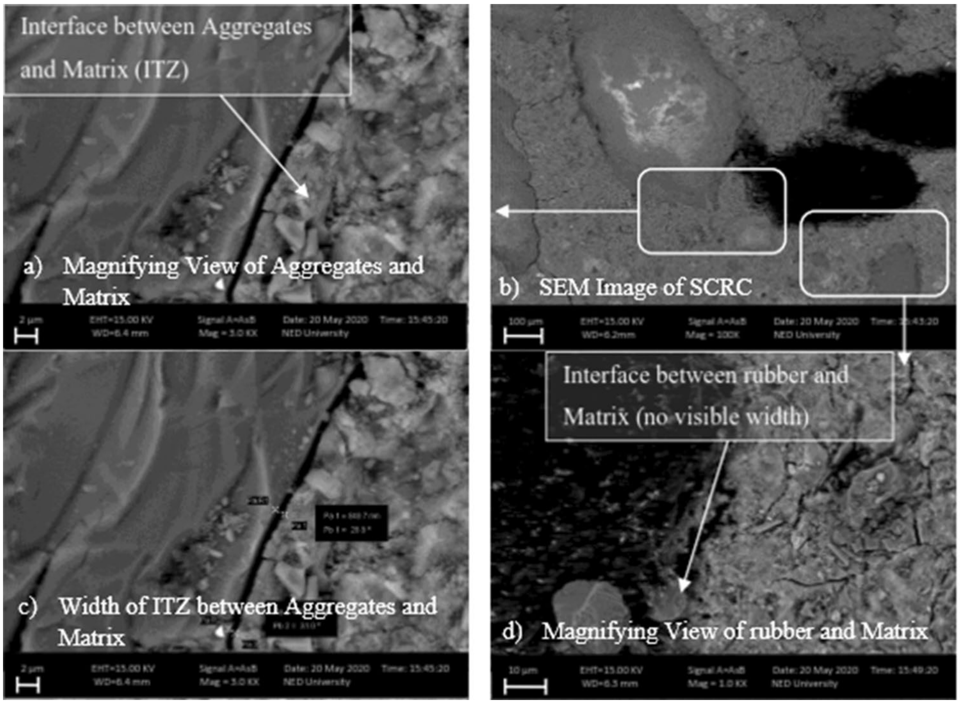
compressive strength. The reason for reduction may be associated with the excessive demand of paste by the addition of higher volume PET fibre, as reported in the literature for a high volume of PVA fibres (Ayub et al. 2019; Nuruddin et al. 2015). The compressive strengths of SCRC mix with PET fibres P-R5, P-R10, P-R15, and P-R20 were 26.56 MPa, 24.90 MPa, 24.30 MPa, and 22.86 MPa, respectively, and in the following mixes, the decrease in the compressive strengths as compared to the control mix P-R0 is found to be 7.53%, 13.31%, 15.39%, and 20.41%, respectively. The compressive strength results obtained at 10% and 15% at 2% volume of PET fibres are closed suggesting 15% as a suitable substitution, as suggested by (Güneyisi et al. 2004) without significantly affecting the compressive strength. Overall, the addition of ground tire rubber as 20% of fine aggregates significantly lowered the compressive strength irrespective of a 2% volume fraction of PET fibres. Thus, the suitable replacement level of fine aggregate with ground tire rubber with and without PET fibres is 15%.

The compressive stress–strain behaviour of SCC mix without PET fibres is shown in Fig. 4. In Fig. 4, the ascending branch of stress–strain curves and modulus of elasticity is observed slightly lower with ground tire rubber as also reported in the literature (Al-Tayeb et al. 2013; Meddah et al. 2014). The SCC mix was less susceptible to the increase in the content of rubber due to the better compaction. A small rise in the post-peak branch of the stress–strain curves was observed (refer to Fig. 4), which was completely absent in the control mix R0 (without rubber). It shows a small contribution of rubber to the pseudo-strain hardening response. Though the response of rubber is better than the control, the steep post-peak branch suggests that the contribution is small and needs to enhance that might be possible by the introduction of fibres such as PET fibres.

Figure 5 shows the scanning electron microscopic (SEM) images of SCC. Figure 5a and c shows the magnifying view of Fig. 5b showing the interfacial transition zone (ITZ) between natural aggregate and cement matrix. The width of the ITZ observed in Fig. 5c is approximately equal to 750 nm. Similarly, Fig. 5d is the magnifying view of Fig. 5b showing the interface between the rubber and cement matrix. There is no visible width observed in Fig. 5d. Thus, the small contribution of rubber in the post-peak response of concrete might be due to the better confinement and gripping of rubber in the cement matrix even after cracking of concrete as depicted in scanning electron microscopic (SEM) images shown in Fig. 5.

Similarly, the decrease in the compressive strength, the slope of the pre-peak branch of stress–strain curves, and modulus of elasticity were observed when 2% PET fibres were added in the SCRC mixes P-R5, P-R10, P-R15, and P-R20 (refer to Fig. 6). The decrease in strength was due to difficulty in compaction with the fibres. The fibres occupied the substantial volume of the cylinder instead of aggregates and paste. Consequently, there was a slight decrease in the strength of concrete with fibres, as also

Fig. 5 Scanning electron microscopic (SEM) images of SCRC



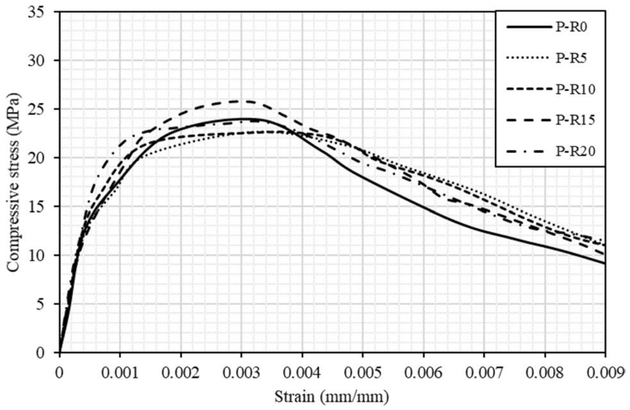


Fig. 6 Stress–strain response under compression with PET fibres

reported by Khan et al. (Khan and Ayub 2020), whereas the strains closed to the failure were higher in the SCRC mixes containing PET fibres (i.e. mixes P-R5, P-R10, P-R15, and P-R20) than the SCRC mixes without PET fibres (i.e. mixes P-R5, P-R10, P-R15, and P-R20) due to crack bridging behaviour of fibres resulting in a better response in terms of overall strain. This behaviour of PET fibres is consistent, which is reported by Khan and Ayub (2020). Unlike SCRC mixes R5, R10, R15, and R20, the toughness of the post-peak branch of stress–strain curves was significantly improved due to the PET fibres, as they provided lateral confinement in the cylindrical specimens. Consequently, the addition of PET fibres improved the ultimate strains.

Figure 7 shows the effect of PET fibres on the stress–strain behaviour of SCRC mixes. The addition of a 2% volume fraction of PET fibres increased the strain attainment corresponding to the peak stress, toughness in the post-peak behaviour, and ultimate strains at all replacement levels of fine aggregates with ground tire rubber. This behaviour is essential, as an ordinary concrete does not carry stresses once it attains peak strength.

As compared to the control mix R0, the strain values corresponding to the peak stresses were increased and were between 0.002 and 0.0035. This improvement was slight in the presence of PET fibres in the SCRC mixes, and there was a slight increase in the strain corresponding to peak stress in SCRC with PET fibres. The higher stresses were born with an increase in the strain even after the cracking of cylinders, and it profoundly occurred in the presence of 15% ground tire rubber as fine aggregate and 2% volume fraction of PET fibres. Thus, it may infer that SCRC with PET fibres offers a ductile failure mode whereas, SCC (without ground tire rubber as fine aggregate and PET fibres) exhibited a brittle failure mode under compression. The failed specimens of concrete without fibres showed a single shear plane or cone type of failure, which was similar to the one reported by (Bencardino et al. 2008).

3.3 Split Tension Test

The split tension test was performed on the cylindrical specimens (without and with PET fibres) using UTM following the ASTM C496 (ASTM 2011) and is shown in Fig. 8. The

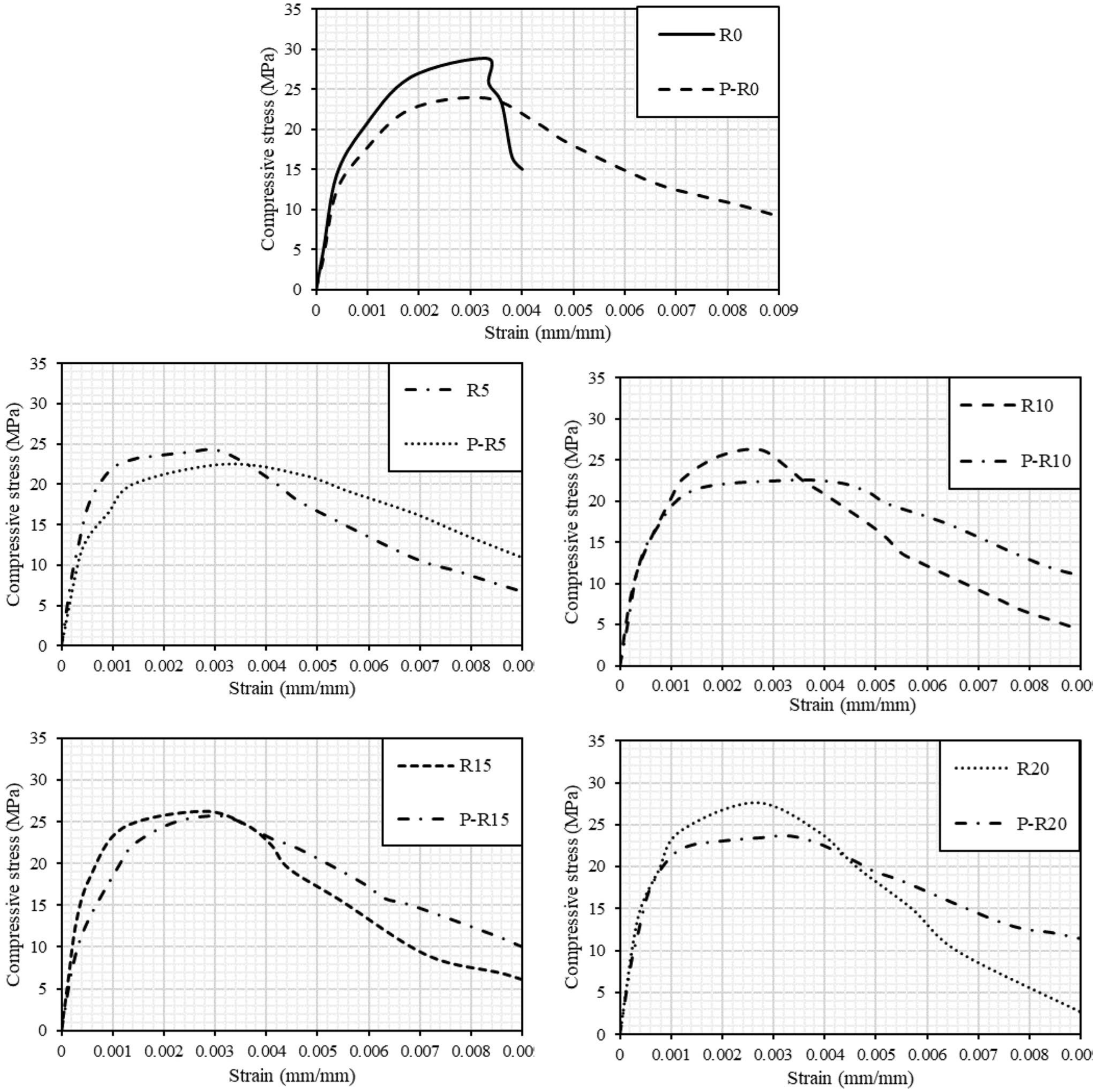


Fig. 7 Comparison of stress–strain response under compression

test results showed that the addition of ground tire rubber decreased the splitting tensile strength of concrete. In a specimen without PET fibres, a single crack appeared after an abrupt failure, which can be seen in Fig. 8a confirming a total brittle behaviour with a single crack. The single crack showing that the stress was not entirely transferred into the adjacent concrete. In the case of specimens containing PET fibres, multiple cracks appeared, showing a sign of ductile behaviour (refer to Fig. 8b). The multiple cracking is due to bridging of crack and transfer of the stress into the adjacent fibres and multiple crack formation. The higher strength was also observed in specimens containing PET fibres due to multiple crack formation.

The results of splitting tensile strength are shown in Fig. 9, which shows that the maximum tensile strength was obtained when only 2% of PET fibres were added in the SCC mix. Also, the minimum tensile strength was obtained with 2% PET and 20% ground tire rubber.

In Fig. 9, the splitting tensile strength results show a reduction in the strength with an increasing replacement

Fig. 8 Splitting tensile specimens' failure with and without PET fibres

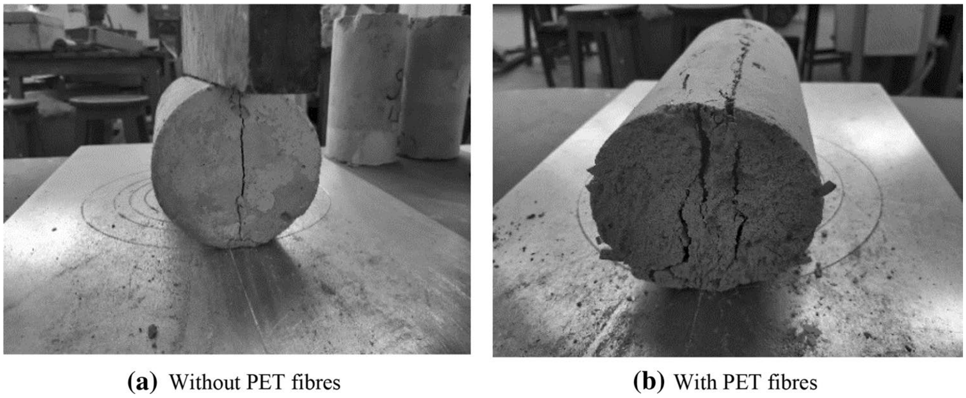
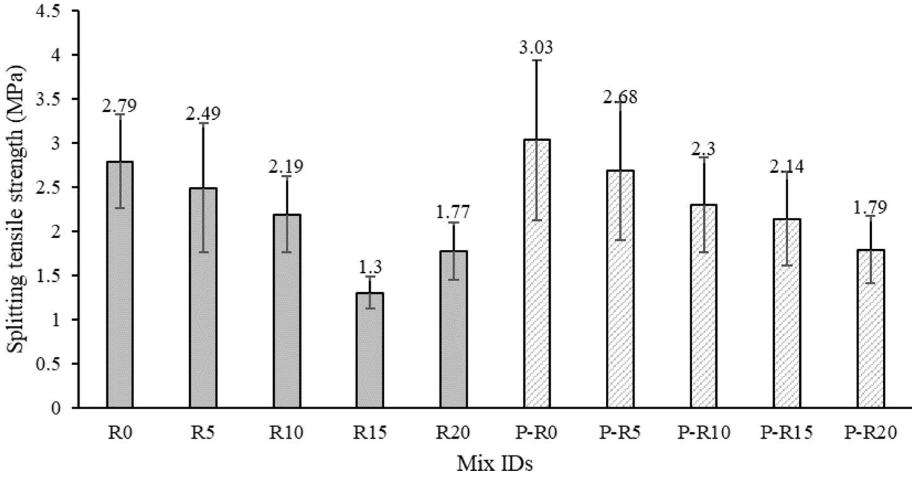

(a) Without PET fibres **(b)** With PET fibres

Fig. 9 Split tensile strength results



percentage of fine aggregates with ground tire rubber. The strength reduction at 5, 10, 15, and 20% replacement of fine aggregates was 10.75%, 21.5%, 53.4%, and 36.6%, respectively, as compared to the control specimen containing 100% fine aggregates (mix R0).

On the other side, the addition of a 2% volume fraction of PET fibres improved the strength at all replacement levels of fine aggregate. The increase in the splitting tensile strength of SCRC mixes with PET fibres was significant up to 15% replacement level of fine aggregates with ground tire rubber. Thus, based on splitting tensile test, it may infer that 15% replacement of fine aggregates with ground tire rubber is optimum in the presence of PET fibres. On the other hand, 10% replacement of fine aggregates with ground tire rubber is optimum in the absence of fibres.

3.4 Flexural Test

The flexure test was performed as per ASTM standard C78 (ASTM 2010) to determine the flexural strength of all SCC and SCRC mixes (with and without PET fibres). The test was performed with a four-point bending arrangement on UTM, as shown in Fig. 10. The two linear variable differential transducers (LVDTs) captured the deformation results at mid-span and under the load point. For the flexure test, a deformation rate of 0.15 mm/min applied to the three prisms of 100 × 100 × 500 mm in size. The data logger recorded the load and corresponding deformation under the point load and at mid-span and later used to calculate the modulus of rupture (refer to Fig. 11) and to plot the load–deformation response under bending (refer to Figs. 12 and 13).


Fig. 10 Flexural test arrangement

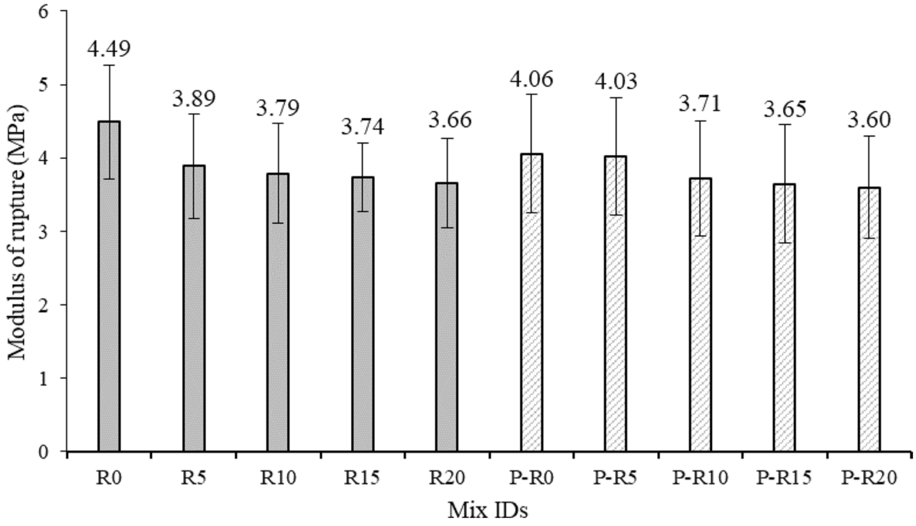


Fig. 11 Modulus of rupture with and without PET fibres

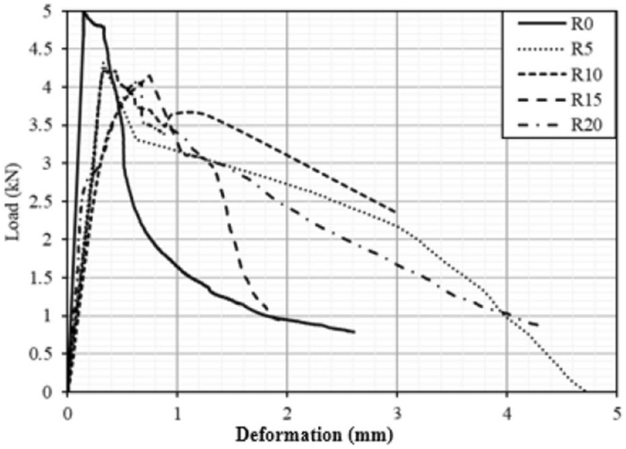


Fig. 12 Load–deformation response of control mix R0 (without rubber and PET fibres) under flexure

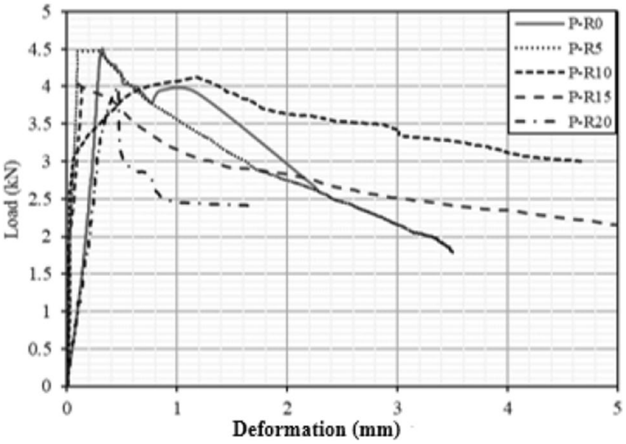


Fig. 13 Load–deformation response of SCRC mixes containing PET fibres under flexure

Similar to the compression and split tension tests, there was a decrease in the modulus of rupture with the increasing mass of ground tire rubber as a partial substitution of fine aggregate (refer to Fig. 11). The addition of PET fibres increased the modulus of rupture. However, the effect of ground tire rubber (as a partial replacement of fine aggregate) on the modulus of rupture did not marginalise substantially. The modulus of rupture of concrete with and without PET fibres was roughly decreased by 18% compared to the control mix R0. The decrease in modulus of rupture is higher with a higher percentage of the ground rubber tire. Thus, it may infer that 5–10% ground rubber tire as fine aggregates is adequate based on the modulus of rupture. The only reason that can justify the response is the slight reduction in the stiffness (elastic modulus) as observed in the compressive stress–strain response shown in Fig. 7. The lower elastic modulus with PET fibres caused more deformation and thus rupturing of the specimen on lower load.

The flexural behaviour of SCRC mixes containing PET fibres is explained by the load–deformation plot, and represented by the two branches, as shown in Figs. 12 and 13. In the following figures, the first and second branches show the response of the concrete before and after cracking. The first branch of the load–deformation curves of mix R0 and SCRC mixes (P-R5, P-R10, P-R15, and P-R20) was almost the same, which did not influence by the presence or absence of PET fibres. There was a slight increase in the deformation capacity of SCRC mixes (P-R5, P-R10, P-R15, and P-R20) by the addition of a 2% volume fraction of PET fibres compared to the control mix R0. In control mix R0 (without rubber and PET fibres), the post-peak branch of load–deformation behaviour after attaining a maximum load was suddenly falling as a crack appeared on the tension face of the specimen, which extended towards the compression zone within no time indicating the brittle failure.

By using ground tire rubber and PET fibres, SCRC showed a higher post-peak loading trend in the post-cracking branch, which is missing in the case of control concrete (R0), as shown in Figs. 12 and 13. Mostly, the post-peak deformation of SCRC mixes containing PET fibres prolonged up to 4 mm, as shown in Figs. 12 and 13; however, the load-carrying capacity was less than the control mix R0. The slight reduction in the stiffness, as shown in Fig. 13 is responsible for lowering in load-carrying capacity. The lower stiffness with PET fibres caused more deformation and thus cracking of the specimen on lower load.

4 Conclusions and Recommendations

This study is based on the use of ground rubber and fly ash to develop sustainable and cost-effective self-compacting rubberised concrete (SCRC). The fly ash as 35% by volume of cement and the ground rubber replacing 0, 5, 10, 15, and 20% volume of fine aggregates were used. Total ten mixes were investigated in which one set of the mix was without fibres, while the second set consisted of 2% volume fraction of PET fibres. The effect of ground rubber and fibre addition on the fresh and hardened state properties was carried out. Slump flow and L-Box test were conducted to find out the flowability and passing ability on the fresh state of concrete, while the compressive strength, splitting tensile strength, and flexural strength were determined in the hardened state as per standards. The stress–strain response under compression and load–deformation response under bending were also recorded. The following conclusions and recommendations are drawn from the study:

1. The SCRC mix with ground rubber tire had lesser flowability and passing ability. However, the rheological properties were within the specified limits prescribed by EFNARC guidelines (BIBM and EFNARC 2005).
2. The compressive strength was reduced with the replacement of fine aggregates with rubber. The inclusion of PET fibres dilutes the influence of rubber on the compressive strength. Overall, there was a decrease in the compressive strength of about 20% with the use of rubber.
3. The SCRC mixes containing PET fibres showed a ductile post-peak response under compression and flexure, which is absent in the control mix without fibres.
4. In SCRC mix having 20% mass of rubber as substitution of fine aggregates and containing a 2% volume fraction of PET fibres, there was a decrease of 30%, 36.55%, and 20% in the compressive strength, split tension, and modulus of rupture, respectively. However, the increase in the splitting tensile strength of SCRC mixes with PET fibres was observed up to 15% replacement level of fine aggregates with ground tire rubber in splitting tensile strength. On the other hand, 10% replacement of fine aggregates with ground tire rubber is optimum in the absence of fibres. Thus, it may infer that the optimum content of rubber is 10% and 15% in the SCRC in the presence and absence of PET fibres, respectively.
5. The addition of PET fibres played a positive role in stabilising the strength and improving the post-peak response under compression and flexure. However, there is a need to study the optimised fibre volume content for the optimum response.

Overall, ground tire rubber (as fine aggregates) and PET fibres (as reinforcement) in fly ash based concrete showed an excellent proposition and improved responses under compression, splitting tensile, and flexural behaviour of all concrete types investigated in this study.

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Compliance with ethical standards

Conflict of interest The authors had not received any research grants whatsoever for this study. The authors declare that there is no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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