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Engineering properties and sustainability assessment of recycled fibre reinforced rubberised cementitious composite

Meng Chen, Hui Zhong, Lyuxi Chen, Yuxi Zhang, Mingzhong Zhang

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Meng Chen: Methodology, Writing - original draft

Hui Zhong: Investigation, Data curation, Visualization, Writing - original draft

Lyuxi Chen: Investigation, Data curation

Yuxi Zhang: Investigation, Data curation

Mingzhong Zhang: Conceptualization, Funding acquisition, Project administration, Supervision,
Writing - reviewing and editing

Meng Chen ^{a,b}, Hui Zhong ^c, Lyuxi Chen ^c, Yuxi Zhang ^c, Mingzhong Zhang ^{c,*}

^a School of Resources and Civil Engineering, Northeastern University, Shenyang 110819, China

^b Science and Technology Innovation Center of Smart Water and Resource Environment,
Northeastern University, Shenyang 110819, China

^c Department of Civil, Environmental and Geomatic Engineering, University College London,
London WC1E 6BT, UK

Abstract: To provide an eco-friendly disposal way of increasingly accumulated waste tyres and reduce the environmental impact caused by the production of industrial fibres, this study explores the feasibility of using recycled tyre materials as substitutes for natural fine aggregates and manufactured fibres in cementitious mortar. The effects of crumb rubber (CR) replacement ratio (5%-15% by volume of fine aggregates), recycled tyre steel (RTS) fibre content (0.5-1.5 vol%) and recycled tyre polymer (RTP) fibre content (0.5-1.0 vol%) on the engineering properties of fibre reinforced cementitious composite (FRRC) were experimentally investigated. Results indicate that the pre-treated CR using NaOH solution is feasible to combine with a high dosage of recycled fibres without considerably weakening the workability, bulk density, ultrasonic pulse velocity and compressive strength of FRRC. The incorporation of CR, RTS fibre and RTP fibre together can reduce the drying shrinkage by up to 41.6% and enhance the flexural strength by at most 174% as compared to the plain mortar. The production cost, embodied carbon and embodied energy of FRRC are decreased by 13.3%-68.2% when replacing the manufactured fibres with recycled tyre fibres. The optimal content of CR and RTS fibre and RTP fibre is 5%-10%, 1.0 vol% and 0.5 vol%, respectively, considering the engineering properties, cost and environmental impact.

Keywords: Hybrid fibre reinforced concrete; Rubber particle; Recycled fibre; Fibre-matrix interaction; Digital image correlation; Sustainability

1. Introduction

As a result of the growing development of the automotive industry, the increasing accumulation of end-of-life tyres is inevitable. Approximately 1500 million waste tyres are generated annually, while the primary disposal ways of these waste tyres are stockpiling or landfilling (Malarvizhi et al., 2012; Thomas and Gupta, 2016). Due to these disposal ways, the growing number of waste tyres has become a major threat to the environment as several issues could be induced, e.g., air and soil contamination, formation of deadly disease and habitat for rodents (Mohajerani et al., 2020; Ramarad et al., 2015). Thus, finding an eco-friendly disposal way for these waste tyres is urgently required. To date, recycling the materials from waste tyres is considered as a sustainable disposal

* Corresponding author. E-mail address: mingzhong.zhang@ucl.ac.uk (M. Zhang)

approach for waste tyres as several benefits can be achieved. For instance, approximately 1525 tonnes of CO₂ emissions can be reduced every year via recycling waste tyres according to a life cycle assessment focusing on the environmental impact of the textile fibre recycled from the waste tyres ([Gigli et al., 2019](#)).

Rubber is the biggest component of a tyre (up to 50%) which can be recovered from a waste tyre through several processing phases including extraction, shredding, pulverisation and separation ([Gigli et al., 2019](#)). Because of the thermoset cross-linked structure of rubber, it presents excellent durable properties and thus has been widely used in automotive, civil and outer space applications ([Nuzaimah et al., 2018](#)). The recycled tyre rubber can be mainly classified into three groups that shredded or chipped rubber, crumb rubber (CR) and ground rubber ([Ganjian et al., 2009](#)). In the past decades, CR has increasingly attracted attention as it can be used to partially replace fine aggregates in normal mortar/concrete (i.e. rubberised mortar/concrete) to relief the environmental problems caused by the waste tyres. Generally, it has been reported that cementitious material incorporating CR presents improved resistances to cracking ([Turatsinze et al., 2007](#)), acid and sulphate attack ([Onuaguluchi and Banthia, 2019](#); [Thomas et al., 2015](#); [Thomas et al., 2016](#)), freeze-thaw cycles ([Si et al., 2017](#); [Zhu et al., 2012](#)), chloride ion penetration ([Oikonomou and Mavridou, 2009](#)) and better sound absorption ability ([Corredor-Bedoya et al., 2017](#)). Besides, the energy absorption capacity of concrete under dynamic loading was enhanced with the incorporation of CR below 10% ([Liu et al., 2012](#)), which can be mainly ascribed to the improved flexibility of the resultant composite ([Nuzaimah et al., 2019](#)). Nevertheless, as compared with the plain concrete, considerable reductions in compressive and tensile strengths of rubberised concrete are observed (33%-80%) ([Copetti et al., 2020](#); [Luhar et al., 2019](#); [Onuaguluchi and Banthia, 2019](#); [Si et al., 2018](#); [Turatsinze et al., 2007](#)) as well as the drying shrinkage resistance ([Chylík et al., 2019](#); [Mohammadi and Khabbaz, 2015](#); [Si et al., 2017](#)). Poor adhesion between cementitious matrix and rubber and the low stiffness of rubber are the main causes of weakening these properties ([Huang et al., 2013](#); [Nuzaimah et al., 2020a](#)).

To mitigate the reduction in above-mentioned properties of rubberised mortar/concrete, manufactured steel (ST) fibres are commonly incorporated. For instance, [Fu et al. \(2019\)](#) studied the mechanical properties of ST fibre reinforced rubberised concrete with various content of 0.5-1.0 vol% and found that the incorporation of 0.75 vol% ST fibres considerably increased the compressive, tensile and flexural strengths of rubberised concrete when 10%-20% of fine aggregate was replaced by CR. It was reported that the combination of CR and ST fibre improved the compressive ductility and toughness of recycled aggregate concrete ([Xie et al. \(2015\)](#)), and the fracture energy of plain concrete was enhanced by 190%-246% when 0.5 vol% ST fibre and 5%-20% CR were incorporated ([Noaman et al., 2017](#)). ST fibres played an essential role in improving the

unstable fracture toughness of recycled aggregate concrete ([Xie et al., \(2019\)](#)). Apart from the ST fibres, manufactured polypropylene (PP) fibres can also improve the mechanical properties of rubberised concrete especially in the post-cracking region ([Aslani and Kelin, 2018](#); [Hossain et al., 2019](#); [Raj et al., 2020](#); [Wang et al., 2019](#)). Nevertheless, the incorporation of a single type of fibre can only enhance a specific property of cementitious material, e.g. strength ([Pakravan et al., 2017](#)). Besides, the improvement range of a certain property caused by a single type of fibre is finite ([Alwesabi et al., 2020](#)). To tackle these drawbacks, the effect of hybrid fibre reinforcement (i.e. two or more types of fibre are used) in concrete/mortar is increasingly studied. The primary benefit of applying hybrid fibre reinforcement is the synergistic effects created by different types of fibre to further enhance the overall properties of the resultant composites. Depending on the fibre properties, two hybrid fibre reinforcement types can be mainly applied which are, fibres with different lengths or different moduli ([Banthia and Gupta, 2004](#); [Pakravan et al., 2017](#)). Among all the possible hybrid fibre reinforcement types, the combination of ST and PP fibres is considered as the most effective one to enhance the engineering properties of plain concrete/mortar especially strength and ductility, which can be attributed to the synergistic effect of fibre bridging behaviour ([Xu et al., 2019](#)). Until now, only one relevant study is found in open literature regarding the effect of hybrid ST and PP fibres in rubberised concrete. [Alwesabi et al. \(2020\)](#) experimentally investigated the mechanical properties of rubberised concrete incorporating hybrid ST and PP fibres with a total fibre dosage of 1.0 vol%. They observed that the compressive strength, elastic modulus, splitting tensile strength and flexural strength of rubberised concrete were improved by 43.1%-66.2% when 0.9 vol% ST fibre and 0.1 vol% PP fibre were present. However, although manufactured ST and PP fibres are effective in improving the engineering properties of cementitious materials, the production of which consumes many non-renewable resources especially fossil fuel ([Mastali et al., 2018a](#); [Merli et al., 2019](#); [Onuaguluchi and Banthia, 2018](#)). Besides, the massive production of ST fibres emits inevitable greenhouse gases ([Liew and Akbar, 2020](#)), which may intensify the issue of global warming. Therefore, to promote the sustainable development of construction industry, it is vital to find potential alternatives for these manufactured fibres.

Despite the recycled tyre rubber, recycled tyre steel (RTS) and recycled tyre polymer (RTP) fibres are also the main recycled materials from the waste tyres. Considering the difference between RTS fibres and ST fibres, [Aiello et al. \(2009\)](#), [Centonze et al. \(2012\)](#) and [Leone et al. \(2018\)](#) have compared the effectiveness in concrete between ST and RTS fibres and concluded that under a certain fibre dosage, mixtures reinforced with RTS fibres were comparable to that incorporating ST fibres in terms of post-cracking behaviour, toughness and shear behaviour. In addition, RTS fibres were found to be effective in mitigating the flexural strength loss of rubberised concrete induced by the addition of recycled tyre rubber ([Alsaif et al., 2018](#)). Due to the difficult storage of RTP fibre

([Baricevic et al., 2018](#)), an increasing number of experimental studies have explored the feasibility of incorporating this kind of fibre into cementitious materials, which generally indicate that RTP fibres were effective in improving the early-age shrinkage resistance ([Baričević et al., 2018](#); [Baricevic et al., 2018](#); [Onuaguluchi and Banthia, 2017](#); [Serdar et al., 2015](#)) and fibre spalling resistance of concrete/mortar ([Huang et al., 2015](#)) as well as the mechanical behaviours under high strain rate and cyclic loading ([Chen et al., 2019](#); [Chen et al., 2020](#)). A few studies have devoted to the use of mixed CR (i.e. with fibres) into cementitious materials as additive or replacement of aggregates. [Medina et al. \(2017\)](#) and [Flores Medina et al. \(2016\)](#) studied the effect of mixed CR on the mechanical, thermal and acoustic properties of concrete. It was found that the rubberised concrete presented better mechanical properties when 20% of coarse aggregates was replaced by the mixed CR as compared with that incorporating normal CR (without any fibres). Besides, this mixed CR can be used in precast concrete elements for certain application such as noise barrier. [Gheni et al. \(2019\)](#) applied the mixed CR containing a certain quantity of nylon fibre to partially replace cement content in mortar and observed that the mortar mixture incorporating this kind of CR exhibited better corrosion resistance. Although these studies reported the positive improvement of using recycled rubber and recycled fibre together in the engineering properties of resultant composite, the individual effect of these recycled materials (CR, RTS fibre and RTP fibre) has not been investigated. To better understand this effect, the content of CR, RTS fibre and RTP fibre should be considered as individual influencing parameter. In addition, the usage of recycled materials can be maximised, which can help promote the sustainable development of the construction industry via mitigating environmental impact of waste tyre and relieving shortage of non-renewable resource.

Therefore, this study aims to develop a new sustainable fibre reinforced rubberised cementitious composite (FRRC) using recycled tyre materials including CR, RTS fibre and RTP fibre and investigate its engineering properties. The influencing factors included CR replacement ratio of fine aggregates (5%, 10% and 15%), RTS fibre content (0.5, 1.0 and 1.5 vol%) and RTP fibre content (0.5 and 1.0 vol%), which were carefully designed to get more insights regarding the individual and combined influence of these recycled materials on the engineering properties of FRRC. First, a series of tests were conducted to estimate the effects of these factors on fresh and hardened properties of FRRC including workability, bulk density, ultrasonic pulse velocity (UPV), drying shrinkage, compressive strength and flexural strength. Whilst the evaluation of flexural strength, full strain field and fibre-matrix interaction were explored using digital image correlation (DIC) technique and digital microscope, respectively. Then, the relationships between compressive strength and UPV/flexural strength were established and compared with other existing studies. Afterwards, the economic and environmental factors including production cost, embodied carbon

and embodied energy of all studied mixtures were discussed and compared with those of mixtures incorporating manufactured fibres. Finally, the optimal mixture was determined considering the engineering properties and environmental impact.

2. Experimental program

2.1 Raw materials

In this study, the used cement is CEM I 52.5N, the chemical composition of which is shown in Table 1. Polycarboxylate-based superplasticiser (SP) (Sika®ViscoFlow®2000) with a density of 1.08 kg/L and pH value of 4-5 was used to adjust the workability of all mixtures. The content of SP was kept constant as 1.0% by the mass of cement content. Natural river sand and CR obtained from the ambient grinding of truck tyre buffing were utilized as the fine aggregates, the specific gravity of which is 2.6 and 1.1, respectively. The CR particles with different sizes were mixed based on our previous study (Zhong et al., 2019), where the mixing proportion was 10% of 2-6 mm CR, 50% of 12 mesh CR and 40% of 30 mesh CR, respectively, to match the particle size distribution of sand. The particle size distribution of sand and CR is shown in Fig. 1. To minimise the strength loss of mixture containing CR, the CR was pre-treated chemically before the mixing. Sodium hydroxide (NaOH) solution is commonly used to pre-treat the CR (Guo et al., 2017; Nuzaimah et al., 2020a; Si et al., 2017). Thus, prior to the mixing, CR was soaked in a 1 M NaOH solution for 40 min. Afterwards, all treated CR was washed by tap water to remove the attached NaOH residue and then left to be dried at ambient temperature.

Regarding the fibre reinforcement, recycled tyre fibres including RTS and RTP fibres (see Fig. 2) were used. It is worth mentioning that the surface of as-received RTP fibre attaches a large number of CR particles, which may slightly weaken the mechanical properties of the hardened mixture. Therefore, a sieving method based on a previous study (Chen et al., 2020) was applied to remove most of the CR particles and impurities from the fibres. As shown in Fig. 2c, the RTP fibres used in this study only consist of a tiny number of CR particles. The properties of RTS and RTP fibres are listed in Table 2.

2.2 Mix proportions

Table 3 shows the mix proportions of all studied FRRC. Specifically, 'R', 'S' and 'P' stand for CR, RTS fibre and RTP fibre, respectively. For the denoted numbers, 5-10 means the replacement ratio of CR, while 0.5-1.0 represents the fibre content. As seen in Table 3, R0S0P0 was regarded as the reference mixture without CR and recycled fibres, while the cement dosage, water-to-binder (w/b) ratio ($w/b = 0.4$) and SP content of R0S0P0 were kept the same with other FRRC mixtures. For FRRC, it contains two main components that are mortar matrix and randomly distributed recycled fibres (RTS and RTP fibres). Different from R0S0P0, part of the aggregates of FRRC was replaced by CR. The influencing parameters were CR replacement ratio and fibre dosage. To avoid a

significant reduction in strength properties of the resultant composite, the upper limit of CR replacement ratio should be around 20% (Lv et al., 2015; Thomas and Gupta, 2016). Thus, the maximum CR replacement ratio adopted was 15% in this study. As shown in Table 3, in series A, i.e. mixture R5S1.0P0.5 to mixture R15S1.0P0.5, three CR ratios including 5%, 10% and 15% were adopted to replace sand, while the content of RTS and RTP fibres was kept constant as 1.0 vol% and 0.5 vol%, respectively. In series B, i.e. mixture R10S0.5P0.5 to mixture R10S1.5P0.5, the content of RTS fibres was changed from 0.5 vol% to 1.5 vol%, while the CR replacement ratio and RTP fibre content were fixed as 10% and 0.5 vol%, respectively. In series C, i.e. mixture R10S1.0P0 to mixture R10S1.0P1.0, the content of RTP fibres was altered from 0 to 1.0 vol%, while the CR replacement ratio (10%) and RTS fibre content (1.0 vol%) were constant. A previous study (Chen et al., 2020) indicated that the mechanical properties of concrete containing 0.8 vol% RTP fibre were significantly lower than that without fibre incorporation. Thus, 1.0 vol% was selected as the upper limit for RTP fibre content. Series A was used to estimate the effect of CR replacement ratio on the engineering properties of FRRC. The mixture R10S1.0P0.5 in series A was also used to compare with the mixtures in series B and series C to investigate the effects of RTS and RTP fibres on the engineering properties of FRRC. It is worth noting that all FRRC mixtures were compared with the reference mixture (R0S0P0) to explore the combined influence of CR, RTS and RTP fibres on engineering properties of plain mortar.

2.3 Specimen preparation

The mixing process of all mixtures shown in Table 3 was conducted under ambient temperature. First, all dry materials except fibres were mixed for about 2 min. Then, liquid materials including water and SP were gradually added to the mixture followed by the addition of fibres. It is worth noting that prior to the addition of RTP fibres, they should be mixed with part of water and SP to avoid fibre clumping or balling (Chen et al., 2020; Onuaguluchi and Banthia, 2017). Upon the completion of mixing, part of the fresh mixture was used for workability test, while the rest was poured into moulds with different sizes. All samples were demoulded after 24 h and then cured in a water tank with a controlled constant temperature of 20 °C until desired testing ages, except samples for drying shrinkage test.

2.4 Testing methods

In this study, workability of all mixtures was determined by conducting flow table tests according to ASTM C1437 (2015). Before the compressive strength test, the cubic samples (100 mm) were used for the tests of bulk density and UPV value. The bulk density was measured as per ASTM C642 (2013). UPV test was considered as a non-destructive test to determine the velocity needed for an ultrasonic pulse to pass through the tested mixture. A schematic diagram of the ultrasonic pulse measurement system is presented in Fig. 3, where the direct transmission is used in this study. The

required time for an ultrasonic pulse to pass through the tested specimen was first recorded by the ultrasonic pulse analyser and the corresponding UPV value can then be calculated as:

$$UPV = \frac{L}{T} \quad (1)$$

where L represents the path length of the ultrasonic pulse, and T denotes the time measured by the ultrasonic pulse analyser.

The compressive strength of all mixtures at 7 and 28 d was measured using a universal testing machine with a loading rate of 6000 N/s according to BS EN 12390-3 (2009). Four-point bending test was conducted to determine the flexural strength of all mixtures at 28 d in accordance with ASTM C1609 (2012). Herein, the specimen size used was 100 mm × 100 mm × 350 mm. Whilst the testing, the DIC technique was applied to determine the full transverse strain field with a recording rate of one image per second. More details about the DIC testing setup and the process can be found in (Zhong and Zhang, 2020). The fibre-matrix interaction across the crack was analysed with the help of a digital microscope (Dino-Lite Edge AM73115MZT).

Regarding the drying shrinkage test, the original length of the specimen (50 mm × 50 mm × 285 mm) was first measured after demoulding. Afterwards, the specimen was cured in a drying environment with a temperature of 20 ± 2 °C and relative humidity of $55 \pm 5\%$. The drying shrinkage was evaluated by measuring the length change of the specimen as per ASTM C490 (2017).

3. Results and discussion

3.1 Workability

Workability is an important fresh property of cementitious materials, where its reduction would accompany with the formation of excessive void and the decrease of compactness (Ranjbar and Zhang, 2020) weakening the properties of hardened cementitious materials. Fig. 4 shows the flow values (i.e. flowability) of the studied mixtures that represent the workability of the mixtures. The shadowed areas correspond to different series of mixtures described in Section 2.2. It can be found that the highest flowability of 165% was recorded for the reference mixture (R0S0P0), which was higher than all FRRC mixtures.

3.1.1 Effect of crumb rubber

As seen in Fig. 4, increasing the CR replacement ratio consistently reduced the flowability of FRRC. As compared with R5S1.0P0.5, the flowability of R10S1.0P0.5 and R15S1.0P0.5 was declined by about 13.1% and 14.8%, respectively, which can be ascribed to the irregular shape of CR with slightly jagged edges (Hesami et al., 2016) and rough surface (Eisa et al., 2020) as compared with normal sand particles. Previous studies (Si et al., 2018; Su et al., 2015b) observed similar phenomenon that the workability of rubberised cementitious mixtures was decreased up to 25.2%

with the increase of CR replacement ratio. It can be noted from Fig. 4 that the reduction in flowability beyond 10% CR replacement ratio was not pronounced (1.9%), which can be associated with the effect of NaOH treatment of CR. It was reported that NaOH treatment can help increase the functional O-H groups on the surface of CR, which results in a reduction in contact angle and improvement in hydrophilicity ([Nuzaimah et al., 2020b](#); [Si et al., 2018](#)). Thus, the flowability of FRRC was improved as a result of smoother contact between CR and other constituent materials. Besides, this phenomenon can be further evidenced by comparing the results here with a previous study ([Si et al., 2018](#)), which reported that the flowability of rubberised mortar was decreased by 17.8% when 15% untreated CR was present, while the reduction magnitude was comparable to that of R15S1.0P0.5 here (only 3.4% difference) even when 1.5 vol% recycled fibres (RTS fibres plus RTP fibres) were included. As a result, it can be suggested that although fibres can decrease the workability of FRRC, the use of pre-treatment for CR would not further lower the workability, which is helpful for engineering application.

3.1.2 Effect of recycled fibres

As stated in Section 2.2, mixture R10S1.0P0.5 in series A was also used to compare with the mixtures in series B and C. Thus, the purple line was added in Fig. 4 to highlight the flowability of R10S1.0P0.5 for a better comparison. As expected, regardless of fibre type, increasing the fibre content caused a reduction in flowability of FRRC. In comparison with R10S0.5P0.5, the FRRC mixtures containing 1.0 vol% and 1.5 vol% RTS fibres exhibited approximately 5.4%-25.0% lower flowability. While the flowability of FRRC was decreased by 8.6% and 13.8% when the RTP fibre content was increased from 0 to 0.5 vol% and 1.0 vol%, respectively. These results are consistent with previous studies ([Alsaif et al., 2018](#); [Chen et al., 2020](#)) that the presence of either RTS or RTP fibres reduced the workability of cementitious materials, which can be primarily due to the contact network between fibres and cementitious matrix, restricting the movement of the constituent materials especially aggregates. Besides, when the fibre dosage for RTS fibre and RTP fibre was increased to 1.0 vol% and 0.5 vol%, respectively, the reduction in flowability was not significant (below 10%). This is in agreement with the postulation proposed by [Martinie et al. \(2010\)](#) that the fibre effect on the rheological behaviour of the cementitious material is low when the corresponding fibre volume fraction is far smaller than $\phi_{fc} = 3.2/r$, where ϕ_{fc} and r denote the dense packing factor and fibre aspect ratio, respectively. It is worth noting that vibration time should be longer during the casting of FRRC containing 1.5 vol% RTS fibre, although no obvious fibre balling was noticed whilst the mixing process.

3.2 Bulk density and ultrasonic pulse velocity

Bulk density is normally considered when the lightness of cementitious materials is an important parameter. It can be observed from Fig. 5 that the 28-d bulk density of all mixtures is in the range

between 2130 and 2285 kg/m³. UPV can be used in various applications, e.g. detection of concrete quality, correlations with concrete strength, and determination of dynamic elastic modulus and Poisson's ratio for concrete ([International Atomic Energy Agency, 2002](#)). Fig. 6 shows the UPV values of all mixtures, which can be classified into different levels of concrete quality based on Table 4. Generally, a higher value of UPV means a better quality of concrete, which indirectly implies that the number of flaws inside the concrete is lower. As seen in Fig. 6, the UPV of all mixtures at 28 d was slightly higher than that at 7 d (0.4%-6.9%). Besides, with the presence of CR and recycled fibres, the UPV of FRRC was lower than that of R0S0P0 at both 7 and 28 d. The results of R10S1.0P0.5 were highlighted in Figs. 5 and 6.

3.2.1 Effect of crumb rubber

As shown in Fig. 5, the bulk density of R10S1.0P0.5 and R15S1.0P0.5 was slightly lower (2.0%-4.2%) than that of R5S1.0P0.5, which can be attributed to the lower specific gravity of CR (1.1) compared to that of sand (2.6) ([Chaikaew et al., 2019](#); [Roychand et al., 2020](#)). Nevertheless, the difference can be considered as insignificant. Similar results were reported for the rubberised mortar ([Angelin et al., 2015](#)) and FRRC containing steel fibres ([Eisa et al., 2020](#)), where the reduction range was around 2.0%-16.0% when the CR replacement ratio was 5%-20%. Despite the lower specific gravity of CR, the reduction in bulk density could be associated with the increase in air content of FRRC by increasing the CR content ([Di Mundo et al., 2019](#); [Ramdani et al., 2019](#)).

A similar trend can be observed for UPV (see Fig. 6) that the UPV of FRRC decreased with the increase of CR replacement ratio at both testing ages (0.4%-3.9% smaller), which can be also ascribed to the increased air content entrapped by the CR during the mixing. The porosity inside FRRC would be increased when the CR content increases, where [Angelin et al. \(2015\)](#) reported that the porosity of rubberised mortar was approximately 130.3%-424.2% higher than that of the plain mortar when the CR replacement ratio was 5%-15%. Thus, the travel time of ultrasonic pulses would be higher because of the longer travel path. The observed trend of UPV here is in good agreement with the findings by [Hesami et al. \(2016\)](#) and [Ramdani et al. \(2019\)](#). Besides, the decrease in UPV of FRRC is also associated with the low elastic modulus of CR ([Si et al., 2018](#)).

3.2.2 Effect of recycled fibres

With respect to the effect of recycled fibres on the bulk density (see Fig. 5), the specific gravity of the incorporated fibres plays a governing rule on the bulk density of the resultant composites. RTS fibres have a higher specific gravity of 7.8 and thus, increasing the RTS fibre dosage from 0.5 vol% to 1.5 vol% led to an approximately 5.9% increment in bulk density of FRRC. A similar finding was observed by [Chaikaew et al. \(2019\)](#) that the increase in ST fibre content led to an increase in bulk density of FRRC, where the increment ranged from 1.3%-3.7%. This is because the specific gravity of steel fibre is much larger than that of the cementitious matrix, although the fibre dosage is

small. On the contrary, the bulk density of FRRC reduced with the addition of RTP fibres mainly due to their lower specific gravity (around 0.4) than the cementitious matrix. In addition, as mentioned earlier, the induced air content (i.e. increased porosity) caused by the fibres may also lower the bulk density of FRRC.

Considering the effect of recycled fibres on the UPV shown in Fig. 6, independent of fibre type, the increase of fibre content resulted in a continuous reduction in UPV of FRRC. For instance, the UPV of R10S1.5P0.5 was about 4.4% lower than that of R10S1.0P0.5, which can be explained by the fact that more air voids may present inside the specimens due to the increasing number of incorporated fibres (Wang et al., 2019). Overall, the UPV of all FRRC was in the range of 3.71 and 4.26 km/s, which can be classified as ‘good’ in terms of quality based on Table 4.

3.3 Drying shrinkage

Drying shrinkage can reflect the dimensional stability of cementitious materials within a drying environment, which may result in cracking at early ages and thus affect the long term durability of cementitious materials (Yousefieh et al., 2017). Fig. 7 shows the effects of CR, RTS fibres and RTP fibres on the drying shrinkage of FRRC. To better observed the evolution of drying shrinkage for each mixture, the corresponding values of standard deviation were not included in Fig. 7. At the early age, the drying shrinkage of all mixtures increased rapidly, while at the later age (approximately after 14 d), the shrinkage strain increased with time at a gradually reducing rate.

3.3.1 Effect of crumb rubber

As shown in Fig. 7a, increasing the CR replacement ratio from 5% to 10% slightly reduced the drying shrinkage of FRRC. For instance, at 28 d, R10S1.0P0.5 presented about 6.8% lower drying shrinkage than R5S1.0P0.5, while the difference was not surprisingly distinct. This can be ascribed to the NaOH treatment of CR. The surface of CR can be mechanically etching by the NaOH, which improves its roughness and thus increases its adhesion with the matrix (Nuzaimah et al., 2020b). Besides, the presence of zinc stearate on the surface of CR forms a layer, which makes the cementitious matrix difficult to well adhere with the CR (Nuzaimah et al., 2020a). However, using NaOH solution as pre-treatment for CR can transform the zinc ions to more water-soluble ions, which can be removed by the washing process. Therefore, the improved adhesion between CR and matrix would contribute to the increase in the internal restraint in FRRC, which leads to a reduction in drying shrinkage. With the further increment of CR replacement ratio to 15%, the drying shrinkage of FRRC was approximately 13.2% higher at 28 d, which can be attributed to the lower elastic modulus of CR in comparison with sand (Si et al., 2018; Turatsinze et al., 2007) and the increasing rate of moisture loss (Alsaif et al., 2018). It is worth noting that the drying shrinkage resistance of FRRC could be enhanced when appropriate content of pre-treated CR is incorporated, while the resistance may be weakened when the amount of CR is excessive.

3.3.2 Effect of recycled fibres

Fig. 7b indicates that the effect of RTS fibres on the drying shrinkage of FRRC was conspicuous. The FRRC mixture containing 1.0 vol% RTS fibre considerably outperformed other two mixtures at later ages, which is in good agreement with ([Zhong and Zhang \(2020\)](#)) that utilizing 1.0 vol% RTS fibre greatly restrained the drying shrinkage as a result of fibre bridging mechanism. R10S1.5P0.5 presented less effectiveness than R10S1.0P0.5 in reducing the drying shrinkage, which can be attributed to the poor compaction at the presence of high fibre dosage, i.e. 2.0 vol% ([Ranjbar et al., 2016](#)). By contrast, as seen in Fig. 7c, increasing RTP fibre dosage consistently led to a better shrinkage-restraining performance with the greatest improvement of 22.3% as compared with the mixtures without RTP fibre (R10S1.0P0). Similar superior shrinkage-restraining performance for RTP fibre reinforced cementitious composites was also reported by [Baričević et al. \(2018\)](#) and [Serdar et al. \(2015\)](#) that RTP fibres can transfer the shrinkage stress across the crack. It is interesting to note that all FRRC outperformed the plain mortar considering shrinkage resistance with an enhancement ranging from 7.9% to 41.6%, which shows a great potential of combining CR, RTS fibre and RTP fibre to mitigate the drying shrinkage of plain mortar. Additionally, the reduction in drying shrinkage can help avoid the cracking and thus enhance the durability.

In general, the incorporation of fibres can control the drying shrinkage either by improving the bond behaviour between matrix and fibres or restraining the cracks ([Afroughsabet and Teng, 2020](#); [Kayali et al., 1999](#); [Li et al., 2006](#)). For hybrid fibre reinforced cementitious composites, the performance of controlling the cracks is more pronounced than that of fibre reinforced cementitious composites containing only one type of fibre, as the hybridisation of fibres with different properties can better restrain the cracks at different scales. For instance, when the fibres with different lengths are incorporated, fibres with a longer length can better bridge the macro crack and restrain its development, while fibres with a shorter length can control the growth of the micro crack. As a result, the drying shrinkage of the resultant composites can be significantly reduced. This is also the primary reason why R10S1.0P1.0 exhibited the best behaviour in reducing the drying shrinkage of FRRC. However, as mentioned earlier, the internal porosity of FRRC could weaken the drying shrinkage resistance of the mixture such as R10S1.5P0.5 in this study. When the porosity is higher in FRRC, the moisture may be easier to move towards the surface via the pore network ([Afroughsabet and Teng, 2020](#)), which results in a higher drying shrinkage strain.

3.4 Mechanical properties

Compressive strength is an important parameter of judging the long-term performance of concrete structures. Fig. 8 shows the compressive strength of all mixtures at 7 and 28 d. As shown in Fig. 8, R0S0P0 achieved the highest strengths of 53.4 and 67.5 MPa at 7 and 28 d, respectively. Flexural strength can indirectly reflect the tensile strength of cementitious materials. The effects of CR and

recycled fibres on the flexural strength of FRRC are presented in Fig. 10, which indicates that combining CR and recycled fibres led to a significant increase in flexural strength compared to R0S0P0 that has a flexural strength of 3.14 MPa. The results of R10S1.0P0.5 were highlighted as purple dash lines.

3.4.1 Effect of crumb rubber

As seen in Fig. 8, with the increase of CR replacement ratio, the compressive strength of FRRC at 7 and 28 d was decreased by 6.4%-19.5% and 3.7%-19.0%, respectively, which can be caused by several reasons. This can be attributed to the reduced workability and increased entrapped air content as discussed in Sections 3.1 and 3.2, which increases the non-homogeneity of FRRC. Then, CR with a lower stiffness tends to deform more easily under compression, which increases the stress concentration around it (Wang et al., 2019). Therefore, the compressive cracks are more likely to present near the CR (Reda Taha et al., 2008). Besides, the bonding between CR and cementitious matrix is also one of the main concerns, which degrades the compressive strength of FRRC. Although, as mentioned before, the CR after NaOH treatment can enhance its bond behaviour with the matrix, the content of treated-CR should not exceed a certain value. As reported by Safan et al. (2017), the NaOH treatment may damage the surface of CR, which may in turn weaken the mechanical properties of cementitious materials. However, the surface-treated CR can slightly compensate the loss of compressive strength caused by untreated CR. The 28-d compressive strength of R5S1.0P0.5, R10S1.0P0.5 and R15S1.0P0.5 was decreased by 1.9%, 5.6% and 20.5%, respectively compared to R0S0P0, which were significantly lower than that of FRRC containing ST fibres (1.0 vol%) when an equal dosage of untreated CR (5%-15%) was utilized, i.e. 6.2%, 21.3% and 31.5%, respectively (Xie et al., 2018). This compensation in strength loss can be explained by the reaction mechanism between NaOH solution and CR, as introduced by Guo et al. (2017) and displayed in Fig. 9. Fig. 9a shows the chemical structure of the cis-polyisoprene with carboxyl group, where cis-polyisoprene is the main component of natural rubber (Tanaka et al., 1983). It was reported that the acid carboxyl group can react with the hydration products of cement, e.g. C-S-H, which may damage the structure of concrete when un-treated CR is incorporated (Li et al., 2019). While, as seen in Fig. 9b, when the CR is pre-treated with NaOH, the hydrogen ion on the acid functional group can be replaced with Na^+ , which would promote the cement hydration.

Similar to the trend of compressive strength, as shown in Fig. 10, the presence of CR was not beneficial to the enhancement of flexural strength. With an increase in CR replacement ratio, the 28-d flexural strength of FRRC declined by 8.7%-18.6%, which could be attributed to the reasons explained in the reduction in compressive strength. Similar results were reported by Chaikaew et al. (2019) and Eisa et al. (2020) that the flexural strength of FRRC incorporating ST fibres reduced with the increase in CR content (5%-20%). The final failure modes of the specimens after flexural

loading were analysed using the DIC technique in the form of full strain fields shown in Fig. 11. To ensure a fair comparison, the images of the transverse strain field were computed using the same scale and colour. As seen in Fig. 11, the FRRC mixtures containing various CR contents presented ductile failure modes instead of a brittle failure mode observed for R0S0F0. Besides, increasing CR replacement ratio tended to reduce the sharpness of the crack tip ([Mohammadi et al., 2014](#)) and more derivative cracks were present along the main macro crack. This is possibly owing to that CR can behave as a barrier to resist the growth of the crack ([Khorrami et al., 2010](#)).

3.4.2 Effect of recycled fibres

It can be found from Fig. 8 that the increase in compressive strength occurred for FRRC with RTS fibres up to 1.0 vol%, after which the compressive strength reduced. This may imply that 1.0 vol% can be considered as the optimal RTS fibre content in FRRC, which is in consistence with [Eisa et al. \(2020\)](#) that combining 1.0 vol% ST fibre with 10% CR replacement in FRRC exhibits the optimal mechanical properties. The interaction between fibre and matrix plays a critical role in the compressive strength of fibre reinforced cementitious composite, where the composite with a stronger fibre-matrix interaction tends to have a higher load-carrying capacity ([Ranjbar and Zhang, 2020](#)). Nevertheless, with the increase of fibre content, the total surface area of reinforced fibre increases as well as the area reduction of the deposited matrix around the fibre ([Dehghani and Aslani, 2020](#)). Thus, the porosity in the interfacial transition zone (ITZ) and cementitious matrix increases, leading to a reduction in compressive strength when the fibre content is excessive (e.g. R10S1.5P0.5). This is also evidenced by the microstructural investigation performed by [Lee and Jacobsen \(2011\)](#) that porous areas were found when excessive steel fibres agglomerated together. By contrast, the compressive strength is also related to the stiffness of the fibres, which can be evidenced by analysing the results of FRRC containing RTP fibres here. The compressive strength of R10S1.0P1.0 was approximately 23.1% lower than that of FRRC containing 0.5 vol% RTP fibre. However, it is worth pointing out that under a suitable total fibre content, the compressive strength of FRRC would not be significantly weakened. For instance, the compressive strength of R5S1.0P0.5, R10S1.0P0.5 and R10S1.0P0 was only 1.9%-5.5% lower compared to that of R0S0P0. According to [ACI 318M \(2005\)](#), the compressive strength of concrete at 28 d should be at least 28 MPa for basic construction purposes. As illustrated in Fig. 8, all FRRC mixtures satisfied this minimum requirement.

As seen in Fig. 10, there is a substantial strength improvement of about 76.1% when the RTS fibre content increased from 0.5 vol% to 1.0 vol%. Similar findings were observed by [Alwesabi et al. \(2020\)](#) and [Alsaif et al. \(2018\)](#) that the flexural strength of FRRC was superiorly enhanced at the presence of either RTS or ST fibres. This strength improvement is largely associated with the fibre-matrix interaction within the composite (see Fig. 12). It should be noted that a large exposure level

was used for the microscope during the image capturing process to improve the clarity of the fibres, i.e. the brightness of fibres was higher as shown in Fig. 12. Owing to the fibre bridging effect, the tensile stress caused by the bending moment during the flexural loading can be transferred to the interface between fibre and matrix as shear stress, which would be resisted by their contact surfaces (Ranjbar and Zhang, 2020). Fig. 12a indicates that the RTS fibre with high tensile strength and stiffness can effectively resist the shear stress, which delays the opening and propagation of the crack. This phenomenon can be observed from Fig. 11 that the effectiveness of fibre bridging behaviour was lower when the RTS fibre content was low (0.5 vol%), leading to a wide crack for R10S0.5P0.5. The similar behaviour was presented by Grzymiski et al. (2019) that concrete reinforced with 0.3 vol% RTS fibre exhibited very brittle nature, and the specimens failed when the crack appeared. When the RTS fibre content was increased to 1.0 and 1.5 vol%, the final crack widths of the composites become smaller than that of FRRC containing 0.5 vol% RTS fibre. As shown in Fig. 12b, the ruptured RTS fibre can be observed as a result of its hydrophilic nature. Because of this surface nature, the RTS fibre tends to strongly adhere to the matrix, where fibre often ruptures when the accumulated tensile stress exceeds the limit of fibre. Although the toughness of FRRC with a higher content of RTS fibre may be lower (Grzymiski et al., 2019; Zhong and Zhang, 2020), the flexural strength can be enhanced. This reduced toughness can be mitigated by incorporating polymeric fibres, which will be discussed in detail below. Besides, it is worth noting that under a good fibre orientation, randomly distributed RTS fibres can effectively restrain the formation and propagation of the tensile cracks, resulting in an increased loading-carrying capacity of the composites. Similar to the performance of drying shrinkage and compressive strength, 1.0 vol% can be also regarded as the limit of RTS fibres in FRRC in terms of flexural strength, as a further increment of RTS fibres slightly reduced the flexural strength (see Fig. 10).

On the contrary, a greater use of RTP fibres in FRRC resulted in a rapid drop in flexural strength. For instance, the flexural strength of R10S1.0P1.0 was about 21.4% lower than that of R10S1.0P0, which can be asserted to the reason causing the reduction in compressive strength for FRRC incorporating RTP fibres. However, the addition of RTP fibres can improve the post-peak performance of the composites. Regarding the post-failure patterns of FRRC containing RTP fibres (see Fig. 11), the patterns were comparable to cementitious composites containing PP fibres (Wang et al., 2019; Zhong and Zhang, 2020) that the pathways of the crack propagation were changed with the increase in RTP fibre content. Besides, more small cracks were appeared along the main macro crack because of the smaller fibre spacing. This implies that more RTP fibres are present within a specified area of the matrix, which can be evidenced by Fig. 12c that, more RTP fibres appeared to bridge the crack rather than the presence of only one RTS fibre nearby. In summary, the

combination of CR, RTS fibre and RFF fibre can create a synergistic effect to improve not only the flexural strength (42.1%-174.0%) of FRRC but also its post-cracking behaviour.

3.4.3 Relationships between different properties

As mentioned in Section 3.2, the results of UPV can be used to correlate with the compressive strength. It is worth noting that developing a reliable equation between UPV and compressive strength can be used to monitor the change of deterioration level of cementitious materials with time especially under aggressive environment. According to Tharmaratnam and Tan (1990), the relationship between UPV and compressive strength (f_c) can be expressed as:

$$f_c = ae^{b \cdot UPV} \quad (2)$$

where a and b are the constant coefficients of the exponential equation.

Fig. 13 shows the fitted exponential curve of the studied FRRC here, which is compared with that of FRRC containing PP fibres (Hesami et al., 2016) and rubberised concrete with pre-treatment of CR (Si et al., 2018) and without pre-treatment of CR (Ramdani et al., 2019). The R^2 presented in Fig. 13 can be used to judge the fitness of the developed equations. Independent of R^2 , the trends of all exponential curves were similar that the compressive strength rises with an increase in UPV. It can be noted that the FRRC investigated here had the highest increase rate of compressive strength with UPV (with a 'b' value of 1.1183), while FRRC incorporating PP fibres exhibited a slightly lower increase rate (with a 'b' value of 0.8928) (Hesami et al., 2016). Considering the influence of surface treatment of CR, it can be found that rubberised concrete without pre-treatment of CR showed a higher increase rate of compressive strength (see blue line) (Ramdani et al., 2019) than the rubberised concrete with pre-treatment of CR (see green line) (Si et al., 2018). Besides, as shown in Fig. 13, the developed equation in the current study had a R^2 of about 0.867, which can be considered as a reliable model, as previous research stated that a reasonable model normally has a R^2 of over 0.7 (Ostle, 1996).

Typically, the flexural strength of cementitious materials also shows a strong dependence with the corresponding compressive strength. ACI 318M (2005) introduces a predicted equation for the flexural strength of conventional concrete (f_f) in relation to its compressive strength (f_c):

$$f_f = 0.62\sqrt{f_c} \quad (3)$$

Fig. 14 illustrates a comparison between the measured flexural strength of FRRC and predicted flexural strength using Eq. (3). The relationships between flexural strength and compressive strength of FRRC reinforced with hybrid ST and RTS fibres (Alsaif et al., 2018) and FRRC containing mixed CR (with recycled fibres) (Medina et al., 2017) are presented in Fig. 14 for comparison. It is apparent that regardless of fibre types, all FRRC mixtures exhibit higher flexural strength than the predicted flexural strength by ACI 318M (2005) suggesting that, Eq. (3) underestimates the flexural strength of FRRC, which could be owing to the superior flexural

strength of FRRC, and thus a more suitable equation, $f_f = 0.956\sqrt{f_c}$ with a R^2 of about 0.717, was developed to predict the flexural strength, i.e. the red dash line shown in Fig. 14.

4. Cost and environmental analysis

Given that reducing the production cost of material can certainly enhance its overall sustainability, the estimated cost of each studied mixture in USD/m³ is illustrated in Fig. 15, which is calculated based on the commercial market prices listed in Table 5 ([Abdollahnejad et al., 2017](#); [Mastali et al., 2018a](#); [Su et al., 2015a](#); [Yang et al., 2017](#); [Zhang et al., 2020](#)). It is worth noting that the unit costs listed in Table 5 are only used to represent the general market price of each material, where they may vary with regions, manufacturers and producing years. Besides, the estimated costs of FRRC containing ST and PP fibres with equal dosages of recycled fibres are shown in Fig. 15 for comparison. The mixture symbols of FRRC incorporating manufactured fibres were denoted as ‘M’ (see Fig. 15). As shown in Fig. 15, the cost of the sum of cement, sand, water and SP accounts for over 50% of the total cost of the composite. Increasing the CR replacement ratio tended to increase the total cost of the composites, in which every 5% increment of CR replacement ratio resulted in an increase of about 15.696 USD/m³. This is because sand generally has a lower market price than CR (see Table 5). Besides, in this study, CR was pre-treated with 1 M NaOH solution, which may further increase the cost of used CR. The cost of this quantity of NaOH pellets accounts for about 38.8% of the total cost of CR illustrated in Fig. 15. Among all FRRC, R10S0.5P0.5 had the lowest cost of around 155.9 USD/m³, which reveals that the FRRC tends to have a lower product cost at the presence of smaller quantities of CR and RTS fibres. In addition, it is surprising to note that the composites containing recycled fibres exhibited much lower costs than those incorporating manufactured fibres (52.2%-68.2%). To sum up, although replacing normal sand with CR slightly increases the total production cost of the composites, utilizing recycled fibres as alternatives to manufactured fibres considerably lowers the corresponding production cost. It is worth noting that the cost of RTP fibre used in this study for cost comparison only considered the cost of as-received fibre, while the potential cost of cleaning and packing ([Gigli et al., 2019](#)) was not considered in this study. However, this cost assessment can still recommend that FRRC containing recycled tyre fibres could be potentially considered as the substitute to the FRRC incorporating manufactured fibres.

To assess the environmental impact of the studied FRRC mixtures, the embodied carbon and embodied energy of all mixtures per m³ are depicted in Figs. 16 and 17, respectively, based on the embodied parameters from the production of raw materials. The embodied parameters of each constituent material are listed in Table 6 ([Fantilli et al., 2016](#); [Hammond et al., 2008](#); [Mastali et al., 2018b](#); [Ohno and Li, 2018](#); [Yu et al., 2020](#)). As shown in Table 3, cement has the second highest unit weight of 631 kg for every m³ of the composite and thus cement should be responsible for the

biggest proportion of total embodied carbon and energy. Although sand has the highest unit weight of about 1278-1420 kg/m³, its embodied carbon and energy per kg can be considered as negligible (0.0024 kg CO₂.eq/kg and 0.1 MJ/kg), as listed in Table 6. Similar to the cost contribution, FRRC incorporating a higher content of CR resulted in a higher embodied carbon and energy, as the embodied carbon and energy of NaOH pellet are about 0.86 kg CO₂.eq/kg and 18 MJ/kg, respectively. These values were significantly larger than those of un-treated CR (330%-350%). RTP fibres contributed more to the total embodied carbon and energy of the composites as compared with RTS fibres, which is different from the cost contribution. Compared to the embodied parameters of the FRRC incorporating manufactured fibres, the incorporation of recycled fibres greatly reduced the embodied carbon and energy, with the reductions ranging from 13.3%-29.0% and 21.4%-37.5%, respectively.

In this study, considering the investigated properties, cost and environmental impact, R5S1.0P0.5 and R10S1.0P0.5 were found to be as the optimal mixtures, which not only achieved acceptable workability (132.5%-152.5%) and 28-d compressive strength (63.8-66.2 MPa) but also presented a 150.2%-174.0% higher flexural strength and a 27.8%-32.7% lower drying shrinkage than the plain mortar. The production cost of R5S1.0P0.5 and R10S1.0P0.5 was acceptable, which ranges from 162.7 to 177.0 USD/m³ as compared with the plain mortar (105.3 USD/m³).

5. Conclusions

This study presents an experimental study on the engineering properties of fibre reinforced cementitious composite (FRRC) incorporating recycled tyre materials including crumb rubber (CR), recycled tyre steel (RTS) fibre and recycled tyre polymer (RTP) fibre to explore the feasibility of utilizing recycled materials from waste tyres in cementitious composites. A comparison between the engineering properties of composites containing various CR content (5%-15% by volume of fine aggregates) and recycled fibre content (0.5-1.5 vol%) and that of the plain mortar (without CR, RTS fibre and RTP fibre) was made to investigate the combined effects of incorporating these recycled materials. Based on the experimental results, the conclusions can be drawn as follows:

- Composites incorporating CR, RTS fibres and RTP fibres presented acceptable flowability of 105%-152.5% as compared to the plain mortar (165%), while comparable results of bulk density and ultrasonic pulse velocity (UPV) were found for all mixtures.
- Increasing the CR content in the composites was not beneficial for controlling the drying shrinkage. However, the incorporation of CR, RTS fibre and RTP fibre together significantly lowered the drying shrinkage of FRRC, i.e. up to 41.6%, particularly when more RTP fibres were utilized.
- Although the increase of CR replacement ratio led to reductions in compressive strength and flexural strength of FRRC, ductile flexural failure modes with reduced sharpness of crack tips

were observed at the presence of high CR content. The inclusion of RTS fibres significantly compensated the loss of compressive strength and flexural strength of FRRC caused by the CR addition. The compressive strength and flexural strength of FRRC were increased by about 29.4% and 76.1% respectively with the increase of RTS fibre content from 0.5 vol% to 1.0 vol%. A detailed analysis of fibre-matrix interaction behaviour points out the positive synergy between RTS and RTP fibres that contributed to enhancing the fibre bridging effect and overall flexural behaviour.

- A reasonable correlation function between UPV and compressive strength with R^2 of 0.867 was developed while existing predicted equation provided by ACI code underestimated the flexural strength of FRRC.
- Replacing manufactured fibres with recycled fibres significantly lowered the production cost, embodied carbon and embodied energy with the reductions ranging from 13.3%-68.2%.
- Considering the engineering properties, cost and environmental impact, R5S1.0P0.5 and R10S1.0P0.5 can be considered as the optimal mixtures, which exhibited a 76.1%-174% higher flexural strength and a 27.8%-32.7% lower drying shrinkage compared to the plain mortar as well as acceptable workability, compressive strength and production cost.

This study suggests that combining CR (with NaOH treatment), RTS fibre and RTP fibre not only can outperform the plain mortar in terms of flexural strength and drying shrinkage resistance but also can reduce the production cost and environmental impact of FRRC as compared with the FRRC incorporated manufactured fibres. Although using CR with NaOH treatment in cementitious mortar increase its production cost as well as embodied carbon and embodied energy compared to that using sand only, the environmental impact of waste tyres can be significantly reduced via recycling the waste tyres. For practical applications of the developed FRRC, it is vital to investigate the durability performance of this material as well. This is a subject of ongoing work and will be presented in a future publication.

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References

Abdollahnejad, Z., Miraldo, S., Pacheco-Torgal, F., Aguiar, J.B., 2017. Cost-efficient one-part alkali-activated mortars with low global warming potential for floor heating systems applications. *European Journal of Environmental and Civil Engineering* 21(4), 412-429.

ACI 318M, 2005. Building Code Requirements for Structural Concrete and Commentary (ACI 318M-05). p. 436.

Afroughsabet, V., Teng, S., 2020. Experiments on drying shrinkage and creep of high performance hybrid-fiber-reinforced concrete. *Cement and Concrete Composites* 106, 103481.

Aiello, M.A., Leuzzi, F., Centonze, G., Maffezzoli, A., 2009. Use of steel fibres recovered from waste tyres as reinforcement in concrete: Pull-out behaviour, compressive and flexural strength. *Waste Manage.* 29(6), 1960-1970.

Alsaif, A., Koutas, L., Bernal, S.A., Guadagnini, M., Pilakoutas, K., 2018. Mechanical performance of steel fibre reinforced rubberised concrete for flexible concrete pavements. *Construction and Building Materials* 172, 533-543.

Alwesabi, E.A., Bakar, B.A., Alshaikh, I.M., Akil, H.M., 2020. Experimental investigation on mechanical properties of plain and rubberised concretes with steel-polypropylene hybrid fibre. *Construction and Building Materials* 233, 117194.

Angelin, A.F., Andrade, M.F.F., Bonatti, R., Cecche Lintz, R.C., Gachet-Barbosa, L.A., Osório, W.R., 2015. Effects of spheroid and fiber-like waste-tire rubbers on interrelation of strength-to-porosity in rubberized cement and mortars. *Construction and Building Materials* 95, 525-536.

Aslani, F., Keli, J., 2018. Assessment and development of high-performance fibre-reinforced lightweight self-compacting concrete including recycled crumb rubber aggregates exposed to elevated temperatures. *Journal of Cleaner Production* 200, 1009-1025.

ASTM C490, 2017. Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete. ASTM International, West Conshohocken, PA, United States.

ASTM C642, 2013. Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. ASTM International, West Conshohocken, PA, United States.

ASTM C1437, 2015. Standard Test Method for Flow of Hydraulic Cement Mortar. ASTM International, West Conshohocken, PA, United States.

ASTM C1609, 2012. Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading). ASTM International, West Conshohocken, PA, United States.

Banthia, N., Gupta, R., 2004. Hybrid fiber reinforced concrete (HyFRC): fiber synergy in high strength matrices. *Materials and Structures* 37(10), 707-716.

Baričević, A., Jelčić Rukavina, M., Pezer, M., Štirmer, N., 2018. Influence of recycled tire polymer fibers on concrete properties. *Cement and Concrete Composites* 91, 29-41.

- Bancevic, A., Fezel, M., Jelic Rukavina, M., Sedai, M., Sumner, N., 2018. Effect of polymer fibers recycled from waste tires on properties of wet-sprayed concrete. *Construction and Building Materials* 176, 135-144.
- BS EN 12390-3, 2009. Testing Hardened Concrete Part 3: Compressive Strength of test Specimens. BSI Standards Publication.
- Centonze, G., Leone, M., Aiello, M.A., 2012. Steel fibers from waste tires as reinforcement in concrete: A mechanical characterization. *Construction and Building Materials* 36, 46-57.
- Chaikaew, C., Sukontasukkul, P., Chaisakulkiet, U., Sata, V., Chindaprasirt, P., 2019. Properties of Concrete Pedestrian Blocks Containing Crumb Rubber from Recycle Waste Tyres Reinforced with Steel Fibres. *Case Studies in Construction Materials* 11, e00304.
- Chen, M., Chen, W., Zhong, H., Chi, D., Wang, Y., Zhang, M., 2019. Experimental study on dynamic compressive behaviour of recycled tyre polymer fibre reinforced concrete. *Cement and Concrete Composites* 98, 95-112.
- Chen, M., Zhong, H., Zhang, M., 2020. Flexural fatigue behaviour of recycled tyre polymer fibre reinforced concrete. *Cement and Concrete Composites* 105, 103441.
- Chylík, R., Fládr, J., Bílý, P., Trtík, T., Vráblík, L., 2019. An analysis of the applicability of existing shrinkage prediction models to concretes containing steel fibres or crumb rubber. *Journal of Building Engineering* 24, 100729.
- Copetti, C.M., Borges, P.M., Squiavon, J.Z., da Silva, S.R., de Oliveira Andrade, J.J., 2020. Evaluation of tire rubber surface pre-treatment and silica fume on physical-mechanical behavior and microstructural properties of concrete. *Journal of Cleaner Production* 256, 120670.
- Corredor-Bedoya, A.C., Zoppi, R.A., Serpa, A.L., 2017. Composites of scrap tire rubber particles and adhesive mortar – Noise insulation potential. *Cement and Concrete Composites* 82, 45-66.
- Dehghani, A., Aslani, F., 2020. The effect of shape memory alloy, steel, and carbon fibres on fresh, mechanical, and electrical properties of self-compacting cementitious composites. *Cement and Concrete Composites* 112, 103659.
- Di Mundo, R., Dilonardo, E., Nacucchi, M., Carbone, G., Notarnicola, M., 2019. Water absorption in rubber-cement composites: 3D structure investigation by X-ray computed-tomography. *Construction and Building Materials* 228, 116602.
- Eisa, A.S., Elshazli, M.T., Nawar, M.T., 2020. Experimental investigation on the effect of using crumb rubber and steel fibers on the structural behavior of reinforced concrete beams. *Construction and Building Materials* 252, 119078.
- Fantilli, A.P., Chiaia, B., Gorino, A., 2016. Ecological and mechanical assessment of lightweight fiber-reinforced concrete made with rubber or expanded clay aggregates. *Construction and Building Materials* 127, 692-701.

- Plores-Medina, N., Plores-Medina, D., Hernandez-Olivares, P., 2010. Influence of fibers partially coated with rubber from tire recycling as aggregate on the acoustical properties of rubberized concrete. *Construction and Building Materials* 129, 25-36.
- Fu, C., Ye, H., Wang, K., Zhu, K., He, C., 2019. Evolution of mechanical properties of steel fiber-reinforced rubberized concrete (FR-RC). *Composites Part B: Engineering* 160, 158-166.
- Ganjian, E., Khorami, M., Maghsoudi, A.A., 2009. Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Construction and Building Materials* 23(5), 1828-1836.
- Gheni, A.A., Alghazali, H.H., ElGawady, M.A., Myers, J.J., Feys, D., 2019. Durability properties of cleaner cement mortar with by-products of tire recycling. *Journal of Cleaner Production* 213, 1135-1146.
- Gigli, S., Landi, D., Germani, M., 2019. Cost-benefit analysis of a circular economy project: a study on a recycling system for end-of-life tyres. *Journal of Cleaner Production* 229, 680-694.
- Grzymiski, F., Musiał, M., Trapko, T., 2019. Mechanical properties of fibre reinforced concrete with recycled fibres. *Construction and Building Materials* 198, 323-331.
- Guo, S., Dai, Q., Si, R., Sun, X., Lu, C., 2017. Evaluation of properties and performance of rubber-modified concrete for recycling of waste scrap tire. *Journal of Cleaner Production* 148, 681-689.
- Hammond, G., Jones, C., Lowrie, F., Tse, P., 2008. Inventory of carbon & energy: ICE. Sustainable Energy Research Team, Department of Mechanical Engineering
- Hesami, S., Salehi Hikouei, I., Emadi, S.A.A., 2016. Mechanical behavior of self-compacting concrete pavements incorporating recycled tire rubber crumb and reinforced with polypropylene fiber. *Journal of Cleaner Production* 133, 228-234.
- Hossain, F.M.Z., Shahjalal, M., Islam, K., Tiznobaik, M., Alam, M.S., 2019. Mechanical properties of recycled aggregate concrete containing crumb rubber and polypropylene fiber. *Construction and Building Materials* 225, 983-996.
- Huang, B., Shu, X., Cao, J., 2013. A two-staged surface treatment to improve properties of rubber modified cement composites. *Construction and Building Materials* 40, 270-274.
- Huang, S.-S., Angelakopoulos, H., Pilakoutas, K., Burgess, I., 2015. Reused tyre polymer fibre for fire-spalling mitigation, *Applications of Structural Fire Engineering*.
- International Atomic Energy Agency, V., 2002. Guidebook on non-destructive testing of concrete structures. International Atomic Energy Agency (IAEA), p. 241.
- Kayali, O., Haque, M.N., Zhu, B., 1999. Drying shrinkage of fibre-reinforced lightweight aggregate concrete containing fly ash. *Cement and Concrete Research* 29(11), 1835-1840.
- Khorrami, M., Khalilitabas, A.A., Desai, C.S., Ardakani, M.M., 2010. Experimental Investigation on Mechanical Characteristics and Environmental Effects on Rubber Concrete. *International Journal of Concrete Structures and Materials* 4(1), 17-23.

- Lee, S.H., Jacobsen, S., 2011. Study of interfacial microstructure, fracture energy, compressive energy and debonding load of steel fiber-reinforced mortar. *Materials and structures* 44(8), 1451-1465.
- Leone, M., Centonze, G., Colonna, D., Micelli, F., Aiello, M.A., 2018. Fiber-reinforced concrete with low content of recycled steel fiber: Shear behaviour. *Construction and Building Materials* 161, 141-155.
- Li, Y., Zhang, X., Wang, R., Lei, Y., 2019. Performance enhancement of rubberised concrete via surface modification of rubber: A review. *Construction and Building Materials* 227, 116691.
- Li, Z., Perez Lara, M.A., Bolander, J.E., 2006. Restraining effects of fibers during non-uniform drying of cement composites. *Cement and Concrete Research* 36(9), 1643-1652.
- Liew, K.M., Akbar, A., 2020. The recent progress of recycled steel fiber reinforced concrete. *Construction and Building Materials* 232, 117232.
- Liu, F., Chen, G., Li, L., Guo, Y., 2012. Study of impact performance of rubber reinforced concrete. *Construction and Building Materials* 36, 604-616.
- Luhar, S., Chaudhary, S., Luhar, I., 2019. Development of rubberized geopolymer concrete: Strength and durability studies. *Construction and Building Materials* 204, 740-753.
- Lv, J., Zhou, T., Du, Q., Wu, H., 2015. Effects of rubber particles on mechanical properties of lightweight aggregate concrete. *Construction and Building Materials* 91, 145-149.
- Malarvizhi, G., Senthul, N., Kamaraj, C., 2012. A study on Recycling of crumb rubber and low density polyethylene blend on stone matrix asphalt. *International Journal of Science and Research* 2(10).
- Martinie, L., Rossi, P., Roussel, N., 2010. Rheology of fiber reinforced cementitious materials: classification and prediction. *Cement and Concrete Research* 40(2), 226-234.
- Mastali, M., Dalvand, A., Sattarifard, A.R., Abdollahnejad, Z., Ilkainen, M., 2018a. Characterization and optimization of hardened properties of self-consolidating concrete incorporating recycled steel, industrial steel, polypropylene and hybrid fibers. *Composites Part B: Engineering* 151, 186-200.
- Mastali, M., Dalvand, A., Sattarifard, A.R., Ilkainen, M., 2018b. Development of eco-efficient and cost-effective reinforced self-consolidation concretes with hybrid industrial/recycled steel fibers. *Construction and Building Materials* 166, 214-226.
- Medina, N.F., Medina, D.F., Hernández-Olivares, F., Navacerrada, M.A., 2017. Mechanical and thermal properties of concrete incorporating rubber and fibres from tyre recycling. *Construction and Building Materials* 144, 563-573.
- Merli, R., Preziosi, M., Acampora, A., Lucchetti, M.C., Petrucci, E., 2019. Recycled fibers in reinforced concrete: A systematic literature review. *Journal of Cleaner Production* 248, 119207.

- Monajerani, A., Burnett, L., Smith, J. V., Markovski, S., Rodwell, G., Rahman, M. T., Kurnias, H., Mirzababaei, M., Arulrajah, A., Horpibulsuk, S., Maghool, F., 2020. Recycling waste rubber tyres in construction materials and associated environmental considerations: A review. *Resources, Conservation and Recycling* 155, 104679.
- Mohammadi, I., Khabbaz, H., 2015. Shrinkage performance of Crumb Rubber Concrete (CRC) prepared by water-soaking treatment method for rigid pavements. *Cement and Concrete Composites* 62, 106-116.
- Mohammadi, I., Khabbaz, H., Vessalas, K., 2014. In-depth assessment of Crumb Rubber Concrete (CRC) prepared by water-soaking treatment method for rigid pavements. *Construction and Building Materials* 71, 456-471.
- Noaman, A.T., Abu Bakar, B.H., Akil, H.M., Alani, A.H., 2017. Fracture characteristics of plain and steel fibre reinforced rubberized concrete. *Construction and Building Materials* 152, 414-423.
- Nuzaimah, M., Sapuan, S.M., Nadlene, R., Jawaidd, M., 2018. Recycling of waste rubber as fillers: A review. *IOP Conference Series: Materials Science and Engineering* 368, 012016.
- Nuzaimah, M., Sapuan, S.M., Nadlene, R., Jawaidd, M., 2019. Microstructure and Mechanical Properties of Unsaturated Polyester Composites Filled with Waste Rubber Glove Crumbs. *Fibers and Polymers* 20(6), 1290-1300.
- Nuzaimah, M., Sapuan, S.M., Nadlene, R., Jawaidd, M., 2020a. Effect of Surface Treatment on the Performance of Polyester Composite Filled with Waste Glove Rubber Crumbs. *Waste and Biomass Valorization*.
- Nuzaimah, M., Sapuan, S.M., Nadlene, R., Jawaidd, M., 2020b. Sodium Hydroxide Treatment of Waste Rubber Crumb and Its Effects on Properties of Unsaturated Polyester Composites. *Applied Sciences* 10(11), 3913.
- Ohno, M., Li, V.C., 2018. An integrated design method of Engineered Geopolymer Composite. *Cement and Concrete Composites* 88, 73-85.
- Oikonomou, N., Mavridou, S., 2009. Improvement of chloride ion penetration resistance in cement mortars modified with rubber from worn automobile tires. *Cement and Concrete Composites* 31(6), 403-407.
- Onuaguluchi, O., Banthia, N., 2017. Durability performance of polymeric scrap tire fibers and its reinforced cement mortar. *Materials and Structures* 50(2).
- Onuaguluchi, O., Banthia, N., 2018. Scrap tire steel fiber as a substitute for commercial steel fiber in cement mortar: Engineering properties and cost-benefit analyses. *Resources, Conservation and Recycling* 134, 248-256.
- Onuaguluchi, O., Banthia, N., 2019. Long-term sulfate resistance of cementitious composites containing fine crumb rubber. *Cement and Concrete Composites* 104, 103354.

- Osue, B., 1990. Engineering statistics: the industrial experience. Wadsworth Publishing Company.
- Pakravan, H.R., Latifi, M., Jamshidi, M., 2017. Hybrid short fiber reinforcement system in concrete: A review. *Construction and Building Materials* 142, 280-294.
- Raj, A., Arshad, P.U., Nagarajan, P., Shashikala, A., 2020. Experimental Investigation on the Fracture Behaviour of Polypropylene Fibre-Reinforced Rubcrete, *Structural Integrity Assessment*. Springer, pp. 335-345.
- Ramarad, S., Khalid, M., Ratnam, C.T., Chuah, A.L., Rashmi, W., 2015. Waste tire rubber in polymer blends: A review on the evolution, properties and future. *Progress in Materials Science* 72, 100-140.
- Ramdani, S., Guettala, A., Benmalek, M.L., Aguiar, J.B., 2019. Physical and mechanical performance of concrete made with waste rubber aggregate, glass powder and silica sand powder. *Journal of Building Engineering* 21, 302-311.
- Ranjbar, N., Mehrali, M., Behnia, A., Javadi Pordsari, A., Mehrali, M., Alengaram, U.J., Jumaat, M.Z., 2016. A Comprehensive Study of the Polypropylene Fiber Reinforced Fly Ash Based Geopolymer. *Plos One* 11(1), e0147546.
- Ranjbar, N., Zhang, M., 2020. Fiber-reinforced geopolymer composites: A review. *Cement and Concrete Composites* 107, 103498.
- Reda Taha, M.M., El-Dieb, A.S., Abd El-Wahab, M., Abdel-Hameed, M., 2008. Mechanical, fracture, and microstructural investigations of rubber concrete. *Journal of materials in civil engineering* 20(10), 640-649.
- Roychand, R., Gravina, R.J., Zhuge, Y., Ma, X., Youssf, O., Mills, J.E., 2020. A comprehensive review on the mechanical properties of waste tire rubber concrete. *Construction and Building Materials* 237, 117651.
- Safan, M., Eid, F.M., Awad, M., 2017. Enhanced properties of crumb rubber and its application in rubberized concrete. *Int. J. Curr. Eng. Technol* 7(5), 1784-1790.
- Serdar, M., Baričević, A., Jelčić Rukavina, M., Pezer, M., Bjegović, D., Štirmer, N., 2015. Shrinkage Behaviour of Fibre Reinforced Concrete with Recycled Tyre Polymer Fibres. *International Journal of Polymer Science* 2015, 1-9.
- Si, R., Guo, S., Dai, Q., 2017. Durability performance of rubberized mortar and concrete with NaOH-Solution treated rubber particles. *Construction and Building Materials* 153, 496-505.
- Si, R., Wang, J., Guo, S., Dai, Q., Han, S., 2018. Evaluation of laboratory performance of self-consolidating concrete with recycled tire rubber. *Journal of Cleaner Production* 180, 823-831.
- Su, H., Yang, J., Ghataora, G.S., Dirar, S., 2015a. Surface modified used rubber tyre aggregates: effect on recycled concrete performance. *Magazine of Concrete Research* 67(12), 680-691.

- Su, H., Tang, J., Ling, T.-C., Ghataora, G.S., Dilar, S., 2015b. Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes. *Journal of Cleaner Production* 91, 288-296.
- Tanaka, Y., Sato, H., Kageyu, A., 1983. Structure and biosynthesis mechanism of natural cis-polyisoprene from Goldenrod. *Rubber Chem. Technol.* 56(2), 299-303.
- Tharmaratnam, K., Tan, B.S., 1990. Attenuation of ultrasonic pulse in cement mortar. *Cement and Concrete Research* 20(3), 335-345.
- Thomas, B.S., Gupta, R.C., 2016. A comprehensive review on the applications of waste tire rubber in cement concrete. *Renewable and Sustainable Energy Reviews* 54, 1323-1333.
- Thomas, B.S., Gupta, R.C., Mehra, P., Kumar, S., 2015. Performance of high strength rubberized concrete in aggressive environment. *Construction and Building Materials* 83, 320-326.
- Thomas, B.S., Gupta, R.C., Panicker, V.J., 2016. Recycling of waste tire rubber as aggregate in concrete: durability-related performance. *Journal of Cleaner Production* 112, 504-513.
- Turatsinze, A., Bonnet, S., Granju, J.L., 2007. Potential of rubber aggregates to modify properties of cement based-mortars: Improvement in cracking shrinkage resistance. *Construction and Building Materials* 21(1), 176-181.
- Wang, J., Dai, Q., Si, R., Guo, S., 2019. Mechanical, durability, and microstructural properties of macro synthetic polypropylene (PP) fiber-reinforced rubber concrete. *Journal of Cleaner Production* 234, 1351-1364.
- Xie, J.-h., Guo, Y.-c., Liu, L.-s., Xie, Z.-h., 2015. Compressive and flexural behaviours of a new steel-fibre-reinforced recycled aggregate concrete with crumb rubber. *Construction and Building Materials* 79, 263-272.
- Xie, J., Fang, C., Lu, Z., Li, Z., Li, L., 2018. Effects of the addition of silica fume and rubber particles on the compressive behaviour of recycled aggregate concrete with steel fibres. *Journal of Cleaner Production* 197, 656-667.
- Xie, J., Li, J., Lu, Z., Li, Z., Fang, C., Huang, L., Li, L., 2019. Combination effects of rubber and silica fume on the fracture behaviour of steel-fibre recycled aggregate concrete. *Construction and Building Materials* 203, 164-173.
- Xu, L., Lu, Q., Chi, Y., Yang, Y., Yu, M., Yan, Y., 2019. Axial compressive performance of UHPC filled steel tube stub columns containing steel-polypropylene hybrid fiber. *Construction and Building Materials* 204, 754-767.
- Yang, D., Fan, L., Shi, F., Liu, Q., Wang, Y., 2017. Comparative study of cement manufacturing with different strength grades using the coupled LCA and partial LCC methods—A case study in China. *Resources, Conservation and Recycling* 119, 60-68.
- Yousefieh, N., Joshaghani, A., Hajibandeh, E., Shekarchi, M., 2017. Influence of fibers on drying shrinkage in restrained concrete. *Construction and Building Materials* 148, 833-845.

- Tu, J., Wu, H.-L., Leung, C.K.T., 2020. Feasibility of using ultra-high-volume limestone-calcined clay blend to develop sustainable medium-strength Engineered Cementitious Composites (ECC). *Journal of Cleaner Production* 262, 121343.
- Zhang, D., Yu, J., Wu, H., Jaworska, B., Ellis, B.R., Li, V.C., 2020. Discontinuous micro-fibers as intrinsic reinforcement for ductile Engineered Cementitious Composites (ECC). *Composites Part B: Engineering* 184, 107741.
- Zhong, H., Poon, E.W., Chen, K., Zhang, M., 2019. Engineering properties of crumb rubber alkali-activated mortar reinforced with recycled steel fibres. *Journal of Cleaner Production* 238, 117950.
- Zhong, H., Zhang, M., 2020. Experimental study on engineering properties of concrete reinforced with hybrid recycled tyre steel and polypropylene fibres. *Journal of Cleaner Production* 259, 120914.
- Zhu, X., Miao, C., Liu, J., Hong, J., 2012. Influence of Crumb Rubber on Frost Resistance of Concrete and Effect Mechanism. *Procedia Engineering* 27, 206-213.

Fig. 1. Particle size distribution of sand and crumb rubber (CR) (Zhong et al., 2019).

Fig. 2. Fibres used in this study: (a) picture of recycled tyre steel (RTS) fibre; (b) image of RTS fibre taken by digital microscope; (c) picture of recycled tyre polymer (RTP) fibre; (d) SEM micrograph of RTP fibre.

Fig. 3. Schematic diagram of ultrasonic pulse measurement system.

Fig. 4. Flowability of all mixtures.

Fig. 5. Bulk density of all mixtures.

Fig. 6. Ultrasonic pulse velocity (UPV) of all mixtures.

Fig. 7. Drying shrinkage of all mixtures: (a) effect of crumb rubber (CR); (b) effect of recycled tyre steel (RTS) fibre; (c) effect of recycled tyre polymer (RTP) fibre.

Fig. 8. Compressive strength of all mixtures at 7 and 28 d.

Fig. 9. Mechanism for NaOH treatment on crumb rubber (CR) (Guo et al., 2017).

Fig. 10. Flexural strength of all mixtures at 28 d.

Fig. 11. Effect of crumb rubber (CR), recycled tyre steel (RTS) fibre and recycled tyre polymer (RTP) fibre content on final failure patterns of composites under four-point bending.

Fig. 12. Images of fibre-matrix interaction taken by digital microscope.

Fig. 13. Relationships between compressive strength and ultrasonic pulse velocity (UPV).

Fig. 14. Comparison between experimental and predicted flexural strength of fibre reinforced rubberised cementitious composite (FRRC).

Fig. 15. Estimated cost of all mixtures per m³ where M represents the samples containing manufactured steel and polypropylene fibres with equal dosages of recycled fibres.

Fig. 16. Embodied carbon of all mixtures per m³ where M represents the samples containing manufactured steel and polypropylene fibres with equal dosages of recycled fibres.

Fig. 17. Embodied energy of all mixtures per m^3 where M represents the samples containing manufactured steel and polypropylene fibres with equal dosages of recycled fibres.

Table 1. Chemical composition (wt%) of cement.

Oxide	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	CaO	MgO	Na ₂ O	SO ₃	LOI
Cement	20.18	4.87	3.23	0.68	63.35	1.09	0.13	2.96	1.64

Note: LOI (loss on ignition).

Table 2. Properties of recycled fibres adopted in this study (Chen et al., 2020; Zhong and Zhang, 2020).

Fibre type	Length (mm)	Diameter (μm)	Tensile strength (MPa)	Elastic modulus (GPa)
RTS	23 ¹	220 ¹	2570	200
RTP	8.7 (4.1) ²	21.1 (2.5) ²	475 ¹	3.21 ¹

Note: RTS (recycled tyre steel fibre); RTP (recycled tyre polymer fibre); ¹ (nominal value); ² (standard deviation).

Table 3. Mix proportions of specimens investigated.

Series	Label	Cement (kg/m ³)	Water (kg/m ³)	SP (kg/m ³)	Sand (kg/m ³)	CR (kg/m ³)	RTS (vol%)	RTP (vol%)
A	R0S0P0	631	254	6.31	1420	0	0	0
	R5S1.0P0.5	631	254	6.31	1349	30	1.0	0.5
	R10S1.0P0.5	631	254	6.31	1278	60	1.0	0.5
	R15S1.0P0.5	631	254	6.31	1207	90	1.0	0.5
B	R10S0.5P0.5	631	254	6.31	1278	60	0.5	0.5
	R10S1.5P0.5	631	254	6.31	1278	60	1.5	0.5
C	R10S1.0P0	631	254	6.31	1278	60	1.0	0
	R10S1.0P1.0	631	254	6.31	1278	60	1.0	1.0

Note: SP (superplasticiser); CR (crumb rubber)

Table 4. Classification of concrete quality according to ultrasonic pulse velocity (UPV) value (International Atomic Energy Agency, 2002).

UPV (km/s)	Quality of concrete
>4.5	Excellent
3.0-4.5	Good
3.0-3.5	Doubtful
2.0-3.0	Poor
<2.0	Very poor

Table 5. Cost of each constituent material in fibre reinforced rubberised cementitious composite (FRRC) ([Abdollahnejad et al., 2017](#); [Su et al., 2015a](#); [Mastali et al., 2018a](#); [Yang et al., 2017](#); [Zhang et al., 2020](#)).

Type	Cement	Sand	Water	SP	CR	RTS	RTP	ST	PP	NaOH
Cost (USD/kg)	0.0687	0.02	0.11	0.89	0.32	0.54	0.5	3.8	9.8	2.54

Note: ST (manufactured steel); PP (manufactured polypropylene).

Table 6. Embodied carbon and embodied energy of each constituent material in fibre reinforced rubberised cementitious composite (FRRC) ([Fantilli et al., 2016](#); [Hammond et al., 2008](#); [Mastali et al., 2018b](#); [Ohno and Li, 2018](#); [Yu et al., 2020](#)).

Type	Embodied carbon (kg CO ₂ .eq/kg)	Embodied energy (MJ/kg)
Cement	0.912	5.5
Sand	0.0024	0.1
Water	0.001	0.1
SP	1.064	42.67
CR	0.2	4
RTS	0.5	9.5
RTP	1.94	83.1
ST	2.75	35.3
PP	2.7	100
NaOH	0.86	18

The authors declare no conflict of interest.

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