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Effect of Rubber Aggregate Size on Static and Dynamic Compressive Properties of Rubberised Concrete

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Abstract

This study experimentally examines the effect of rubber aggregate size on the static and dynamic behaviour of rubberised concrete. Rubberised concrete specimens were prepreaed with different maximum rubber aggregate sizes ranging from 1-3 mm to 3-5 mm while the rubber content was kept constant at 15% by volume. The dynamic compressive behaviour of rubberised concrete was investigated by using split Hopkinson pressure bar (SHPB) tests. The experimental results have shown that rubberised concrete with smaller rubber aggregates showed higher static compressive strength as compared to that with larger rubber aggregates. Meanwhile, the rubber aggregate size did not considerably affect the density of rubberised concrete. The use of smaller rubber aggregate size mitigated the slump reduction of rubberised concrete. Rubberised concrete exhibited obvious sensitivity to strain rate and those with larger rubber aggregates showed higher strain rate sensitivity. The progressive damage of rubberised concrete showed more ductile behaviour with bulging failure which was different from the typical concrete under compression. In general, the use of smaller rubber aggregate size was beneficial to the static compressive strength but less effective to the dynamic compressive strength of rubberised concrete as compared to those with larger rubber aggregates.

Keywords: Rubberized concrete; Strain rate; SHPB; Impact loading; Energy absorption.

Introduction

With the increase in globalisation and vehicle manufacturing sector over the past few decades, used car tyres being dumped into landfills have become an environmental problem. These tyres are made from rubber, which takes centuries to decompose [1]. Consequently, various adversely environmental effects have been associated with landfills, such as mosquitoes, releasing toxic chemicals, and fire hazards, which places people in the surrounding areas at risk. Previous reports have stated that 242 million tyres have been discarded annually in the United States [2] while the corresponding number in Australia is 56 million [3]. Therefore, recycling or reusing these used tyres helps to solve the relevant environmental issues.

Recently, used car tyres have been utilized as aggregates in concrete, namely rubberized concrete (RuC), and this relatively new material has proven some distinguished properties such as high energy absorption and flexibility [4-8]. Incorporating rubber aggregates into concrete mixes have two main advantages: (1) reducing the amount of landfill waste accumulated annually; and (2) replacing the amount of natural gravel aggregates consumed by the production of traditional concrete by a recycled material. More specifically, sand and natural aggregates, which originate from rocks, take millions of years to form, making incorporation of waste rubber in concrete a sustainable option. However, research on rubberised concrete is still limited, especially with regards to dynamic loading.

Many important structures may experience dynamic loads during their service life, for example, high-rise buildings, airport runways, road-side barriers, and asphalt pavements, therefore may need be designed accordingly to resist impact, blast, and seismic loads [4, 9]. Various researchers have looked into the effects of incorporating different ratios of natural to recycled aggregates ranging from 5% to 80% [10-15]. Despite previous tests showing that the addition of rubber aggregates into concrete mixes reduces the quasi-static compressive strength, it is compensated by other benefits of being more ductile, enhanced energy absorption, and improved resistance to impact loads. Previous studies have stated that fine and coarse rubber aggregates exhibited different influences on the static and dynamic properties of rubberised concrete [7, 16, 17]. Su et al. [16] found that using rubber crumbs (1-5 mm) yielded a higher compressive strength than that using coarser rubber crumbs (6-10 mm) for the same rubber content. This finding was also supported by the experimental results with low rubber content from another study by Raffoul et al. [18]. Meanwhile, Najim and Hall [17] observed that replacing solely fine aggregates leads to lower compressive strength as compared to that of coarse aggregates for rubberized concrete with less than 10% rubber content. There has not been a consensus for this phenomenon and understanding about this phenomenon is still not yet comprehensive. Therefore, this study investigates the effect of aggregate size on the static and dynamic properties of rubberized concrete. The rubberised concrete with the same rubber content (i.e. 15% by volume) but different sizes of rubber aggregates was cast and tested under static and dynamic loading.

Literature review

Physical properties of RuC

A brief review was conducted on the availlable studies and understanding of the effect of using rubber in concrete as aggregates on the physical and mechanical properties. The physical properties of rubberized concrete are reviewed in terms of three factors including slump, air void, and density. Previous studies have observed that the addition of rubber crumbs to fresh concrete results in a negative effect on the slump values [10-13]. However, Huang et al. [19] found that the addition of rubber to the concrete mix enhanced the slump values while Li et al. [20] also observed that the adverse effect of adding rubber to slump was minimal with 15% rubber content. The contradictory finding of the effect of rubber aggregates on slump was discussed in the previous study by Su [21]. In general, most of the previous studies found a reduction of slump when adding rubber aggregates to concrete [21]. This reduction of the slump values is attributed to the increased friction due to the rough surface of rubber crumbs as compared to smoother surfaces of natural aggregates, which results in a slow movement of the mixture. In addition, the water absorption of rubber is higher than that of natural aggregates and thus less water for the mix and lower slump. Meanwhile, the specific density of rubber is much lighter than that of natural aggregates, leading to more difficult to flow on its self-weight and thus lower slump.

Previous studies have suggested that there exists a proportional correlation between the addition of rubber crumbs and the resultant air content in rubberized concrete [22-24]. Adding rubber aggregates to a mixture results in a higher air content in concrete. The increase in air content may be due to the shape and texture of rubber crumbs, in addition to the possible entrapped air around a jagged surface [25]. This phenomenon was observed through submerging rubber crumbs in water, which resulted in air bubbles being trapped on the surface of the crumbs [26]. This simple, yet effective, experiment showed the difficultly of crumbs to sink and highlighted the hydrophobic properties of rubber. The hydrophobic property means that rubber is more difficult to get wet compared to natural aggregates and thus rubber has lower bond strength to concrete matrix than that of natural aggregates. In general, it can be stated that the increase in the volume of rubber content caused a subsequent increase in the air voids within a mixture.

In concrete, the density of natural aggregates can surpass 2.5 times that of rubber crumbs [13]. As a result, the density of concrete structures decreased when rubber crumbs are utilised to substitute a portion of natural aggregates [27-30]. Most of the previous studies have concluded that the density of concrete decreased linearly with the increase of rubber content [21]. On the other hand, Benazzouk et al. [31] reported that the relationship between concrete density and rubber content is non-linear due to the increase in the air-entrainment associated with rubber content, which further lightening rubberised concrete.

Quasi-static and dynamic properties of RuC

The quasi-static compressive strength has been examined in the previous studies [10, 16, 24, 32-34]. These studies consistently reported that the compressive strength of concrete reduced with the addition of rubber crumbs. The strength reduction can be attributed to two aspects. Firstly, the mechanical properties of rubber are much weaker than those of natural aggregates. Furthermore, the modulus dissimilarity between rubber and matrix results in stress concentration and thus more cracks appear at the interface between rubber and matrix [34]. Secondly, rubber is non-polar in nature so that it entraps air on the interface, leading to more voids and thus strength reduction [21]. Accordingly, the reduction becomes more pronounced as the rubber content increases.

Research on the dynamic compressive strength of rubberised concrete is still limited when compared to that of traditional concrete [5, 35-37]. Existing studies of dynamic properties of rubberized concrete used a split Hopkinson pressure bar (SHPB) and considered four rubberised concrete mixes, which respectively contained a 5%, 10%, 15% and 20% replacement of natural aggregates with rubber crumbs. Yang et al. [36] used rubber crumb sizes ranging from 1-5 mm while the average rubber aggregate size in the study by Liu et al. [35] was 2 mm. They reported that rubberized concrete was more sensitive to the strain rate, which is quantified by the dynamic increase factor (DIF). DIF is defined as a ratio of the dynamic strength to the static strength. Yang et al. [36] observed that this trend was clear for the 5%, 10% and 15% but not for 20% rubber content. This finding agrees well with experimental results from Pham et al. [5] who replaced both fine and coarse aggregates (1-10 mm) and also found that RuC is more sensitive to strain rate than normal concrete. Pham et al. [5] also reported that all specimens with two different rubber contents (15% and 30%) exhibited relatively high sensitivity to strain rate. In addition, Pham et al. [37] investigated the dynamic behaviour of rubberised geopolymer concrete and also found a similar behaviour, therefore concluded that rubberised geopolymer concrete was also strain rate sensitive. As can be seen that these studies replaced both coarse and fine natural aggregates with similar size rubber aggregates. The effect of rubber aggregates size on the static compressive properties was reported but there is no study regarding its effect on the dynamic properties yet. Therefore, this study investigates the effects of aggregate size on the compressive strength of RuC under both static and impact loading conditions.

Experimental program

Mixture design and material preparation

To compare the effect of rubber aggregate size on the properties of RuC, two different sizes of rubber aggregates were used and they were classified into two categories, namely fine aggregates (1-3 mm) and coarse aggregates (3-5 mm). In total, four different mixes were prepared, including a control mix which did not contain any rubber (REF), and three mixtures containing (i) 15% fine rubber crumbs (RC15A), (ii) a combination of 7.5% fine and 7.5% coarse rubber crumbs (RC15B), and (iii) 15% coarse rubber crumbs (RC15C). The rubber replacement by volume and the concrete mix design are presented in Table 1. The mix proportion of 1 m^3 reference concrete included 426 kg cement, 213 kg water, 750 kg coarse aggregates (size less than 10 mm), 130 kg coarse aggregates (size less than 5 mm), and 843 kg sand. The water/cement ratio was fixed for all the mixes while 15% volume of both coarse and fine aggregates were replaced by rubber aggregates, see details in Table 1.

Fine (<5 mm) and coarse (<10 mm) natural aggregates were sourced from Holcim Perth, silica sand of 0.07 mm – 1.025 mm particle size was sourced from Hansen cement, and ordinary Portland cement was sourced from Cockburn cement. The fine (1–3 mm) and coarse (3-5 mm) rubber crumbs were obtained from Tyre recycle [38]. The physical properties of rubbers are summarised in Table 2 [5]. All natural aggregates were washed with water to remove impurities and/or unwanted substances. They were then soaked in a bucket of water for 24 hours and had surface dried before concrete mixing. Meanwhile, rubber crumbs were submerged in water for 24 hours, followed by an additional 24 hour period of air-drying, to achieve a dry surface condition. Obtaining thoroughly dry crumbs were vital because any excess water would adversely impact the chosen water-cement ratio, and in turn, decrease the compressive strength. This pre-treatment method for rubber crumbs was chosen to compromise between effectiveness and simplicity as suggested by the previous studies [5, 39].

Test matrix and specimen preparation

Standard cylinders of 100x200 mm were used in the static tests while cylindrical samples with a diameter of 100 mm and height of 50 mm were used for SHPB tests. Three cylinders were tested to determine the static compressive strength for each mix (12 in total). For dynamic tests, each mix was examined under four different strain rates and two specimens were required for each strain rate. In total, 32 specimens for dynamic tests (100x50 mm) were cut from standard cylinders (100x200 mm). The dynamic samples were then ground off to ensure good finishing (Fig. 1) for the high requirement of SHPB tests [5, 37]. Materials were prepared according to AS 1012.2 [40] while AS 1012.8.1 [41] was adopted for moulding, compaction, curing, demolding, handling, recording, and reporting.

Fig. 1. Polished concrete specimens before tests

Laboratory testing

The quasi-static compressive tests of each mix were done in accordance with AS 1012.9 [42]. Three cylinders were tested for each mix and the average strength was recorded. The computerised compression machine was used in the tests at a rate of 0.33 MPa per second, corresponding to the quasi-static strain rate of 10^{-4}/s.

Split Hopkinson Pressure Bar (SHPB) system with a diameter of 100 mm was used to conduct dynamic material tests as shown in Fig. 2. SHPB system has been widely used to obtain dynamic material properties [5, 37, 43, 44]. The dynamic properties including failure progress, failure patterns, compressive strength, and energy absorption capacity can be obtained from the testing data. The incident and reflected waves were measured by a strain gauge mounted at mid-length of the incident bar while the transmitted wave was measured by another strain gauge mounted at the mid-length of the transmission bar. A high-speed camera with a sampling rate of 50,000 frames per second was used to capture the failure processes of the specimens for further analysis. Equations (1), (2) and (3) below are used to determine the stress – $\sigma(t)$, strain rate – $\dot{\varepsilon}(t)$ and strain – $\varepsilon(t)$ of each specimen from the SHPB tests. The equilibrium state of each sample was examined and only valid data was presented.

$$\sigma(t) = E_b \frac{A_s}{A_b} \varepsilon_t(t) \tag{1}$$

$$\dot{\varepsilon}(t) = -\frac{2C_b}{L} \varepsilon_r \tag{2}$$

$$\varepsilon(t) = \int_0^T \dot{\varepsilon}(t)dt \quad (3)$$

where,

E_b= elastic modulus of the transmission bar

A_b= cross-sectional area of the transmission bar

A_s= cross-sectional area of the specimen

C_{b}= longitudinal wave velocity of the bars

L= thickness of the specimen

ε_t= transmitted strain

ε_r= reflected strain

To increase the rise time of the incident wave, a rubber pulse shaper was attached to the incident bar as shown in Fig. 2. The rubber pulse shaper had a circular shape with a diameter of 20 mm and thickness of 3 mm, which was recommended in the previous studies to obtain smoother half-sine stress waves by extending the rising time [5, 37, 44]. This incident waveform helps to achieve the stress equilibrium condition in the tested samples [45].

Fig. 2. Split Hopkinson pressure bar apparatus

Experimental results and discussions

Slump and compression tests

The workability of the rubberised concrete mixtures was assessed by conducting slump tests after mixing each batch. During the tests, all concrete mixtures were visually assessed and found to be cohesive with no segregation or bleeding during the mixing, placing or compaction phase. Three slump tests were carried for each mix to increase the reliability and accuracy (see Table 3). The standard deviation of Specimen REF (0.82) was lower than those of other mixes (1.25-1.70). This observation agrees well with the previous studies [10-13]. The result in this study adds one more finding to the literature that using coarser rubber aggregates leads to a lower slump of rubberized concrete as compared to finer rubber aggregates, considering the same rubber content. It is worth mentioning that superplasticizer was not used in this study to avoid its influence on the compressive strength and workability while it can be used in practice to increase the workability of rubberised concrete.

On the 28th day of curing, three samples from each mix were tested to determine their quasi-static compressive strength. The compressive strength of Specimens REF, RC15A, RC15B, and RC15C was 37.7, 35.8, 32.3, and 28.4 MPa as shown in Table 4, respectively. It was observed that the inclusion of rubber into the concrete mixes resulted in a reduction of compressive strength as compared to the control mix. This trend was similar to the previous studies and the reason was discussed previously [5, 14, 46, 47]. The average compressive strength of Specimens RC15A, RC15B, and RC15C were respectively 5%, 15%, and 25% lower than that of the control mix. This percentage decrease aligns with the findings of Elchalakani et al. [47], which reported a decrease ranging between 2-30% in the compressive strength as compared to their control mix. For all three mixes which contained 15% rubber replacement, an inverse proportional relationship was observed between the steady compressive strength reduction and the increased particle size. This was because the finer rubber crumbs have a better void-filling ability, resulting in lower amounts of void space and higher compressive strengths [46]. In addition, the smaller aggregate size generated a more uniform stress flow. When large-size rubber aggregates were used, the stress flow is interrupted, leading to a higher level of nonuniformity and thus higher stress concentration. Accordingly, given the same rubber content, rubberised concrete with smaller rubber aggregates exhibited higher compressive strength. This observation agrees well with the experimental results resported in the previous studies [16, 18].

Validity and strain-rate determination of SHPB tests

The dynamic tests were undertaken using a 100 mm diameter split Hopkinson pressure bar apparatus. The adjusted pressures to propel impact bar varied from 0.2 MPa to 0.4 MPa to achieve different strain rates. All the voltage data outputs (Fig. 3) obtained from the SHPB oscilloscope recorder were processed to assess the validity of the data. Based on Eqs. 1-3 and the removal of time lags between each wave, the sum of the incident and reflected stress waves was compared to that of the transmitted wave (Fig. 4). It is worth mentioning that it was a challenge to obtain reliable data when the chamber pressure was 0.4 MPa due to the high-frequency oscillation recorded. This issue was later rectified when using a larger 30 mm-diameter rubber waveshaper on the incident bar.

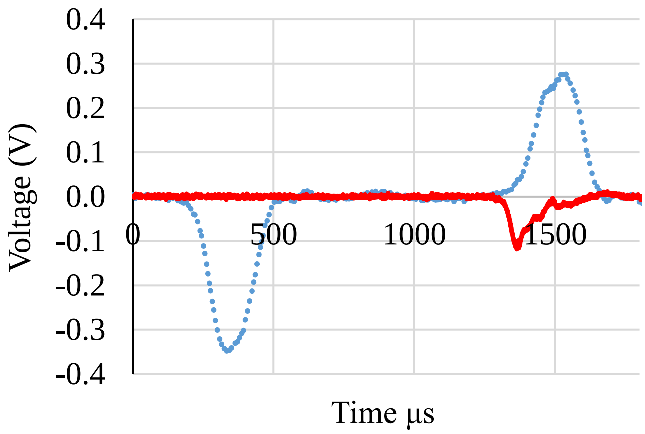

Fig. 3. Typical SHPB voltage data

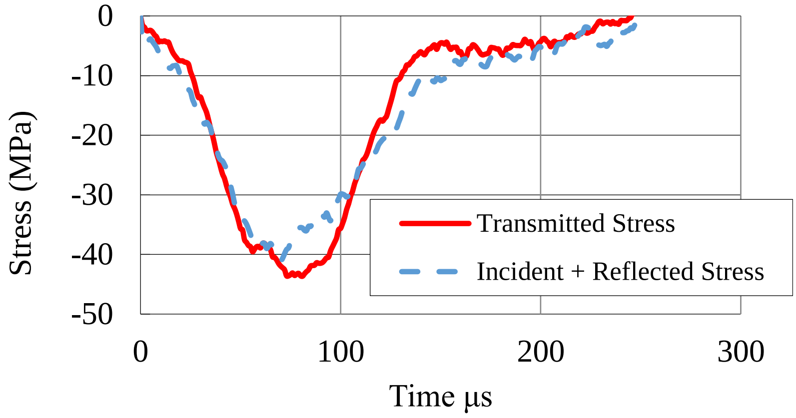

Fig. 4. Typical equilibrium check on stress wave

The strain rate of the tested specimens varied significantly with time. There have been a few methods to determine the strain rate for each specimen [5, 37]. The first method was based on the peak stress at which the corresponding strain rate is defined at the point of vertical intersection of the peak stress curve to the strain rate curve. The second method adopts the averaged strain rate values from the plateau of the strain rate curve during the time duration when the peak stress is achieved. In this study, the first method was adopted to determine the strain rate of SHPB specimens as also recommended by the previous studies [48, 49].

Failure processes and failure modes

A high-speed camera was utilised to capture the progressive failure of the specimens which is shown at different time intervals of 200, 300, and 500 microseconds (Fig. 5). These specific time instants were chosen because it shows the initiation, development and propagation of cracks before the specimens were completely smashed.

At 200 microseconds, the formation of cracks was relatively similar for all the four specimens, consisting of one or two fine cracks starting to propagate from the outer edges to the centre of the specimens. At this instant, there was no noticeable difference in the cracking behaviour among the four specimens.

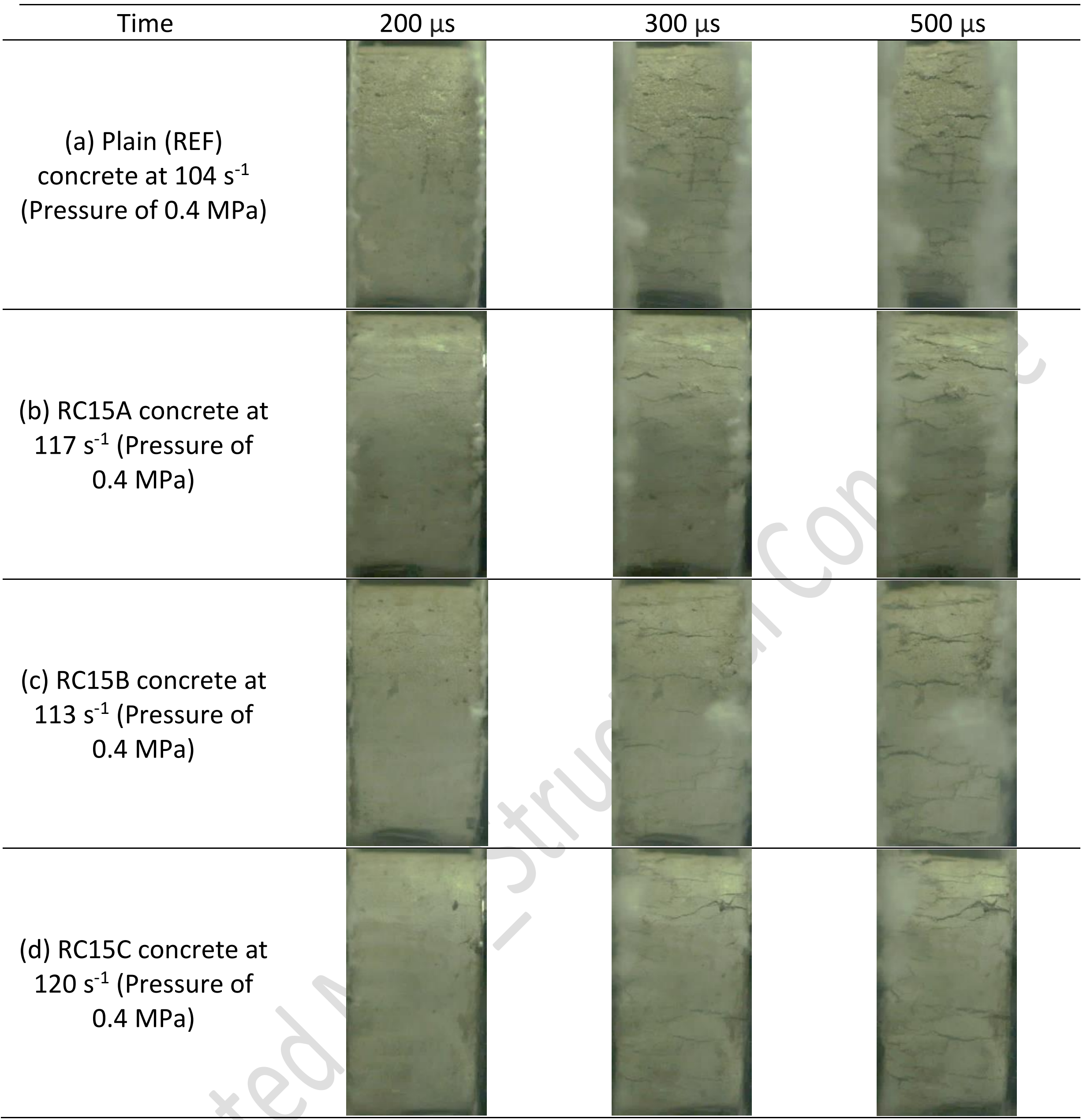

Fig. 5. Progressive failure of the tested specimens

At 300 microseconds, most of the cracks on the four specimens had propagated from the edge to centre or from one edge to another edge. Plain concrete (Specimen REF) had several fine cracks running almost parallel to each other in one direction, whereas, in the rubberised specimens, cracks further developed and ran in different pathways. This phenomenon indicated that cracks of rubberised specimens had longer paths and thus absorbed more energy. At this instance, Specimen RC15C had accumulated fewer cracks than Specimens RC15A and

RC15B; however, its surface was starting to flake off around some of the rubber crumbs that were cast close to the surface of the specimen.

At 500 microseconds, all the four specimens were almost at the complete failure point. No new cracks were observed while the existing cracks were starting to widen. The rubber specimens were bulging outwards (lateral deformation) from the vertical centreline of the specimen, as shown in the high-speed images in Fig. 6, indicating the toughness and ductile characteristics owing to the added rubber crumbs. The bulging failure was not observed on Specimen REF. Specimens RC15A and RC15B had similar widths of crack openings, whereas Specimen RC15C showed higher deformable capacity.

The post-test failure mode of all the specimens at various strain rates, is shown in Fig. 6. Rubberised concrete showed larger fragments and less brittle failure when compared to plain concrete at all pressures, which is attributed to the fact that the rubber improves toughness in concrete. This observation is consistent with the findings of the previous studies [5, 36], which highlighted the favourable properties of using rubber in concrete.

Under the lowest strain rates (corresponding to 0.2 MPa pressure), all the specimens failed into two or three pieces but maintained their overall shape. For plain concrete (Specimen REF), one major crack was observed running along the centre of the specimen. Alternatively, the fine rubber crumb concrete (Specimen RC15A) and the mix of fine and coarse rubber concrete (Specimen RC15B) exhibited two primary cracks propagating in the centre with smaller cracks branching towards the edge. The specimen with coarse rubber crumb (Specimen RC15C) experienced failure mainly on one side with numerous micro-cracks on the surface of the specimen.

At the intermediate strain rate (corresponding to 0.3 MPa champer pressure), all the specimens shattered into smaller fragments with varying average sizes. The smallest size was observed in

Specimen REF and the largest in Specimens RC15B and RC15C. Most of the fragments in Specimen RC15A were of similar size. There were a few pieces in Specimen RC15B that were similar in size to that of Specimen RC15C. In Specimens RC15B and RC15C, some pieces of concrete were still held together by the coarse rubber crumbs, although the specimen itself had been completely damaged. This indicated that the pre-treatment of the rubber crumbs was deemed effective while previous researchers warned that rubber and concrete had poor bonding characteristics when not adequately prepared prior to casting [46].

Fig. 6. Failure modes of REF, RC15A, RC15B, and RC15C specimens at strain rates

Similarly, at the highest strain rate (corresponding to 0.4 MPa champer pressure), all the specimens were smashed into relatively smaller pieces regarding those from a lower strain rate. Specimen REF had the smallest fragments among the four specimens, mainly consisting of the large and fine natural aggregates completely stripped from the concrete matrix, and the hardened cement mostly transformed into fine particles. At the same pressure, Specimens

RC15A, RC15B, and RC15C had larger fragments as compared to Specimen REF. The number of fine particles was also much lower when compared to that of Specimen REF.

The failure trends shown at the three pressures/strain rates are in line with the results of the previous studies [5, 37, 50]. The addition of rubber in concrete delayed and reduced the severity of failure in concrete. Again, this result is primarily due to the ability of the rubber crumbs to deform or elongate within a short duration. Another finding also worth mentioning is that the large rubber aggregates could act as a bridge and hold two fragments together and thus improve their resistance to impact loading while fine rubber aggregates did not show this effect.

Dynamic stress-strain relationship

The stress-strain curves of all the specimens are shown in Figs. 7-10. These figures clearly depict that the dynamic compressive strength of all these specimens increased with the strain rate. At low strain rate (45-65 s^{-1}), the dynamic compressive strength at each strain rate of Specimens RC15A to RC15B to RC15C were smaller with larger percetange of coarse rubber aggregates in the specimen, consistent with the performance of the specimens under quasi-static loading. This phenomenon is attributed to the fine rubber crumbs which have better void filling abilities and are able to transfer load more uniformly [46]. Rubberised concrete with fine rubber aggregates had higher static strength and dynamic strengths at low strain rate (45-65 s^{-1}). At higher strain rate (>100 s^{-1}), the dynamic compressive strength of Specimen RC15C was greater than that of the other specimens. This observation demonstrated that the dynamic compressive strength of Specimen RC15C increased faster as compared to the other specimens when the strain rate increased. This observation can be seen from Fig. 11 showing quite similar dynamic maximum stress (66-72 MPa) of all the mixes at the strain rate of 126-128 s^{-1} even though these mixes had very different static compressive strength (29-38 MPa).

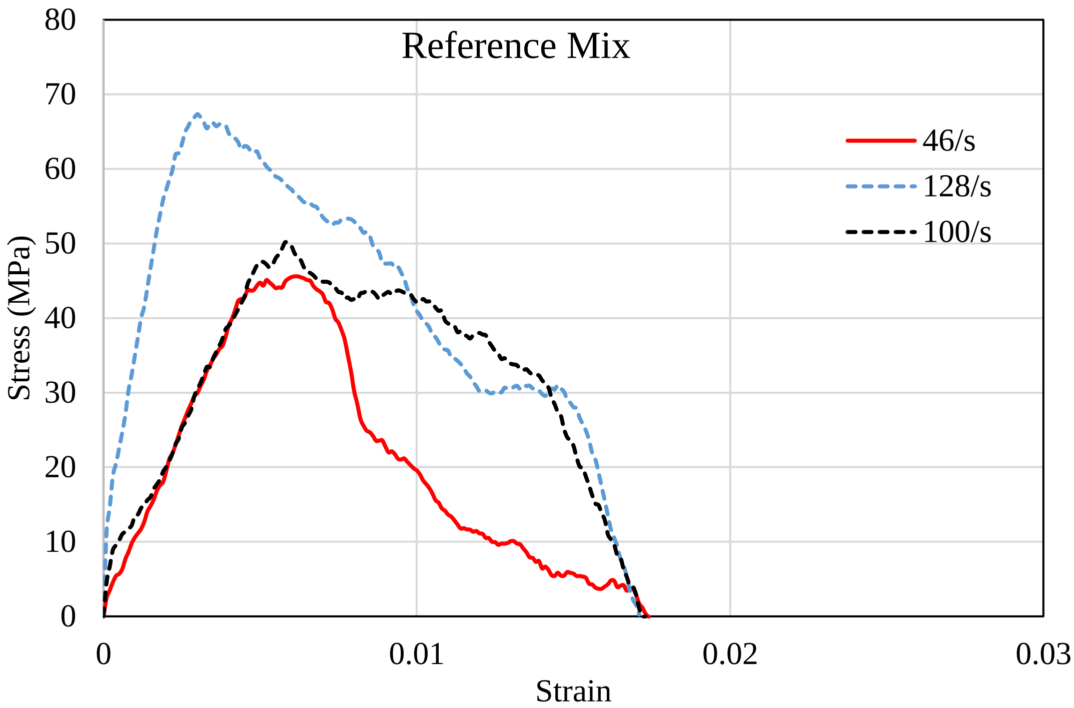

Fig. 7. Typical dynamic stress-strain curves of Specimen REF at different strain rates

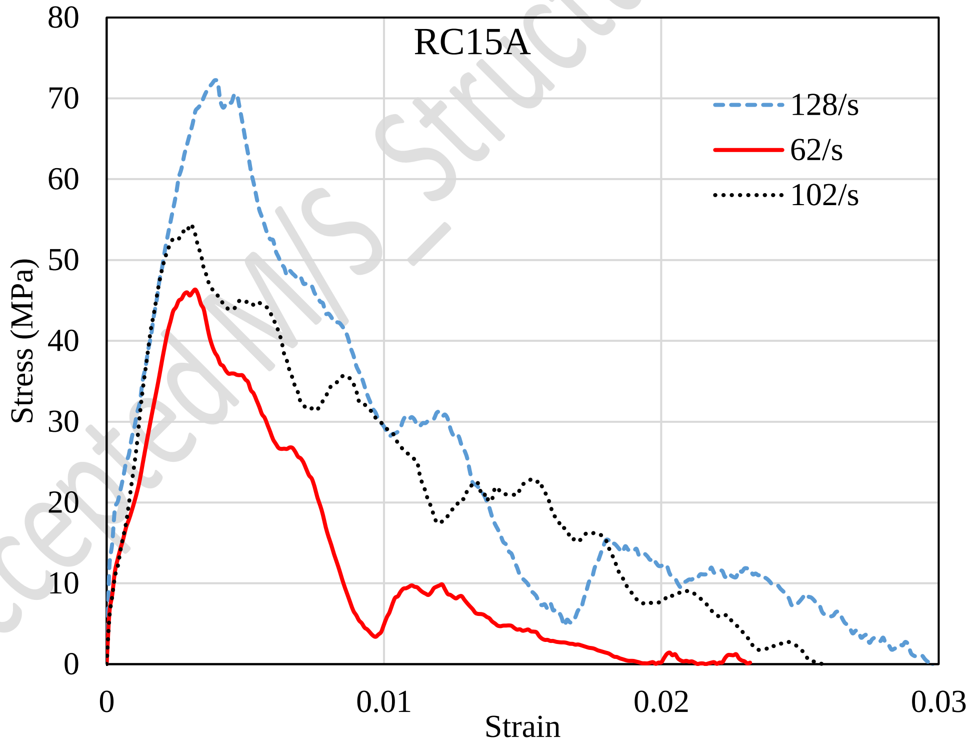

Fig. 8. Typical dynamic stress-strain curves of Specimen RC15A at different strain rates

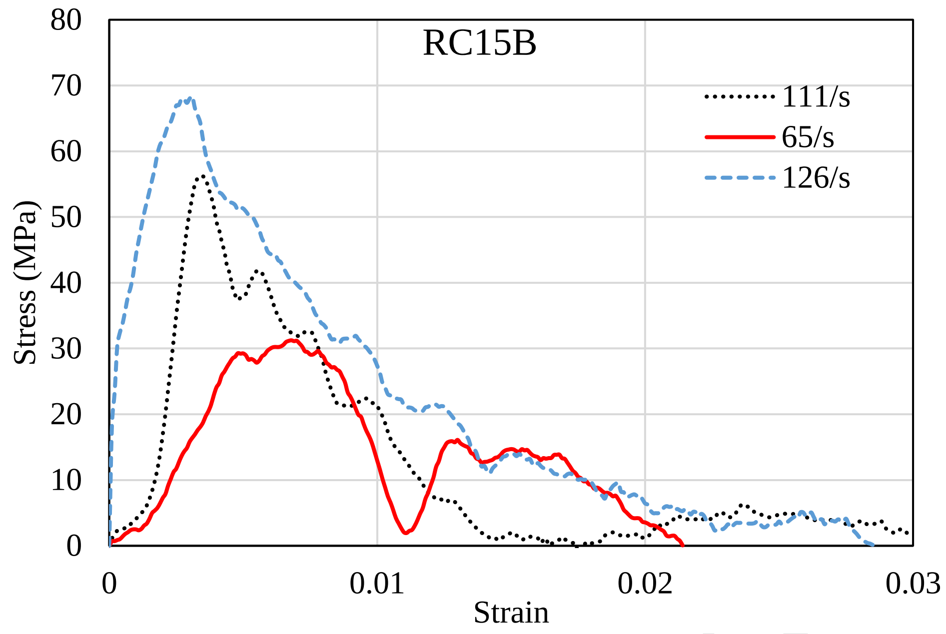

Fig. 9. Typical dynamic stress-strain curves of Specimen RC15B at different strain rates

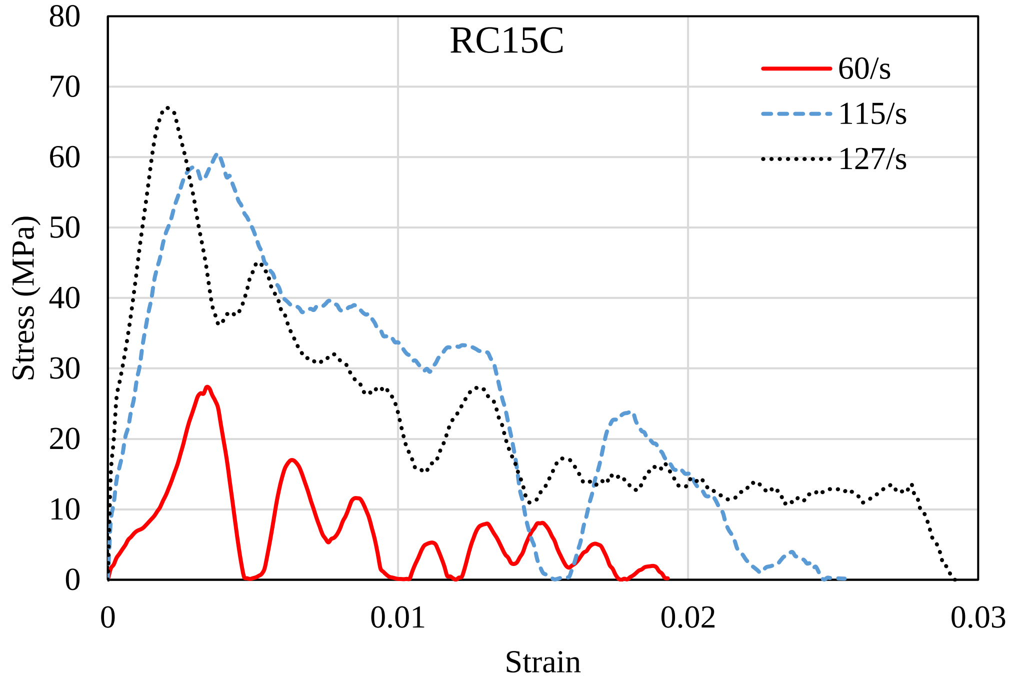

Fig. 10. Typical dynamic stress-strain curves of Specimen RC15C at different strain rates

The maximum strain of Specimen REF at different strain rates was quite consistent at approximately 1.7%, but the maximum strain of rubberised concrete increased with the strain rate and it varied from 1.6% to 2.8%. It can be seen that the slope of the ascending branch of the stress-strain curves of all the specimens increased with the strain rate, which indicated that the elastic modulus of concrete also increased with the strain rate. However, the exact elastic modulus of concrete was not determined due to considerable fluctuation of the stress-strain curves that is the nature of this type of test as also observed in the previous studies [5, 48]. For the descending branch of the stress-strain curves, rubberised concrete exhibited more ductile behaviour because their curves were less stiff than that of the reference specimens. This was another observation that indicated more ductile behaviour of rubberised concrete under impact loading.

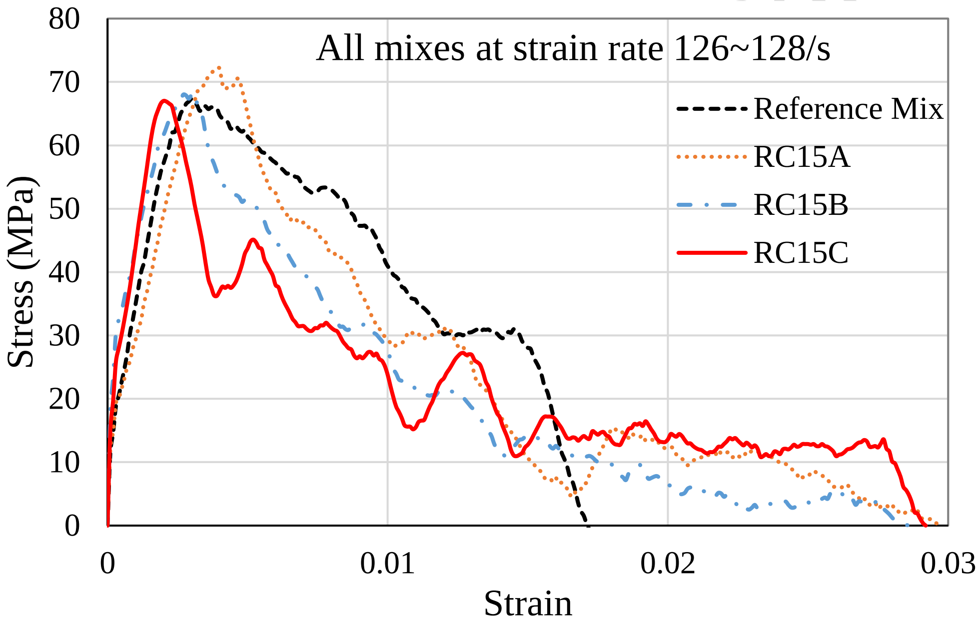

Fig. 11. Stress-strain curves of all the mixes at 126~128/s

Dynamic increase factor (DIF)

As observed above, the compressive strength of normal concrete and rubberised concrete increased with strain rates. To quantify the influence of this phenomenon on the plain and rubberised concrete specimens, the dynamic increase factor (DIF), which is the ratio between the dynamic compressive strength and the quasi-static strength, was evaluated. The DIF of all the tested specimens is presented in Fig. 12. Meanwhile, the prediction of DIF of normal concrete was also calculated by using Eqs. 4-5 for comparison, as suggested by Comite Euro-International du Beton [51] (CEB's model). These values have also been tabulated in Table 5. The strain rate of the reference concrete in this study was lower than those estimated by using CEB's model, this was reasonable since the overestimation of CEB's model has been reported and discussed in the previous study [52]. Considering considerable fluctuation of results of the SHPB tests, the derived DIF is in the common ranges as reported in the previous studies [5, 37, 43, 44, 48].

$$\mathrm{DIF} = \frac{f_{cd}}{f_{cs}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_s}}\right)^{1.026\alpha} \quad \text{for } \dot{\varepsilon} \leq 30\ \mathrm{s}^{-1} \tag{4}$$

$$\mathrm{DIF} = \frac{f_{cd}}{f_{cs}} = \gamma\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_s}}\right)^{\frac{1}{3}} \quad \text{for } \dot{\varepsilon} > 30\ \mathrm{s}^{-1} \tag{5}$$

where:

f_{cd} = dynamic compressive strength at $\dot{\varepsilon}$

f_{cs} = static compressive strength at $\dot{\varepsilon}$

$\dot{\varepsilon}$ = strain rate in the range of $30 \times 10^{-6}\ \mathrm{s}^{-1}$ to $300\ \mathrm{s}^{-1}$

$\dot{\varepsilon}_s$ = $30 \times 10^{-6}\ \mathrm{s}^{-1}$ static strain rate

α = $1/(5 + 9\frac{f_{cs}}{f'_{co}})$

$\log\gamma$ = $6.15\alpha - 2$

f'_{co} = 10 MPa

The DIF of all the tested specimens increased with strain rate as shown in Figure 12, indicating strain rate sensitivity. At the lowest tested strain rate of approximately 60-65 s^{-1}, Specimen RC15B had the highest DIF of 1.28 followed by Specimens REF, RC15A and RC15C with the DIF of 1.22, 1.08 and 1.00, respectively. The low DIF of rubberised concrete at low strain rate was resulted from its significantly fluctuated stress-strain curves as shown in Figs. 7-10. Consequently, there were large variations in the peak stress and thus the DIF of rubberised concrete at low strain rate. Meanwhile, at a higher strain rate, i.e. greater than 100 s^{-1}, the DIF of rubberised concrete was higher than that of the reference concrete as reported in the previous studies [5, 35-37]. Also, rubberized concrete with larger rubber aggregates exhibited higher DIF (more strain rate sensitivity) than others with smaller rubber aggregates. This phenomenon was also reported in a previous study at low strain rate (<100 s^{-1}) [53]. The authors observed the strain rate sensitivity increased with both the rubber size and rubber content, which supports the findings in this study. The experimental results from this study covered higher strain rate (up to 128 s^{-1}) and have shown that the DIF of Specimens RC15C, RC15B, RC15A, and REF was 2.04, 1.80, 1.51, and 1.49 at the strain rate of about 100 s^{-1}, respectively. This phenomenon became more prominent with higher strain rates.

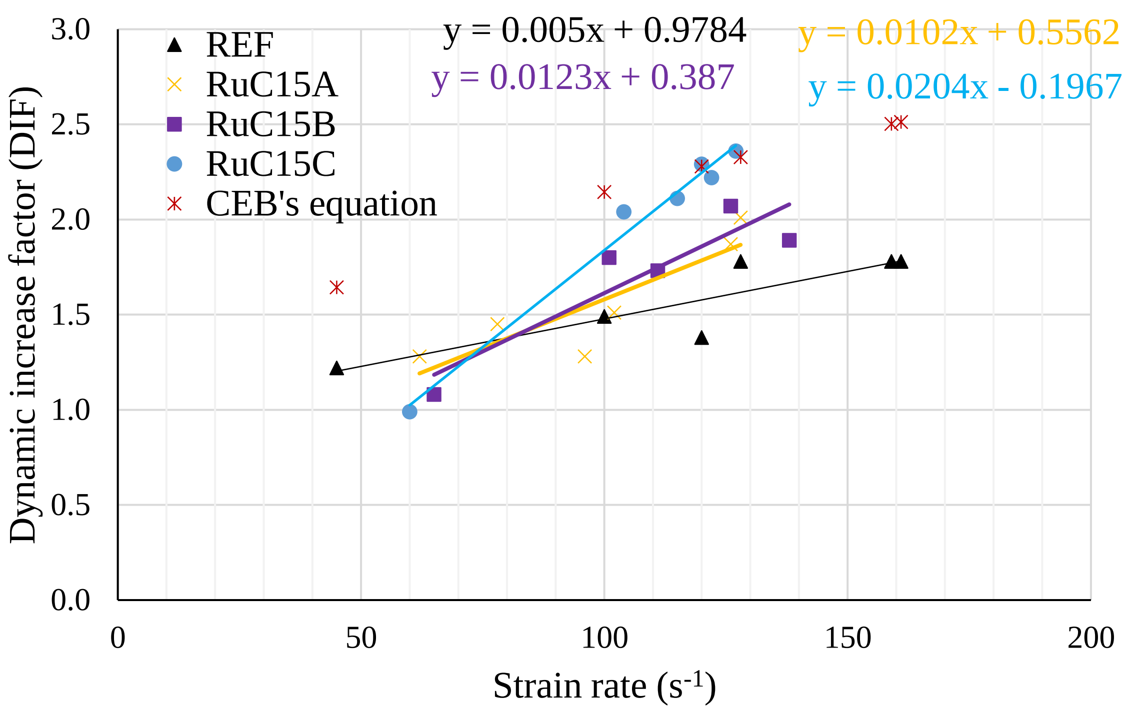

Fig. 12. Dynamic increase factor vs strain rate

To quantify the strain rate effect of rubberized concrete, regression analysis was adopted for the experimental data as shown in Fig. 11. As can be seen from the figure, the slope of the fitted curves of rubberised concrete was higher than that of the reference concrete. Particularly, the slope of the fitted curves of Specimens RC15A and RC15B (about 0.01-0.012) was quite similar and higher than that of the reference specimen (0.005). When larger rubber aggregates were used in the mix (i.e. Specimen RC15C), the slope of the fitted curve (0.02) was considerably higher than other curves, which indicated higher strain rate sensitivity. The DIF of rubberised concrete can be estimated by using the following equations:

$$DIF_{RC15A} = 0.0102\dot{\varepsilon} + 0.5562 \text{ for } 62 \leq \dot{\varepsilon} \leq 128 \quad (6)$$

$$DIF_{RC15B} = 0.0123\dot{\varepsilon} + 0.3870 \text{ for } 65 \leq \dot{\varepsilon} \leq 138 \quad (7)$$

$$DIF_{RC15C} = 0.0204\dot{\varepsilon} - 0.1967 \text{ for } 60 \leq \dot{\varepsilon} \leq 127 \quad (8)$$

Concluding remarks

This study experimentally evaluates the effect of rubber aggregate size on the static and dynamic compressive behaviour of rubberised concrete by using SHPB tests. The rubber content was fixed at 15% by volume while the aggregate size was varied. The findings from this study can be summarized as follows:

1. The use of large rubber aggregates led to a reduction of the slump of rubberised concrete while its effect on the density was negligible.
2. Rubberised concrete with smaller rubber aggregates exhibited higher static compressive strength than the corresponding rubberised concrete with larger rubber aggregates.
3. Rubberised concrete with a large rubber aggregate size was more sensitive to strain rate than that of rubberised concrete with a smaller rubber aggregate size. However, the experimental results showed considerable variations at low strain rate.

In general, it can be concluded that rubberised concrete was more sensitive to strain rate than normal concrete. As compared to the larger rubber aggregates, the use of small rubber aggregates can achieve higher static compressive strength but lower dynamic increase factor.

Therefore, the use of either small or large rubber aggregate size depends on applications in which a structure is intended to resist static or dynamic loads.

Conflict of interests

The authors declare no conflict of interest.

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References

Tables

Table 1. Concrete mix design (kg/m^3)

Specimen	Fine rubber (%)	Coarse rubber (%)	Water (kg/ m^3)	Cement (kg/ m^3)	Aggregate ≤ 10mm (kg/ m^3)	Aggregate ≤ 5mm (kg/ m^3)	Sand (kg/ m^3)	Rubber 1- 3 mm (kg/ m^3)	Rubber 3-5 mm (kg/ m^3)
REF	0	0	213	426	750	130	843	0	0
RC15A	15	0	213	426	638	111	717	112	0
RC15B	7.5	7.5	213	426	638	111	717	56	56
RC15C	0	15	213	426	638	111	717	0	112

Table 2. Physical properties of crumb rubber [5, 37]

Mechanical Property	**Value**
Specific gravity (crumb Rubber)	0.54
Fineness modulus (crumb Rubber)	2.36 %
Water absorption % (crumb Rubber)	85 %
Young's modulus @100% (truck tire rubber)	1.97 MPa
Young's modulus @ 300% (truck tire rubber)	10 MPa
Young's modulus @ 500% (truck tire rubber)	22.36 MPa
Resilience @ 23 °C (truck tire rubber)	44 %
Resilience @ 75 °C (truck tire rubber)	55 %
Tensile strength (truck tire rubber)	28.1 MPa
Break point strain (truck tire rubber)	590 %

Table 3. Results of the slump tests for each concrete mix (measured in mm).

Specimen	Test 1	Test 2	Test 3	Average	Standard Deviation
REF	116	118	117	117	0.82
RC15A	108	107	105	107	1.25

RC15B	103	100	101	101	1.25
RC15C	99	95	98	97	1.70

Table 4. Quasi-static compressive strength of rubberised concrete.

ID	Test 1 (MPa)	Test 2 (MPa)	Test 3 (MPa)	Average (MPa)	Strength reduction (%)	Standard deviation
REF	39.1	36.3	37.8	37.7	-	1.4
RC15A	36.1	35.8	35.5	35.8	5	0.3
RC15B	33.0	32.3	31.6	32.3	15	0.7
RC15C	29.2	28.7	28.1	28.7	25	0.6

Table 5. DIF of compressive strength of rubberised concrete.

REF		CEB		RuC15A		RuC15B		RuC15C	
Strain rate	DIF	Strain rate	DIF	Strain rate	DIF	Strain rate	DIF	Strain rate	DIF
45 s^{-1}	1.22	45 s^{-1}	1.64	62 s^{-1}	1.28	65 s^{-1}	1.08	60 s^{-1}	1.00
100 s^{-1}	1.49	100 s^{-1}	2.14	78 s^{-1}	1.45	101 s^{-1}	1.80	104 s^{-1}	2.04
120 s^{-1}	1.38	120 s^{-1}	2.28	96 s^{-1}	1.28	111 s^{-1}	1.73	115 s^{-1}	2.11
128 s^{-1}	1.78	128 s^{-1}	2.33	102 s^{-1}	1.51	126 s^{-1}	2.07	120 s^{-1}	2.29
159 s^{-1}	1.78	159 s^{-1}	2.50	126 s^{-1}	1.87	138 s^{-1}	1.89	122 s^{-1}	2.22
161 s^{-1}	1.78	161 s^{-1}	2.51	128 s^{-1}	2.01	-	-	127 s^{-1}	2.36