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ORIGINAL ARTICLE

Anti-vibration characteristics of rubberised reinforced concrete beams

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Abstract The flexural and vibration properties were examined in order to evaluate the anti-vibration characteristics of rubber modified reinforced concrete beam. The rubberised mixtures were produced by replacing 5, 7.5, and 10 % by mass of the fine aggregate with 1–4 mm scrap truck tyre crumb rubber particles. A series of reinforced concrete beam (1,200 × 135 × 90 mm^3) was tested in a free vibration mode and then subsequently in a four point flexural tests. The input and output signals from vibration tests were utilised to calculate various dynamic parameters such as natural frequencies, frequency response function, dynamic modulus of elasticity and damping ratio. The results showed that compared to control mixture, gradual reductions of natural frequencies in first six modes of all rubberised beams with the highest being in the mixture with 10 % rubber contents. In addition, despite the reduction in overall strength, rubberised mixtures showed flexibility under loading due to the higher energy absorption capacity of rubber particles. Compared to control mixture, the results also showed a uniform global decrease in the dynamic modulus over the span. The reduction was found as high as 26 % in the mixture with 10 % rubber content. The results indicated that the rubberised concrete exhibits better anti-vibration properties and could be a viable alternative to use as vibration attenuation material where resistance to impact or blast is required such as in railway buffers, jersey barriers (a protective concrete barrier used as a highway divider and a means of preventing access to a prohibited area) and bunkers.

Keywords Rubber modified reinforced concrete beam · Frequency response function · Dynamic modulus · Damping ratio · Anti-vibration concrete

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1 Introduction

In the last two decades, utilisation of scrap tyres as a construction material, especially in concrete and asphalt mixtures, has gained significant popularity in the research community as an alternative use of waste material to consume a large quantity in a most environmental friendly way [1, 2, 4, 5, 11]. Despite signifcant amount of research, in reality, usage of waste tyres in civil engineering is currently low. This is because the addition of rubber aggregate in concrete or in asphalt mixtures exhibits a loss in strength. The common misconception that has held the application of this innovation back has been the traditional idea that the most important property of concrete is its compressive strength. This view needs to change to a design by function approach which will allow concrete incorporating rubber to be the preferred material over the applications stated above in projects across the world [15]. In 2001, Ei-Dieb et al. [5] reported that adding less than 10 % rubber by the replacement of coarse aggregate, does not hinders the performance of the concrete significantly, with reduction of strength may be only around 5–10 %. Eldin and Sanouci [4] also reported that although addition of rubber in concrete causes reduciton in strenght, the mixtures exhibits a ductile and plastic failure therefore the ability to absorb a large amount of plastic energy under compressive and tensile loads [3, 4]. There were noticeable effect caused by increasing the size and percentage of rubber aggregate. Similar findings were also reported by other researchers [7, 10, 12, 14, 16–19]. If the material is to be adopted widely, it is important to understand the material properties and how it would perform in its intended application.

Recent research [21] has demonstrated that rubberised concrete may provide a distinct advantage to absorb vibration and could possibly be used where vibration damping is needed, such as in foundation pad for rotating machinery and in railway stations; for trench filling and pipe bedding, pile heads, and paving slabs. In addition, it can also be used where resistance to impact or blast is required such as in railway buffers, jersey barriers (a protective concrete barrier used as a highway divider and a means of preventing access to a prohibited area) and bunkers. However, the study was conducted on mass concrete with as high as 45 % rubber in the mixture, compromising strength and durability significantly. If the quantity of rubber is kept within 10–15 % of the fine aggregate, the mixture may provide a distinct advantage to absorb vibration without compromising the strength significantly due to high energy absorption quality of rubber particles. In addition, as reinforcements are added in most of these above applications, the vibration properties of rubberised reinforced concrete structures would simulate field application better.

There is increasing acceptance that compared to other complementary localised static methods; the vibration technique can be an efficient non-destructive technique to measure the global response of a structural system from a relatively inexpensive easily deployable sensors. In essence, the global assessment includes dynamic characteristics of the structures such as natural frequencies, mode shapes, and modal damping. These responses are a function of spatial physical properties of the structure (mass, damping, and stiffness) and therefore, changes in physical

Table 1 Mixture composition

Elements	Control	5 % rubber	7.5 % rubber	10 % rubber
Coarse (kg)	21.25	21.25	21.25	21.25
Fine (kg)	14.1	13.35	13.04	12.69
Rubber (kg)	**0**	**0.75**	**1.06**	**1.41**
Cement (kg)	5	5	5	5
Water (L)	3.175	3.175	3.175	3.175

Bold values highlight the quantity of rubber

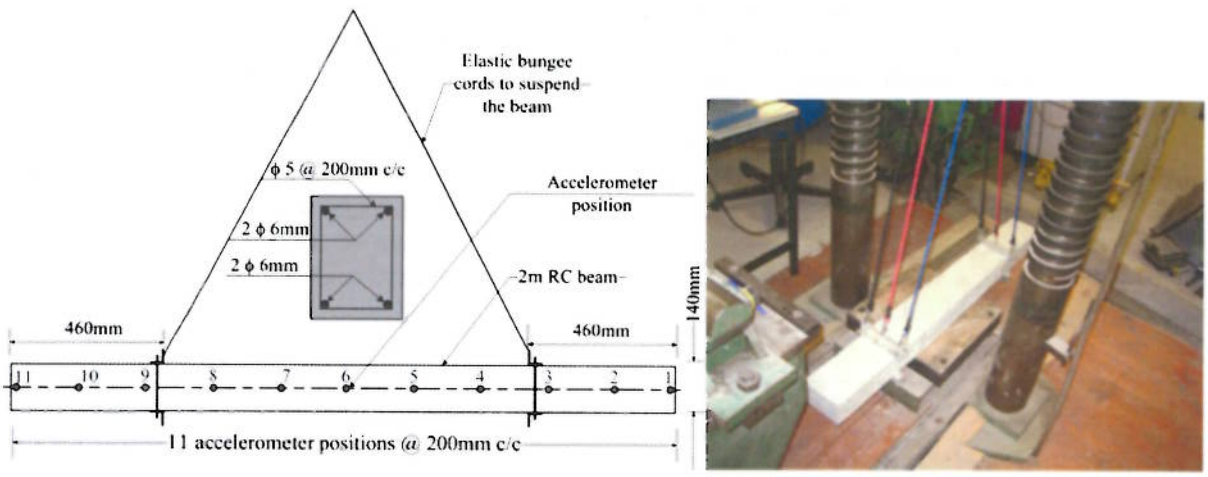

Fig. 1 Typical dimensions and free–free vibration test set-up

properties determined by geometry, distribution of mass, changes in stiffness, and boundary conditions will induce changes in its modal properties [9].

The primary objective of this research is to evaluate the changes in the dynamic properties of reinforced rubberised concrete beams under incremental loading. Results from a laboratory study on reinforced concrete mixtures containing 0 % (control), 5, 7.5, and 10 % rubber are presented in this paper. The proportion of the rubber content in the mixtures was kept at a level so that the strength and durability of the mixtures are not compromised adversely. The following section presents a brief overview on vibration testing in solids. Then the subsequent sections present the mixture design and experimental programmes followed by the results and discussions on the load deflection and dynamic parameters such as natural frequencies, frequency response function, dynamic modules and damping ratio at 0, 25, 50 and 70 % of the failure load. The final section summerises the major conclusions of this paper.

Fig. 2 Four point flexure test

2 Modal analysis

Modal analysis is a broad field with a plethora of tools and techniques. Hence it is not possible to reasonably summarize the research within the context of this paper. An interested reader is directed to review papers edited by Maia andSilva in this area of research [13]. In brief, after hitting a system, it will vibrate with the exact same frequency no matter how hard it is hit [20]. If a resonant mechanical structure is set in motion and left to its own devices, it will continue to oscillate

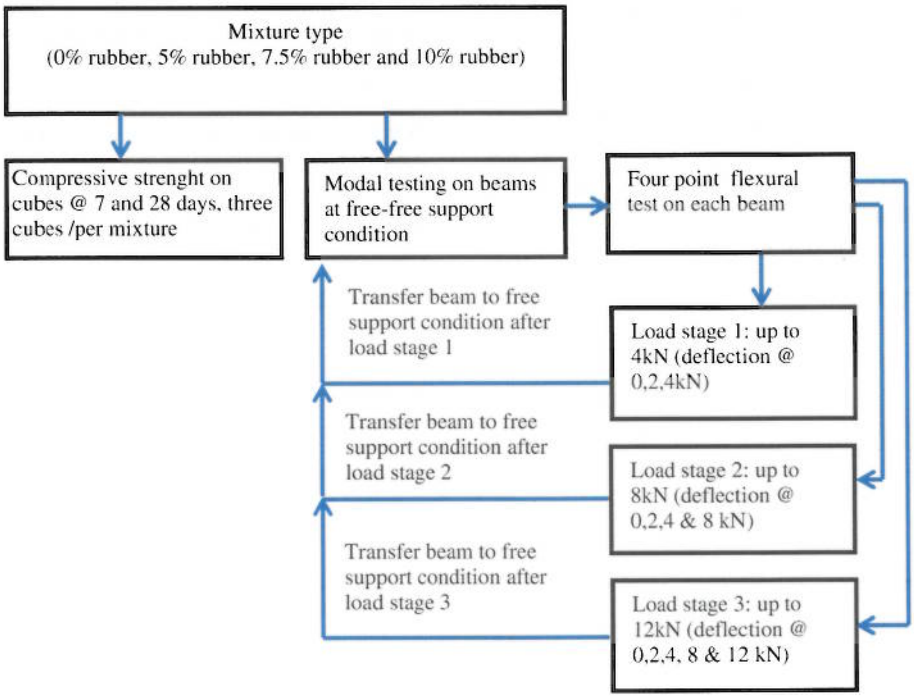

Fig. 3 Experimental sequence

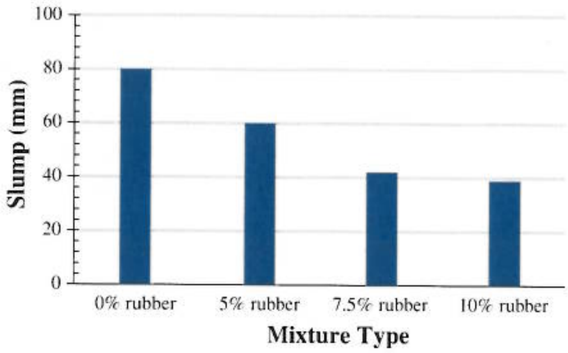

Fig. 4 Slump for control and rubberised mixtures

at a particular frequency known as natural frequency. The frequency with which the periodic force is applied is called the forced frequency. If the force frequency equals the natural frequency of a system, then the amplitude of the oscillations will grow further and this effect is known as resonance. A system may have several natural frequencies, and the ones with the strongest response are known as resonant frequencies. Hence by measuring these vibration features could be a key phenomenon for structural health monitoring, performance monitoring of mechanical and electrical system and damage detection.

The frequency response function (FRF) is the fundamental output in the experimental modal test. It is the input–output relationship of any system for localising and quantifying the amount of change in material properties or lose of strength at the successive loading [8]. The continuous FRFs give a complete illustration of the overall condition of the tested structure. The FRF can be formulated by taking the ratio of the output response to the input force, as shown in Eq. 1.

$$\mathrm{FRF} = X\,(\text{acceleration signal})/F\,(\text{force signal})$$

FRF is a transfer function expressed in the frequency domain. It is a particular tool for performing analysis and testing which can be formed from either analytical functions or measured data. The response may be in terms of acceleration, displacement, or velocity. The FRF can be expressed in terms of system properties such as mass, stiffness, and damping and as in most real structures, mass, stiffness, and damping are constant, it can be considered that FRF is constant. Therefore, any change in material properties will be reflected in FRFs. In addition, as the FRFs are experimental measurements, the method overcomes the difficulties associated with application of model-based methods at non-linear stages. At the same time, as the FRFs provide comprehensive response parameters, their engagement into damage identification will make the process robust and straightforward.

In general, during vibration, a real system dissipates energy in different mechanisms. Whilst this dissipative process is the simultaneous result of all those mechanisms and is difficult to identify, a viscous damping ratio is the simplest form to represent a dissipative mechanism [8, 13]. Damping occurs as a result of friction between moving objects, or interactions of moving objects with their surrounding environments such as rough surface, air, and fluids. The presence of damping causes the amplitude of free vibrations to delay, and leads to the reduction in amplitude of forced vibrations. In addition, the damping can be intentionally introduced to suppress resonant or extreme vibrations. When damping occurs, the amplitude of oscillations decreases with time and the higher the damping, the faster the oscillations will reduce in size. Critical damping is the damping required to make the oscillations stop at the quickest possible time without passing the equilibrium position.

Table 2 Slump of the fresh mixtures and compressive strength at 7 and 28 days

Mixture type with % rubber	Average mass of cube (kg)	Compressive strength (MPa)			
		7 days		28 days	
		Average	Std	Average	Std
0	2.34	18.17	0.31	28.87	0.50
5	2.26	16.30	0.87	24.60	1.10
7.5	2.24	15.73	0.31	23.43	0.90
10	2.20	13.87	0.29	21.40	0.56

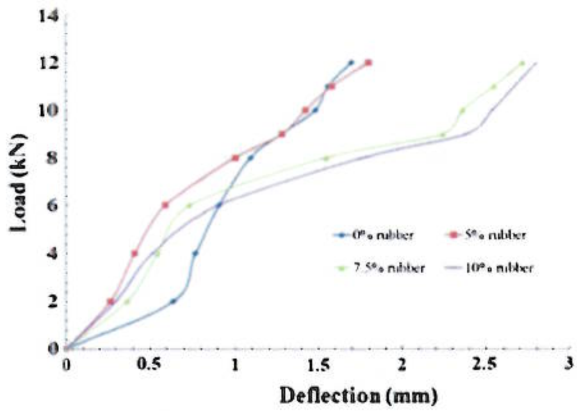

Fig. 5 The load deflection behaviour of different rubberised concrete mixtures

The natural frequencies obtained from the FRF can be utilised to calculate viscous damping (ζ) using the following formula;

$$\zeta = \frac{f_b - f_a}{2f_r}$$

where, f_r is resonant frequency, f_a and f_b is half power points derived from, $\frac{Y}{\sqrt{2}} = \frac{Y}{1.414}$, where Y is the peak of the natural frequency of all the modes. It is also known as half bandwidth.

3 Mixture design and experimentation

3.1 Specifications

Depending on the purpose, concrete with strength 20–40 MPa are typically used in the infrastructure applications and, therefore, to meet a target compressive strength of 20–25 MPa of rubberised concrete mixture, a mixture with a compressive strength of 30 MPa was selected, accepting that some reduction will take place due to the introduction of rubber particles. The results were then compared with control mixtures of 25 MPa in order to keep the strength as close as possible.

The coarse aggregate used in this study was crushed stone with maximum nominal size 20 mm. Prior to mixing rubber particles, a sieve analysis was conducted to separate material retains in 5 mm sieve. Once separated, 5, 7.5 and 10 % of the material was replaced by mass with 1–4 mm sized crumb rubber particles where 80 % of the rubber particles were between 2.36 and 4 mm. After mixing, each mixture went through a slump test to evaluate their consistently. The mixture composition is shown in Table 1.

3.2 Experimental sequences

For each mixture type, one beam (1,200 × 135 × 90 mm^3) and six cubes (100 × 100 × 100 mm^3) were produced. The reinforcement ratio was kept at an acceptable level of 1.3 %, and was placed in the tension zone with 25 mm clear cover. After 28 days, each beam was tested under a free–free support condition by applying the excitation on the minor axis, perpendicular to the direction of the suspension, as shown in Fig. 1. After completing free–free vibration tests, the specimen was then placed in a four point bending test set up (as shown in Fig. 2) to investigate the flexural and dynamic behaviour under loading. The four point bending test is suitable to get pure flexural behaviour at the zero shear region at the middle third span of the beam.

Figure 3 shows the experimental sequence at free–free and flexural test for each load step. The load was applied at 1 kN increment and corresponding mid-span vertical deflection was measured by a linear variable differential transducer (LVDT). When the loading reached at 4 kN, the beam was removed from the loading frame and was positioned again in a free–free support condition (as shown in Fig. 1) to measure the vibration properties at 4 kN, representing approximately 25 % of failure load. The test at free–free

Table 3 Maximum deflection at each load stage

Load		Maximum deflection (mm)			
Stage	Level (kN)	0 % rubber	5 % rubber	7.5 % rubber	10 % rubber
1st	0–4	0.42	0.55	0.46	0.45
2nd	4–8	0.31	0.45	0.45	0.74
3rd	8–12	0.59	0.65	0.62	0.52

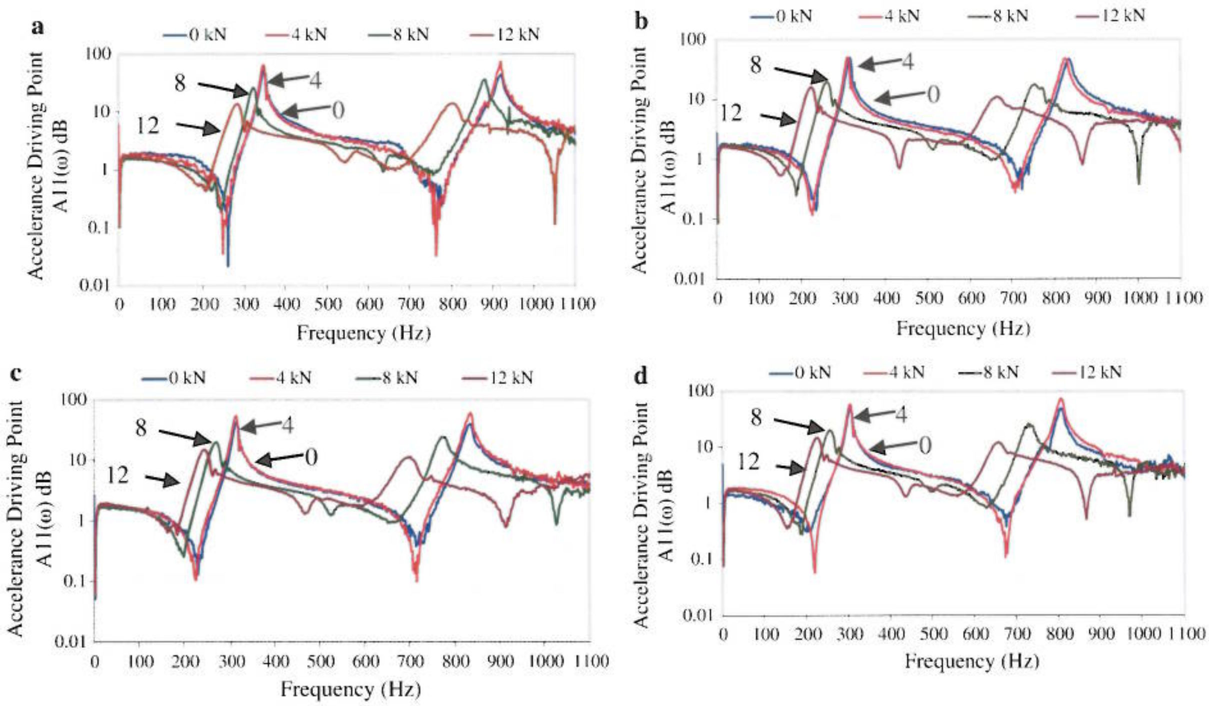

Fig. 6 **a** FRF for mixture with 0 % rubber. **b** FRF for mixture with 5 % rubber. **c** FRF for mixture with 7.5 % rubber. **d** FRF for mixture with 10 % rubber

Table 4 Natural frequencies of all specimens under different load cycles

Rubber content (%)	Natural frequency (Hz)	Load (kN)			
		0	4	8	12
0	f_1	349.6	349.6	321.6	285.7
	f_2	920.9	920.9	880.9	807.0
5	f_1	317.6	311.6	259.7	225.7
	f_2	835.0	827.0	757.1	669.2
7.5	f_1	313.6	313.6	267.7	243.7
	f_2	835.0	833.0	771.1	703.1
10	f_1	305.6	305.6	253.7	225.7
	f_2	807.0	807.0	735.1	659.2

condition was done to avoid the influence of the support on the vibration properties. A similar sequence of testing was followed after applying 8 and 12 kN, which represent approximately 50 and 70 % of a failure load respectively. The loading was stopped at 70 % failure load to avoid the possibility of shear plane failure. It should be noted that extra precaution

Table 5 The reduction of f_1 between last and first load cycle

f_1 (Hz)	Load stage (kN)				Reduction (%) [0–12 kN]		
Rubber (%)	0	4	8	12	0–4	0–8	0–12
0	349.6	349.6	321.6	285.7	0	8.0	18.3
5	317.6	311.6	259.7	225.7	1.9	18.2	28.9
7.5	313.6	313.6	267.7	243.7	0	14.6	22.3
10	305.6	305.6	253.7	225.7	0	17.0	26.1

Table 6 The reduction of f_2 between last and first load cycle

f_2 (Hz)	Load stage (kN)				Reduction (%) [0–12 kN]		
Rubber (%)	0	4	8	12	0–4	0–8	0–12
0	920.9	920.9	880.9	807.0	0.0	4.3	12.4
5	835.0	827.0	757.1	669.2	1.0	9.3	19.9
7.5	835.0	833.0	771.1	703.1	0.2	7.7	15.8
10	807.0	807.0	735.1	659.2	0.0	8.9	18.3

was taken to prevent any internal or external damage while moving the beam from one test set up to other.

4 Results

4.1 Consistency of fresh mixtures

Figure 4 shows that depending on the rubber content, the slump values decreases with increasing rubber contents. Although these results indicate moist type mixture with acceptable workability and homogeneity, the mixture becomes dryer with increasing rubber contents. Compared to the 80 mm slump in control mixtures, the value reduced to 25, 47 and 52 % mm for 5, 7.5 and 10 % rubberised mixtures respectively. This is because the jagged surface of the crumb rubber increases the friction between the particles, and hence reduces the flow.

4.2 Compressive strength

To determine batch consistency, the cubes were manufactured for each mixture and tested for compressive strength in accordance with BS EN 12390-3:2009 [2]. The compressive strength results, as shown in Table 2, are found consistent for each individual mixture with an acceptable batching tolerance. The average compressive strength, as expected, has decreased with increasing amount of rubber particles. Compared to control mixtures, the reduction of 28 days compressive strength was in an average 10, 13 and 24 % for mixture with 5, 7.5 and 10 % rubber contents respectively. The decrease in compressive strength is the influence of low density rubber particles in the mixtures, which can be seen as the reduction of the average weight of the mixture in Table 2.

4.3 Flexural behaviour

The four-point bending tests were undertaken in accordance to BS EN 12390-5:2009 [2]. The mid-span load deflection behaviour for each type of mixture is shown in Fig. 5 and the corresponding maximum deflection at each load cycle for different mixtures as well as maximum percentage increase at each load stage are presented in Table 3. As expected, the reduction in load bearing capacity was noted with increasing rubber content, although beam with 10 % rubber showed greater flexibility (better strain capacity) with a high number of cracks before failure. The incremental change in deflections (Table 3) demonstrates that at an early stage, pre-cracked region up to 4 kN load, the deflection is similar in all beams although in cracked regions (4–12 kN), rubberised mixtures exhibit more deflection under the same load, indicating better flexibility. This increase in flexibility could be due to greater energy absorption capacity of rubber particles.

4.4 Vibration properties

The purpose of modal testing is to identify the natural frequencies, damping ratio, and the mode shapes of a

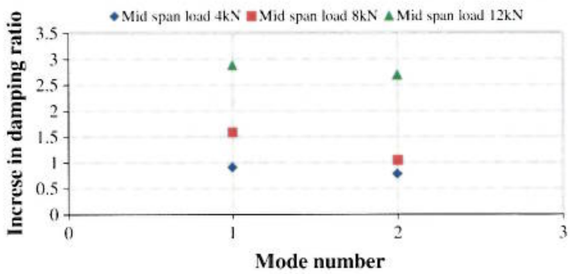

Fig. 7 Increase in damping with loading

Table 7 Damping ratio

Mixture (%)	Damping ratio							
	First mode (f_1)				Second mode (f_2)			
	0 kN	4 kN	8 kN	12 kN	0 kN	4 kN	8 kN	12 kN
0	0.0157	0.0143	0.025	0.0453	0.0095	0.0074	0.0100	0.0256
5	0.0095	0.0074	0.0100	0.0256	0.0176	0.0160	0.0385	0.0439
7.5	0.0176	0.0160	0.0385	0.0439	0.0101	0.0097	0.0254	0.0353
10	0.0101	0.0097	0.0254	0.0353	0.0177	0.0210	0.0355	0.0445

structure. The FRF for all four mixtures at four load stages, 0, 4, 8 and 12 kN, are shown in graphically in Figs. 6a–d and in tabular form in Table 4. Due to the extensive amount of data, the first two modes (f_1 and f_2) of FRF are presented. The first two modes are the most dominant mode of response in concrete structures.

It can be seen that, with increasing load, the FRF in the first two modes decreases in all mixtures indicating changes in vibration properties with load. Compared to control, the reduction is greater in the rubber modified mixtures with maximum reduction being in mixture with 10 % rubber contents. This indicates that the vibration properties changes with increasing rubber contents.

The reduction of the frequencies as presented in Tables 5 and 6 indicate that, at the initial stage of loading, only little or no change happens in all four mixtures. However, the reduction is significantly higher as the load approached the 50 % (8 kN) to 80 % (12 kN) of the failure load. The total reduction of frequencies from the 0–12 kN load for control mixtures was approximately 18 % in the first mode (f_1) and 12 % in the second mode (f_2). On the other hand, the reduction in the rubber modified mixtures was 22–28 % in first mode and 15–20 % in the second mode.

In terms of rubber content, the reduction, depending on the amount of rubber in the mixtures, is approximately 7–11 %. This is indicative that rubber modified mixtures exhibit higher vibration absorption properties than conventional reinforced concrete. It should also be noted that no significant extra benefit achieved with increasing rubber content from 5 to 10 %.

4.5 Damping ratio

The viscous damping ratio for different mixtures in the first two modes is shown in Table 7. It can be seen that the rate of damping increases with load and the rate is higher for mixture with 10 % rubber. It is interesting to note that the dampening effects on other mixtures are similar especially at failure load. A similar response can be seen in the second mode, although the value of damping ratio is very low. This finding mainly correlated with the FRF findings that as the frequency decreases, the damping increases.

The increase in the damping ratio at 4, 8 and 12 kN load stage for 10 % CRM mixtures at first two modes was also analysed and is presented in Fig. 7. As expected, the damping ratio increases almost three times with increasing load indicating progressing dampening of the beam, where the changes are significantly higher at third load stage 8–12 kN as the beam approaches to failure.

5 Conclusions

To address certain flexural and vibrational advantages of reinforced rubberised concrete, the results form a laboratory study is presented in this paper. Instead of using rubberised mass concrete, the study of reinforced rubberised concrete simulates field condition better. The major contributions of this paper are summarized below:

- The addition of 1–4 mm size rubber particles by replacing 5–10 % of fine aggregate reduces workability of the fresh mixtures of approximately 25, 47 and 52 % mm for 5, 7.5 and 10 % rubberised mixtures respectively. Although the mixture becomes dryer with increasing rubber contents, the rubberised mixtures showed acceptable workability and homogeneity.
- Whilst the addition of low density rubber particles decreases compressive strength, the rubberised mixtures exhibits a ductile and plastic failure which indicates the ability to absorb a large amount of plastic energy under loading.
- The reduction in natural frequencies, depending on the amount of rubber in the mixtures, was approximately 7–11 %.
- A reduction in natural frequencies at all load stages and increased dampening (higher vibration absorption) with increasing rubber contents without compromising strength significantly, indicates that if the durability issues are tackled appropriately, the rubberised concrete would have a high potential to be used where vibration damping is desirable.

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