DAMPING PROPERTIES OF CONCRETE WITH SAND COATED RUBBER AGGREGATES

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ABSTRACT

Waste tire rubber disposal causes major environmental problems and serious threats to human health. A viable solution for reducing waste tire rubber is to reuse the material in concrete production. Since ordinary concrete is brittle, and has low energy absorption capacity, elastic rubber could possibly improve the damping behavior of concrete. In this study, the mechanical and dynamic properties of concrete with partial replacement of coarse aggregate by rubber and epoxy-sand coated rubber at different volume fractions ranging from 5 to 25% were investigated. Test results indicate that uncoated rubber chips in concrete cause a significant reduction in strength. However, epoxy-sand coated rubber aggregate partial replacement improved the interfacial properties of the rubber. Accordingly, an optimum compressive strength was achieved with 15% epoxy-sand coated rubber aggregate replacement. Furthermore, the maximum increment in damping ratios for uncoated and sand-coated rubber aggregates were found to be 58% and 23%, respectively as compared to normal concrete. Hence, the utilization of epoxy sand coated rubber presents a promising approach to enhance the dynamic performance of concrete structures, without affecting their mechanical properties.

Key words: waste tire; epoxy, sand coated rubber ; damping ratio; dynamic properties

1. INTRODUCTION

According to several studies, about 1.0 to 1.5 billion waste tires are discarded each year globally [1-3]. Scrap tires represent about 12% of all solid waste material [4]. Their disposal is thus a serious ecological and environmental problem; so, it should be addressed by intensified recycling and reuse, which can create a sustainable environment and help to reduce landfill.

In Ethiopia, the amount of waste tire is increasing every year. Horizon Addis Tyre Factory has the capacity to manufacture around 850,000 tires a year [5]. According to the factory market demand prediction, Ethiopia's annual tire demand is estimated around 1.6 million pieces [6]. An estimated amount of at least one million waste tire is discarded every three years, resulting approximately in ten thousand tons of waste tire annually [7, 8].

In earthquake prone areas, the use of concrete with good damping properties is necessary. Hence, a potential elastic material which has good abilities to dissipate impact energy is waste tire rubber.

Several researchers have used waste tire rubber as chipped (to replace the gravel), crumb (replaces sand) and ground rubber (filler) for the production of so-called "rubberized" concrete [8-10]. The rubber material is characterized of low unit weight, high dynamic modulus and damping, low thermal conductivity and very low water absorption rate. It is a non-biodegradable material [11].

Studies mainly indicate that the utilization of waste tire as coarse aggregate in concrete reduces the compressive, tensile and flexural strength of the modified concretes [12-16]. One of the main causes was adhesion failure between the surface of the rubber and the hardened cement paste [17-20]. Moreover, the partial replacement of fine aggregate by rubber was found to strongly decrease compressive and flexural strength of concrete [20].

A weakening effect was also found with regard to the modulus of elasticity of concrete [21-23]. For instance, in the case of 5% to 10% replacement of coarse aggregate by chipping rubber, a reduction in modulus of elasticity from 17% to 25% was observed [9]. Similar trends were seen in concrete with rubber powder as partial replacement for fine aggregate [16].

The compressive strength of concrete decreases as the percentage replacement of coarse aggregates with shredded rubber increases. The flexural strength increases when the contents of shredded rubber increase. Moreover, the modulus of elasticity of concrete decreases with the increase in percentage replacement of shredded rubber aggregates [24, 25].

However, it was also reported occasionally, that the use of shredded rubber [21, 22] or powdered rubber [10] led to an increase in strength.

Test samples show a relatively higher strain as the percentage of crumb rubber aggregates increases [26, 27].

Previous studies have led to different conclusions on the mechanical properties of rubberized concrete and there is no clear margin on the use of waste rubber as a replacement of coarse aggregate [21].

The effect of rubber incorporation on the dynamic properties of concrete has been often of special interest, as a favorable behavior with regard to dynamic loads could be achieved by the elastic material. Of particular importance is the ability of rubberized concrete to dissipate impact energy. It was found, that the dynamic modulus of rubberized concrete is lower than that of plain concrete. Moreover, it has been observed that with the increase of rubber content, the damping ratio increased accordingly [27].

The viscous damping ratio was investigated previously [28] using free vibration tests with impact hammer on simply supported beams and drop weight tests. The replacement of up to 20% of sand with rubber resulted in an increase in damping. Beyond 20%, the effect on damping was insignificant. It was concluded that the choice of the rubber content and the mixing process can have a significant effect on the dynamic properties of rubberized concrete. Partial replacement of fine aggregate with rubber powder was also found to improve the damping properties of concrete [16].

As the weak bond between the rubber and the hardened cement paste was identified as the cause for the impaired mechanical properties of rubberized concrete, the improvement of the bond might be beneficial for the properties of such concretes.

Several researchers have investigated different treatments to increase the adhesion of the tire rubber waste aggregate. Surface modification of crumb rubber by nonionic surfactant (NaOH) was used to achieve more hydrophilic behavior of the rubber surface. Thus, the interfacial bond between rubber and hardened cement paste was improved [29]. Various other surface treatments of the rubber are reported in literature to improve the interfacial bond, such as soaking in water [30], use of solvents [31], application of oxidizing solutions [32], treatment with alkaline activation and silica fume [33].

As results from previous studies have shown, surface modification of coarse aggregates by silicon, epoxy and sand have the potential to improve the mechanical and dynamic properties of concrete [34].

This study investigated the effect of rubber on mechanical and dynamic properties of concrete, especially on its damping behavior.

Moreover, as the bond between the rubber and the concrete matrix is weak, a novel coating approach with epoxy and sand was investigated in order to improve the interfacial properties of the rubber.

2. MATERIALS AND METHODS

2.1. Materials

The concrete used in this study consisted of OPC 42.5 grade cement, river sand and crushed stone with a maximum size of 25mm. Chipped rubber with specific gravity of 1.16 and particle sizes in the range of 20-25 mm were used for the replacement of coarse aggregates. Sika 161- epoxy resin and hardener were obtained from Sika Abyssinia Chemicals Manufacturing PLC.

The physical properties of standard sand, fine and coarse aggregates that were used in the study are presented in Table 1 and the properties of epoxy resin are summarized in Table 2.

The gradation requirements of natural sand and coarse aggregate were checked and both satisfied the requirement set on AASHTO No. T 27 [36] and ASTM C 136 [37] standards.

Table 1 Physical properties of standard sand, natural sand and coarse aggregates

Material Properties	Standard sand	Sand	Coarse aggregate
Specific gravity	2.62	2.51	2.71
Moisture content %	< 0.2	2.41	1.3
Water absorption %	0.79	2.04	1.02

Table 2 Properties of Sika -161 Epoxy resin [35]

Material Properties	Value	Standards
Density	~1600 kg/m^{3}at +23 °C	DIN EN ISO 2811-1
Shore D Hardness	~76 (7 days / +23 °C)	DIN 53 505
Tensile Adhesion Strength	> 1.5 N/mm² (failure in concrete)	ISO 4624
Compressive Strength	> 45 N/mm² (mortar screed, 28 days / +23 °C / 50 % r.h.)	EN 13892-2
Tensile Strength in Flexure	~15 N/mm² (mortar screed, 28 days / +23 °C / 50 % r.h.)	EN 13892-2

2.2. Methods

2.2.1. Sample preparation

Chipped rubber for replacement of coarse aggregates in normal concrete was prepared by cutting waste tire rubber into small chips. Chipped rubber used in this study is shown in Figure 1.

Figure 1 Chipped rubber samples

To enhance the adhesion of rubber to the concrete mixture, Sika-161 epoxy resin in combination with standard sand 0.75-2.0 mmwas used for coating rubber aggregates. The mix ratio (epoxy resin: hardener) of coating materials was 1:0.265. Figure 2 shows epoxy and sand coated rubber samples.

In the process of coating the rubber surface, the rubber particles were appropriately cleaned and epoxy resin wasapplied using hand coating (manual method). After 45-60 min, the epoxy coated rubber was blended with standard sand. The sand coated rubber was dried for three days at room temperature.

2.2.2. Mix design

The mix proportion of cement, sand and coarse aggregate was 1:1.5:2.5. The water-cement ratio was of 0.45. In developing concrete mixes, all mix design parameters (fine aggregate, cement content, w/c ratio) were kept constant except for the coarse aggregate constituents. Mixture composition of the constituent material for different replacement levels of coarse aggregate is shown in Table 3.

Table 3 Mix proportions of concrete with different replacement level

Material quantity (kg)	Replacement Level (%)					
	0	5	10	15	20	25
Cement	16.6	16.6	16.6	16.6	16.6	16.6
Sand	27.7	27.7	27.7	27.7	27.7	27.7
Gravel	42.7	40.5	38.4	36.3	34.2	31.9
Rubber/ Sand coated	0.0	2.2	4.3	6.4	8.5	10.8

(a) (b)

Figure 2(a) Epoxy coated rubber and (b) Sand coated rubber samples

Concrete mixtures with replacement of a maximum 25 % coarse aggregate by chipped rubber particles (uncoated or coated) with an increment of 5% were considered. The control mix was designated as CM-0, concrete with rubber as RA-n, with sand coated rubber as SCRA-n. The letter n indicates the replacement level (e.g., SCRA-10 represents concrete with 10% replacement of coarse aggregate by sand coated rubber).

2.2.3. Experimental Setups

i) Mechanical Properties

The measured mechanical properties of concrete, included compressive strength, split tensile and flexural strengths. Tests were carried out at 28 days aged concrete specimens and testing procedures were in accordance with EN Standards. Standards, specimen dimensions for different types of concrete tests are shown in Table 4.

The flexural strength test was carried out by a three-point loading test.

ii) Determination of damping ratio

Damping was utilized to characterize the ability of structures or subsoil to dissipate energy during dynamic response. Damping values depend on several factors, such as: vibration amplitude, material, mode shape, fundamental periods of vibration, etc. [41]. Damping ratio is the parameter representing the property of materials in vibration reduction. Damping properties are expressed by the damping ratio (ξ) which can be identified by analyzing the wave using the logarithmic decrement method [42, 43].

Table 4 Standards, specimen dimensions for different types of concrete tests

No.	Test	Standards	Specimen dimensions
1	Compressive strength	EN 12390-4: 2019 [38]	Cube (150 mm)
2	Split tensile strength	EN 12390-6:2009 [39]	Cylinder (300 mm in length and 150 mm in diameter)
3	Flexural strength	EN 12390-5:2009 [40]	Prismatic beam (100 × 100 × 500 mm)

To determine the damping ratios of the beam, free vibration was generated by dropping a steel ball (2.0 kg) from a height of 450 mm on a 100 mm × 100 mm × 500 mm cantilever beam specimen.

The accelerometer (Arduino type, MPU-6050) was set on the free end of the specimen to measure the vibration response. The position of the accelerometer sensor was set at 20 mm from the free end and the free length of the cantilever is 400 mm. Test setups are shown in Figures 3 and 4.

The Arduino UNO board was connected to a computer via Arduino software to record the acceleration amplitudes for the impact tests and then transformed to the frequency domain through Fast Fourier Transform (FFT) using MATLAB code.

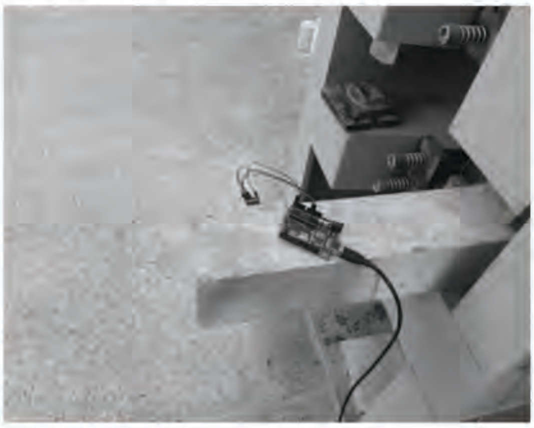

Figure 3 Arduino type accelerometer

Figure 4 Test setup for measuring the acceleration of a concrete beam specimen

Damping ratio was determined by using the free vibration decay method of calculating a logarithmic decrement (δ), which is the simplest and most frequently used method through experimental measurements. The system was excited by performing free oscillations and subsequently, the peak amplitudes over *n* consecutive cycles were measured [44].

The logarithmic decrement is the natural logarithm of the peak amplitude ratio over *n* consecutive cycles, that represents damping characteristics and can be determined using the following Eq. (1) [44].

$$\delta_n = \ln\left(\frac{u_i}{u_{i+n}}\right) \quad (1)$$

where:

u_i and u_{i+n} are peak amplitudes over *n* consecutive cycles.

The damping ratio can be calculated from logarithmic decrement using Eq. (2),

$$\xi = \frac{\delta_n}{\sqrt{4\pi^2 n^2 + \delta_n^2}} \quad (2)$$

where:

ξ is a damping ratio (%),

δ_n is logarithmic decrement

Alternatively, the acceleration amplitudes were recorded for the impact weight tests and the values of the damping ratio were calculated using Eq. (3) [16, 43].

$$\xi = \frac{1}{2n\pi}\ln\left(\frac{A_o}{A_n}\right) \quad (3)$$

where:

A_o is an initial amplitude

A is the amplitude after *n* cycles

3. RESULTS AND DISCUSSIONS

3.1. Mechanical Properties

The mechanical properties of concrete with partial replacement of coarse aggregates by chipped rubber and sand coated rubber, including compressive strength, split tensile and flexural strengths are discussed in the following subsections. The results represent the average values of three individual specimens.

3.1.1. *Compressive strength of concrete*

Figure 5 shows the compression strength of concrete for different concrete mixes. The loading rate was 0.28 MPa/sec.

As shown in Figure 5, for the reference mix, a compressive strength of 45.1 MPa was achieved. The concrete could thus be assigned to strength class C30/37. For 5% replacement of coarse aggregate by rubber chips, the compressive strength of concrete was increased, but a further increase beyond this level caused a reduction in compressive strength. Hence, the optimum compressive strengths were found to be 50.3 MPa (SCRA-15) and 47.0 MPa (RA-5). These results indicated an increase in compressive strength of 12.5% and 4.1%, respectively, as compared to the control mix.

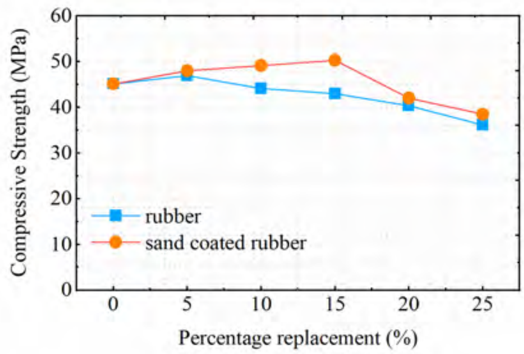

Figure 5 Compressive strength (MPa)

Concrete with sand coated rubber aggregates gained a higher compressive strength than the uncoated rubber aggregates. This positive effect of epoxy-sand coating is due to the improvement of bond between the rubber surface and the cementitious matrix.

3.1.2. *Tensile and Flexural strengths*

Test results related to split tensile and flexural strengths are plotted in Figures 6 and 7 respectively.

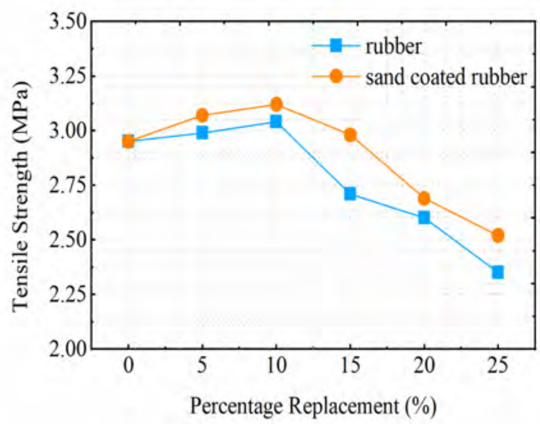

Figure 6 Split tensile strength

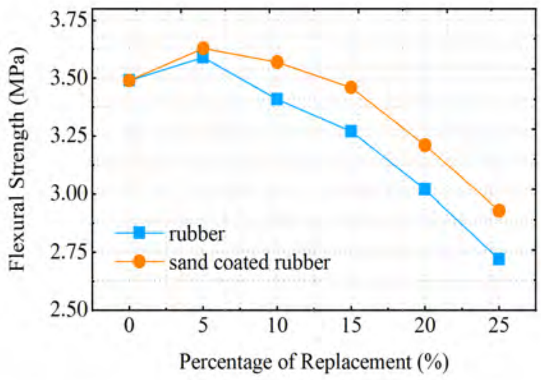

Figure 7 Flexural strength

Figures 6 and 7 show that, for the control mix, split tensile and flexural strengths of 2.9 MPa and 3.5 MPa were achieved, respectively. Moreover, the split tensile strength reached its maximum value at 10% replacement by both rubber and sand coated rubber aggregates. But, beyond the optimum level, reduction in split tensile strength was observed.

For both concrete with rubber and sand coated rubber aggregates, a maximum value of flexural strength was observed at a replacement level of 5%.

3.1.3. Damping ratio

An impact test was conducted to determine the damping ratio of concrete specimens based on free vibration responses. Examples of acceleration time history response are shown in Figures 8-10.

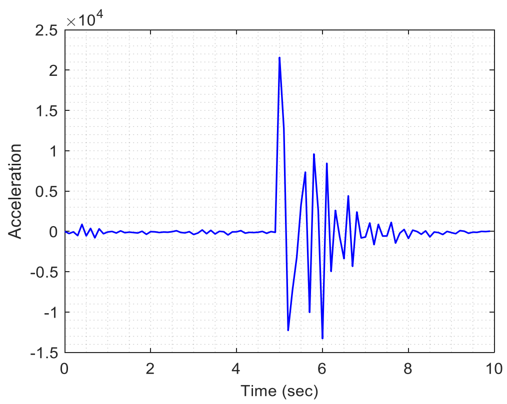

Figure 8 Acceleration time history - CM-0

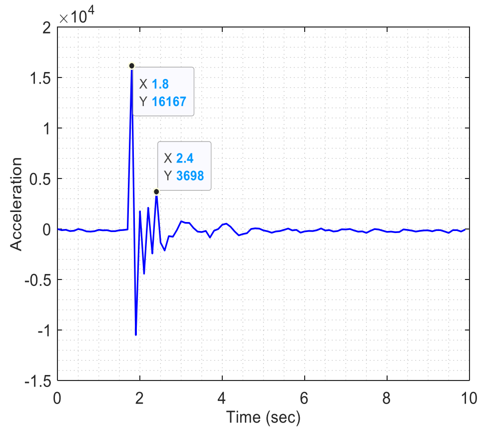

Figure 9 Acceleration time history - RA-25

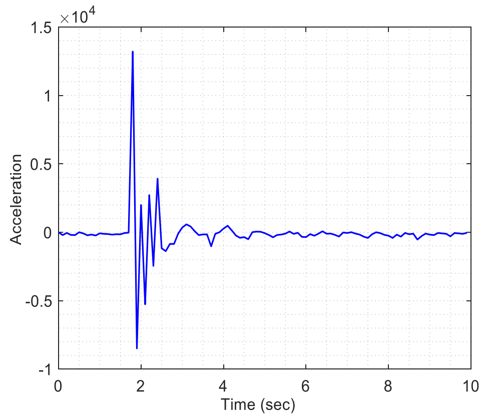

Figure 10 Acceleration time history - SCRA-20

The first and the fourth amplitudes of the vibration response are used to determine the logarithmic decrement and damping ratio. The logarithmic decrement and the damping ratio could be calculated using Eqs. (1) and (3), respectively, and the results are presented in Table 5. Moreover, the damping ratio for concrete with different replacement level of uncoated rubber and sand coated rubber aggregates is shown in Figure 11. From the figure, it can be observed that, the damping ratio increases with increasing percentage of chipped tire rubber content. It was also observed that, the damping ratio increases with an increase in percentage of sand coated rubber aggregates reaches up to 20%. As the percentage of sand coated rubber content increases from 20% to 25%, the damping ratio started to decline. However, the value was higher than that of the control mix, which is an increment of 23%.

Table 5 Damping ratio of concrete with rubber and sand coated rubber aggregates

Mix	acceleration amplitudes		acceleration amplitudes in G - forces (g)		δ_n	Damping ratio (%)
	y_1	y_4	y_1	y_4		
CM-0	21569	8442	1.316	0.515	0.938	4.95
RA-5	14636	5139	0.893	0.314	1.047	5.54
RA -10	11478	3801	0.701	0.232	1.105	5.86
RA -15	16822	4717	1.027	0.288	1.272	6.73
RA -20	15171	3895	0.926	0.238	1.360	7.20
RA -25	16167	3698	0.987	0.226	1.475	7.81
SCRA -5	13808	5093	0.843	0.311	0.997	5.27
SCRA -10	12707	4527	0.776	0.276	1.032	5.47
SCRA -15	12643	3998	0.772	0.244	1.151	6.10
SCRA -20	13207	3917	0.806	0.239	1.215	6.44
SCRA -25	12462	3961	0.761	0.242	1.146	6.09

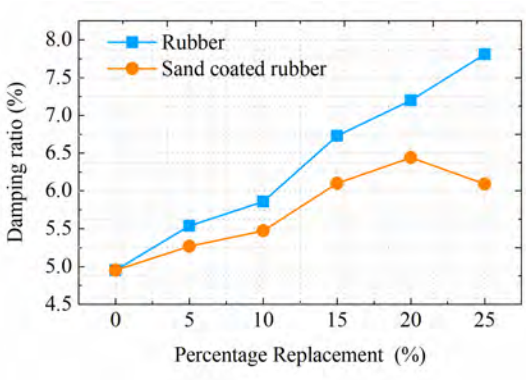

Figure 11 Damping ratio of rubber and sand coated rubber aggregates

3.2. Comparative Study

In this section, test results of this study are compared with previous studies. The comparisons are summarized in Tables 6-8. These comparisons consider only results of compressive strength, flexural strength and damping ratio of concrete with partial replacement of coarse aggregates by uncoated rubber chips.

As shown in Table 6, a study by Sofi, A. [14], showed that the compressive strength of concrete increased by 4.69% when 5% rubber chips were used. Beyond this level, the strength decreased. The trend of the results is similar to our study. However, the results by Vijayan, D. S., kumar, et al. [25] showed that the presence of rubber contents in concrete mixes has a negative effect and there is a very considerable loss in compressive strength is observed.

On the other hand, according to Sibiyone, K. Paul, and M. Lenin Sundar [21] and study by Paparao, A., et al. [22], test results of compressive and flexural strengths increased with increasing percentage of rubber content in concrete ranging from 0% to 40%.

Moreover, the study by Vijayan, D. S., et al. [25], shown in Table 7 indicates, an increment of 2.08% in flexural strength was observed when 5% rubber is used and gradual decrement in flexural strength was noticed as the percentage of rubber increased. The trend of the results is similar to that of this study.

From Table 8, the study by Ching Y., George C. et. al., [16], L. Zheng, X. Sharon, et. al. [27] and Maru Sete [8], indicated that the damping ratio increases as the rubber content in concrete mix increases. However, the increment is much higher than the results of this study.

In general, except for those studies reported by Sibiyone, K. Paul, [21] and Paparao, A., et al., [22], this study showed similar trends (strength reduction, improvement in damping ratio) to previous studies when the natural coarse aggregates were partially replaced by rubber chips. However, the findings of this study are different from other similar studies conducted [21, 22] due to the following reasons; i) Sibiyone, K. Paul, [21] used admixtures for concrete mix design as well as scrap rubber with a size of less than 10 mm in their studies, ii) in the case of a study conducted by Paparao, A., M. Aruntej, [22] scrap rubber with a size of 10-12 mm was used.

Table 6 Comparison of compressive strength

Replacement level (%)	Sofi, A. [14]		Vijayan, D. S., Kumar, et al. [25]		Sibiyone, K. Paul, and M. L. Sundar [21]		Paparao, A., et al. [22]		This study	
	Compressive strength (MPa)	Increment (%)	Compressive strength (MPa)	Increment (%)	Compressive strength (MPa)	Increment (%)	Compressive strength (MPa)	Increment (%)	Compressive strength (MPa)	Increment (%)
0	32.00	-	37.11	-	24.90	-	25.00	-	45.12	-
5	33.50	4.69	32.53	-12.34	27.50	10.44	27.20	8.80	46.95	4.06
10	25.00	-21.88	28.93	-22.04	29.33	17.79	29.30	17.20	44.15	-2.15
15			21.05	-43.27	29.20	17.27	26.60	6.40	42.98	-4.74
20			16.87	-54.54	28.89	16.02	28.89	15.56	40.38	-10.51
25					28.50	14.46	25.33	1.32	36.09	-20.01

Table 7 Comparison of flexural strength

Replacement level (%)	Sofi, A. [14]		Vijayan, D. S., kumar, et al. [25]		Sibiyone, K. Paul, and M. L. Sundar [21]		Paparao, A., et al. [22]		This study	
	Flexural strength (MPa)	Increment (%)	Flexural strength (MPa)	Increment (%)	Flexural strength (MPa)	Increment (%)	Flexural strength (MPa)	Increment (%)	Flexural strength (MPa)	Increment (%)
0	5.25		11.75	-	3.10	-	3.20	-	3.49	-
5	5.20	-0.95	12.04	2.08	3.53	13.87	3.50	9.37	3.59	2.87
10	3.30	-37.11	11.50	-2.13	3.80	22.58	3.90	21.88	3.41	-2.29
15			8.25	-29.79	3.71	19.35	3.62	13.13	3.27	-6.30
20			6.50	-44.68	3.50	12.90	3.40	6.25	3.02	-13.47
25					3.45	11.29	3.30	3.13	2.72	-22.06

Table 8 Comparison of damping ratio

Replacement level (%)	Ching Y., George C., et. al. [16]		L. Zheng, X. Sharon Huo, et. al. [27]		Maru Sete [8]		This study	
	Damping Ratio(%)	Increment (%)	Damping Ratio(%)	Increment (%)	Damping Ratio(%)	Increment (%)	Damping Ratio(%)	Increment (%)
0	1.0	-	0.74	-	6.93	-	4.95	-
5	1.25	25	0.98	32.43	8.34	20.35	5.54	11.92
10			1.19	60.81	8.16	17.75	5.86	18.38
15			1.38	86.49	16.17	133.33	6.73	35.96
20					16.52	138.38	7.20	45.45
25					22.83	229.44	7.81	57.78

4. CONCLUSIONS

In this study, the mechanical properties and damping capacity of concrete with various percentage replacement of coarse aggregates by rubber and epoxy-sand coated rubber up to 25%, were studied. The results revealed that when 5% uncoated rubber and 15% epoxy-sand coated rubber aggregates were used, the compressive strength of concrete was optimal. Beyond the optimum replacement levels, reductions in compressive, splitting tensile and flexural strength were noticed as compared to the reference mix.

The partial replacement of coarse aggregates with rubber and epoxy-sand coated rubber improves the damping ratio of concrete. A maximum of 58% increase in damping ratio was reached for the uncoated rubber, while a 23% increase was reached for epoxy-sand coated rubber aggregates. The epoxy-sand coating thus can mitigate the negative effect of the rubber on the mechanical properties to some extent. Epoxy and sand can be used to coat the rubber in order to enhance the bonding between the rubber surface and the mortar. Partially replacing the natural aggregate by rubber and epoxy-sand coated rubber chips can improve the energy dissipation (damping ratio) of concrete.

Waste tire rubber can be used as an alternative source of construction material to partially replace the natural coarse aggregate in concrete. Therefore, it is recommended to partially replace the natural aggregate by rubber and epoxy-sand coated rubber chips.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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