Crumb Rubber Recycling in Enhancing Damping Properties of Concrete

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Abstract. Damping plays a major role in the design of roadside structures that gets affected due to vibrations transmitted from moving traffic. In this study, fine aggregates were partially replaced with crumb rubber in concrete, at varying percentages of 5, 10, 15 and 20\% by weight. Three different sets of concrete, mixed with crumb rubber were prepared using raw rubber, treated rubber and treated rubber with partial replacement of cement. Cement was partially replaced with Ultra-Fine Ground Granulated Blast furnace Slag (UFGGBS) for this study. Samples were cast, cured and tested for various properties on the 7\textsuperscript{th} and 28\textsuperscript{th} day. The damping ratio and frequency of the peak value from a number of waves in rubber incorporated beams were found out using a FFT Analyser along with its Strength, Damping and Sorptivity characteristics. SEM analysis was conducted to analyse the micro structural bonding between rubber and concrete. The mode shapes of pavement slabs were modelled and analysed using a FEM tool, ANSYS. From the results, the behaviour of the three sets of rubberized concrete were compared and analysed, and an optimum percentage for crumb rubber and UFGGBS was proposed to achieve best possible damping without compromising the strength properties.

1. Introduction
Infrastructure impels the growth of developing countries by the construction of buildings, dams, power plants, transportation facilities etc., leading to an increase in the consumption and demand of natural materials. Hence, alternate sources of construction materials are required to reduce the demand for raw materials and to conserve the environment. The increased usage of automobiles in recent times has caused an exponential increase in the production of scrap rubber tyres. Globally, about 13.5 million tons of scrap tyres are produced every year of which nearly 40\% is from emerging markets like China, India, South America, Southeast Asia and South Africa; with India contribution nearly 1 million tons. The automobile tyres are dumped in landfills or burnt when they become unusable due to wear and tear. Dumping pollutes the ground due to leaching of toxins, whereas burning leads to air pollution. Rubber is well-known to dampen vibrations when exposed to sudden impact. Hence, to overcome the stress on the environment and to improve the longevity of structures, the scrap tyres can be broken, chopped into pieces, cleaned and then used as a replacement for aggregate [1,2].

India, being a highly populated country, has many structures adjacent to roadways. When heavy vehicles move on a road, ground vibrations in the form of waves are induced. These waves pass through...
the underlying soil strata and affect the structures as well as underground structures (like drainage, pipelines, tunnels, etc.) near the road [3,4,5]. These induced vibrations cause discomfort and might weaken the nearby structure, cater for foundation settlements and cause structural damages in the long run. Many previous studies have analysed the performance of rubberized pavements and the results showed that the scrap tyres used in pavements decreases the vibration characteristics, control the detrimental effects to the environment and reduces the usage of natural materials [6,7,8,9,10].

On the contrary, it was also found that increasing the rubber content decreases the strength of concrete [11,12,13]. Other studies on the properties of rubberized concrete observed that with increase in rubber content - the damping ratio reduced [8]; dynamic modulus of elasticity decreased and flexibility increased [2,9,14,15]; strength properties decreased with increase in water cement ratio [16,17]; density reduced because specific gravity of rubber is less than that of sand [18]; hysteretic damping ratio and energy dissipation increased [19]; increased ductility of concrete thereby applicable in shock resisting elements [1]. While 5-20% of crumb rubber replacement was tested, a rapid decrease in strength was observed at around 20% replacement; which was due to weak bonding between crumb rubber and the cement interface. To increase the bonding and to reduce the adverse effects on strength of concrete, crumb rubber can be pre-treated [19]. Experiments conducted on concrete with untreated rubber and NaOH treated rubber showed that treated rubberized concrete had a higher compressive and flexural strength [20]. UFGGBS is a micro fine material with particle size lesser than most cementitious materials. It is a supplementary cementitious material and is used to replace silica fume in concrete.

2. Materials

2.1. Cement

Portland Pozzolana Cement (PPC) of M30 grade, sourced from ACC Cements, Coimbatore, was used for the study. The specific gravity was 2.85 as per IS 1727: 1967.

2.2. Aggregates

Specific gravity of fine aggregate (passing through 2.36mm IS sieve) was 2.8 as per IS 2386(3):1963 and coarse aggregate (passing through 20mm IS sieve and retained on 12.36mm IS sieve) was 2.75 as per IS 383:1970.

2.3. Ultra-fine GGBS (UFGGBS)

UFGGBS obtained from Ambuja Cements, Mumbai, was found to have a specific gravity 2.9. The chemical composition (Alccofine 1203; as per the manufacturer) is given below in Table 1.

| Content | Percentage (%) |
|---------|----------------|
| SiO₂    | 21-23          |
| Al₂O₃   | 5-5.6          |
| Fe₂O₃   | 3.8-4.4        |
| CaO     | 61-64          |
| SO₃     | 2-2.4          |
| MgO     | 0.8-1.4        |
2.4. Crumb Rubber
Crumb rubber (collected from VB rubbers, Coimbatore), was sieved through a 4.75mm IS sieve and was found to be a mixture of fine powder and fibre like materials.

2.5. Treated Rubber
The strength of concrete was adversely affected when raw rubber was added due to a loss in bonding between concrete and rubber. Hence, the rubber was pre-treated with sodium hydroxide solution which removed the zinc stearate layer from the surface; providing a rougher surface with increased area and good bonding between the concrete and crumb rubber. The rubber was initially washed to remove dust particles and then immersed in sodium hydroxide solution for 24 hours, after which the pH was close to 13. The rubber was washed repeatedly to reduce the pH range to 7. The 38 micron IS sieve was used to filter the rubber particles while washing.

3. Methodology

3.1. Preparation of test specimen
The mix ratio considered for all three sets of concrete under study was 1:1.37:2.42:0.48 (as per IS 10262). The three sets of concrete used were: SET 1 – Concrete with raw rubber, SET 2 – Concrete with treated rubber and SET 3 – Concrete with treated rubber and 10% cement replaced with UFGGBS. No super plasticizers were used in this study. 24 cubes and 24 beams were cast to determine the compressive strength and damping property. The concrete was hand-mixed and compacted well using a vibrator. The specimens were demoulded after 24 hours and kept for curing. The specimens were taken out and air dried for testing on the 7th and 28th day. Table 2 shows the quantity of each material used for the various mixes. The water content, quantity of cement and coarse aggregates were kept constant at 228, 465 and 1125.029 kg/m$^3$ respectively.

| SET  | Mix Code | Fine Aggregate | Pre-Treated | UFGGBS |
|------|----------|----------------|-------------|--------|
| SET 1 | R05      | 604.80         | -           | -      |
|      | R10      | 572.00         | -           | -      |
|      | R15      | 541.13         | -           | -      |
|      | R20      | 509.30         | -           | -      |
| SET 2 | TR05     | 604.80         | NaOH        | -      |
|      | TR10     | 572.00         | NaOH        | -      |
|      | TR15     | 541.13         | NaOH        | -      |
|      | TR20     | 509.30         | NaOH        | -      |
| SET 3 | TRA05    | 604.80         | NaOH        | 290    |
|      | TRA10    | 572.00         | NaOH        | 290    |
|      | TRA15    | 541.13         | NaOH        | 290    |
|      | TRA20    | 509.30         | NaOH        | 290    |

3.2. Compressive Strength
Cubes of 100x100x100mm were tested using a compressive strength testing machine having a maximum capacity of 2000kN, confining to IS 516:1959.
3.3. Damping ratio and frequency

A frequency graph was plotted between the acceleration and the amplitude obtained from a Fast Fourier Transform (FFT) device. The frequency value was taken from the peak value of a number of wave cycles, when the system was vibrated. The investigation on damping ratio and frequency was conducted on beam specimens that were fully rigid at the bottom. The surface of the beam was cleaned and a transducer was fixed on the top surface. An impact load was generated using an impact hammer to cause vibrations which were sensed by the transducers, as shown in Figure 1. The damping ratio and the frequency value were found for each set of experiments using a FFT device.

![Figure 1. Testing of damping property using FFT device.](image1)

3.4. Flexural strength

Two-point loading, confining to IS 516:1959, was applied on beam specimens of dimensions 500x100x100mm in an UTM (maximum capacity of 500kN). A dial gauge was placed below the specimen to determine the deflection, as shown in Figure 2.

![Figure 2. Flexural testing of beam specimen.](image2) ![Figure 3. UPV test on rubberized concrete](image3)

3.5. Ultrasonic Pulse Velocity (UPV) test

Cylindrical specimens of size 200x100 mm were tested as per IS 13311(Part 1):1992, as shown in Figure 3. The pulse velocity through the concrete was calculated by dividing the specimen length by the travel time of the pulse.

3.6. Static modulus of elasticity

Static modulus of elasticity (E) is the ratio between the normal stress and normal strain; which can be directly related to the stiffness of the material. Deflection of the specimens in the longitudinal and lateral directions was measured by fixing dial gauges on the sides of the specimen during compression tests.
Hence, the change in stiffness of the material with inclusion of varying percentages of rubber and UFGGGBS was found.

3.7. Sorptivity
Specimens of size 100x100x100mm were cast and cured for 28 days, after which they were kept in an oven at 110°C for 24 hours. After air cooling, these cubes were coated with a non-absorbent material on the bottom side. Water was filled in a pan and the cubes were immersed up to 3mm depth, as shown in Figure 4. The weight of the cubes was noted at time intervals of 5, 10, 30, 60 and 120 minutes [21]. The sorptivity coefficient ($S$) was calculated from the weight of water absorbed ($I$) and the time period ($t$), as shown in equation (1).

$$I = S \sqrt{t} \quad (1)$$

![Figure 4. Sorptivity test on rubberized concrete](image)

3.8. SEM analysis
The micro structural analysis of the specimen obtained from previously tested samples was done using Scanning Electron Microscopy. SEM analysis was used to study the micro structural surface bonding between untreated and treated rubber, and concrete.

3.9. Analysis of mode shape using FEM
A concrete slab of dimensions 3500x4500x250mm was modelled for SET 3 in ANSYS, with optimum rubber and UFGGGBS inclusion. Young’s modulus of 32800 N/mm², Poisson’s ratio of 0.155 and density of 2.314 kg/m³ was taken as the basic inputs for the analyses. A concrete slab resting on a winkler foundation, placed on a soil sub-grade with the stiffness coefficient 10,000 kg/m³, was modelled as an 8 node brick element (SOLID 185). A spring element (COMBIN14) with fixed support was designed for the winkler foundation [22,23,24,25].

4. Results And Discussion

4.1. Compressive strength
The cubes were tested for their 7th and 28th day compressive strengths. From Figure 5, it can be observed that the 7th day compressive strength of all three sets of cubes decreased with increase in the rubber proportion. Also, SET 2 and SET 3 had similar values and variation in the 7th day strength as both sets contained treated rubber.
Similar to the 7th day compressive strength results, there was a constant decrease in the 28th day compressive strength results with increase in rubber proportion, as shown in Figure 6. It can be observed that SET 1 had lower strength than SET 2; which was lower than the strength of SET 3. SET 3 attained the target strength of M30 grade concrete, which can be attributed to the completion of the hydration process and formation of Calcium-Silicate-Hydrate (CSH) gel in the cement–UFGGBS mixture.

4.2. Damping Ratio and Frequency

The damping ration increased and the frequency values decreased with an increase in the rubber proportion in all sets, as shown in Figures 7 and 8. This clearly indicates that the structure has very high vibration tolerance.

4.3. Flexural Strength

Figure 9 represents the variation of flexural strength with rubber proportion. It can be observed that the flexural strength initially decreased with an increase in rubber content, but above 15% replacement there was a slight increase in strength. The strength reduction can be attributed to the poor interlocking of crumb rubber with concrete. Also, it can be concluded that the SET 3 attains better flexural strength than SET 1 and SET 2.
4.4. Ultrasonic pulse velocity

A decrease in the pulse velocity was observed as the rubber content was increased. This reduction in velocity indicates increase in porosity and reduction in density of the rubberised concrete, which suggests that rubberised concrete has better insulation property. The velocity in SET 3 concrete decreased drastically when compared to SET 1 and SET 2, as shown in Figure 10.

4.5. Static modulus of elasticity (E)

An increase in rubber content increased the percentage of voids in the rubberized concrete matrix, which in turn, adversely affected the strength of concrete. Of the three sets, SET 3 gave comparatively higher strength than the other two. Computation of E value from the obtained strength values provided relatable results, which is graphically represented in Figure 11.

4.6. Sorptivity

The sorptivity coefficient for the different sets of rubberised concrete is shown in Figure 12. 5% rubber proportion in SET 3 gave the lowest sorptivity, which might be due to the compact and denser matrix of UFGGBS-added concrete. With an increase in rubber percentage, the sorptivity was found to increase gradually with time, due to ingress of water from the bottom surface. It can be observed that SET 1 has higher sorptivity than the other two sets. Also, SET 1 was found to absorb more water due to its lesser density, higher void ratio, and higher absorption of untreated rubber.
4.7. SEM analysis

The micro structural bonding between cement and rubber was analysed using SEM. Figures 13 and 14 show the magnified images for the surficial bonding of raw and treated rubber with concrete. In Figure 13, it can be observed that raw rubber, having a smoother surface, did not bond well with concrete; whereas, in Figure 14, it is observed that treated rubber, devoid of the zinc stearate layer and having a rougher surface, bonded well. This proper bonding improved the strength characteristics by reducing the voids and porosity.

![Figure 13. Lack of bonding between untreated rubber and concrete](image1)

![Figure 14. Bonding of treated rubber with concrete](image2)

4.8. Analysis of Mode Shape using FEM

ANSYS APDL was used to analyse the mode shapes for the optimum percentage of rubber and UFGGBS in concrete. The contour plot in Figure 15 shows the points of maximum and minimum stress value for the concrete slab on a winkler foundation.

![Figure 15. Contour plot of concrete slab with winkler foundation](image3)

Modal analysis was used to calculate the linear response of the structure, since the response pattern and deformation of the structure will differ for different modes. In this study, five mode shapes were considered for analysing the deflection patterns. The mode shapes and deflection patterns of SET 3 rubberized concrete are shown in Figure 16 (a) and (b).
5. Conclusion
The required target strength of M30 grade concrete was achieved in SET 3, whereas SET 1 and SET 2 had a loss of compressive strength. The percentage increase in compressive strength from 7th day to 28th day at 5%, 10%, 15% and 20% rubber replacement was found to be 69.7%, 63.33%, 70.4% and 77.1% for SET 1; 63.9%, 62.5%, 62.1% and 66.7% for SET 2 and 83.33%, 94.44%, 85.7% and 84.61% for SET 3 respectively. There was a reduction in the flexural strength up to 15% replacement, after which there was a slight increase in the strength. The increase in flexural strength when compared to SET 1 was 8.9%, 3.85%, 14.65%, 8% for SET 2 and 23.46%, 17.89%, 49.5%, 37.13% for SET 3 respectively. At 5% and 10% replacement, SET 3 gave higher strength when compared to the other two sets. Computation of Young's modulus showed that the strength was largely affected when rubber was incorporated in concrete. Also, SET 1 had the least static modulus of elasticity.

Frequency was found to be inversely proportional to the damping ratio, and SET 1 was the most effective in vibration dampening. UPV tests showed that rubberized concrete has good insulation property, especially SET 3, which had the highest pulse velocity. Similarly, Sorptivity was the least in SET 3, which clearly indicates that UFGGBS added rubberized concrete had less voids. From the SEM analysis results, it was observed that the rougher and increased surface area of treated rubber in SET 2 and SET 3 provided a good bonding between rubber and concrete, thereby increasing the strength and elastic properties.

Although addition of crumb rubber affected the compressive strength, it improved the damping properties. The usage of UFGGBS as a cement replacement further improved the strength characteristics. Hence, from this study, it can be established that, by using an optimum percentage replacement of crumb rubber for fine aggregates and UFGGBS for cement, an economic and environmental friendly construction that actively controls vibrations can be achieved.

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Acknowledgement
We would like to thank Amrita Vishwa Vidyapeetham for providing the necessary facilities required for the successful completion of the project. A special thanks to Mr. L. Mahadevan and Mr. S. Saravananmugan, Assistant Professors, Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Coimbatore; for their active support and involvement. Also, I extend my gratitude to Mr. K. Sreenivasan and Ms. G. Keerthana for their valuable contributions and participation. Last but not the least; I thank all my friends and family for their continuous support.