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Experimental study on damping properties of concretes under free vibration with different tyre wastes

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Abstract: Disposing of waste tires presents environmental challenges, making recycling into crumb rubber a sustainable solution, especially in developing countries. Moreover, concrete tends to be brittle, and incorporating crumb rubber enhances its energy absorption, which can help reduce the concrete's brittleness. This study examines the effects of replacing fine aggregates with crumb rubber at 5% and 10% on concrete properties. Two types of crumb rubbers were used namely, low-quality and high-quality crumb rubber treated with CH3COOH solution. Results show that 5% crumb rubber improves compressive strength, and elastic modulus, while these properties decrease at 10% replacement. Free vibration tests using the logarithmic decrement method showed that higher rubber content increases the damping ratio, with 10% replacement yielding the best energy dissipation. Simulation using ANSYS Workbench validated the experimental findings, with natural frequencies and load-displacement behaviors closely matching experimental results. Using 5% crumb rubber enhances compressive strength, damping, and energy absorption, making concrete more versatile. This eco-friendly alternative supports sustainable construction while addressing tire waste disposal, highlighting its potential for dynamic load applications.

Keywords: Waste tires; Crumb rubber; Concrete properties; Energy absorption; Eco-friendly

1. Introduction

Waste tire disposal poses environmental challenges, and using rubber in concrete offers a sustainable solution. Rubberized concrete enhances durability, improving chloride resistance and frost resistance, but reduces workability, permeability, and carbonation resistance. Research confirms its potential as an eco-friendly material, balancing sustainability with performance improvements in construction applications [1] [2]. Concrete is essential in construction, driving economic growth. As the second-most consumed material after water, its widespread use underscores its critical role in infrastructure and development worldwide [3]. Concrete production demands vast raw materials, leading to resource shortages and environmental impact. Global aggregate consumption reached 49 billion tons and was expected to double in the coming decades [4]. Concrete without rubber shows brittle failure, while rubberized concrete exhibits ductile behavior due to rubber's deformability. Rubber particles enhance energy dissipation, preventing chipping and enabling gradual failure with transverse cracking [5].

Global tire use has led to surplus waste, prompting research on rubberized concrete. Studies explored its impact on strength, durability, and sustainability, advancing green concrete solutions [6]. Studies analyzed the effects of crumb rubber in concrete, assessing its impact on strength, durability, and workability to enhance sustainable construction practices [7]. Workability depends on mixing order.

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Studies have shown that increasing rubber content in concrete reduces strength, and density while enhancing flexibility, ductility, and energy dissipation [8]. Rubberized concrete enhances energy dissipation while reducing strength, proving effective as anti-collision cladding for bridge piers in dynamic and static applications [9]. Rubberized concrete (RC) enhances energy absorption, crack resistance and low compressive strength. It has been shown that rubberized concrete specimens with varying rubber sizes (0.1–20 mm) and contents (0–30%) under static and dynamic loads [10].

Modifications in the internal structure and interfacial properties of rubberized concrete introduce new challenges [11]. Crumb rubber size and pretreatment related on concrete properties that larger rubber particles reduce compressive strength and crushed crumb rubber (0.1–4.76 mm) effectively replaced fine aggregates in concrete [12] [13] [14]. Treated and untreated crumb rubber concrete has been found that mechanical properties decrease with higher rubber content and improved with treatments, with lime treatment being most effective and detergent treatment least effective [15]. Increasing rubber content reduces workability and load-bearing capacity although it enhances toughness and peak strain. Rubberized concrete improves seismic performance and provided an eco-friendly solution for waste tire disposal [16]. Reusing waste tire rubber in concrete improves damping behavior, however, reduces strength [17]. Recycling waste rubbers in roller-compacted concrete pavements reduce environmental pollution, enhanced sustainability, and improves ductility while slightly reducing mechanical strength [18].

Based on previous research, few studies focused on the damping properties and natural frequency of rubberized concrete using treated crumb rubber. Further analysis and application of crumb rubber in rubberized concrete, particularly through modal analysis, are required for deeper understanding. In this research, the impact of 5% CH3COOH treated rubber as sand replacement on the dynamic properties of concrete, with a particular focus on its damping behavior. Data were collected through a Data Logger with DC-700 4P software, and MATLAB was used to process the data and calculate the damping ratio using the logarithmic decrement method. The natural frequencies of cantilever rubberized beams were identified through experimental testing and finite element analysis (FEA) simulations.

2. Material and methods

In this experimental study, Ordinary Portland Cement (OPC) was used with a water-cement ratio of 0.38, while natural sand and river gravel are used as fine and coarse aggregates, respectively. Crumb rubber, pre-treated with 5% acetic acid, replaced sand at 5% and 10% increments, following a volume-based mix design.

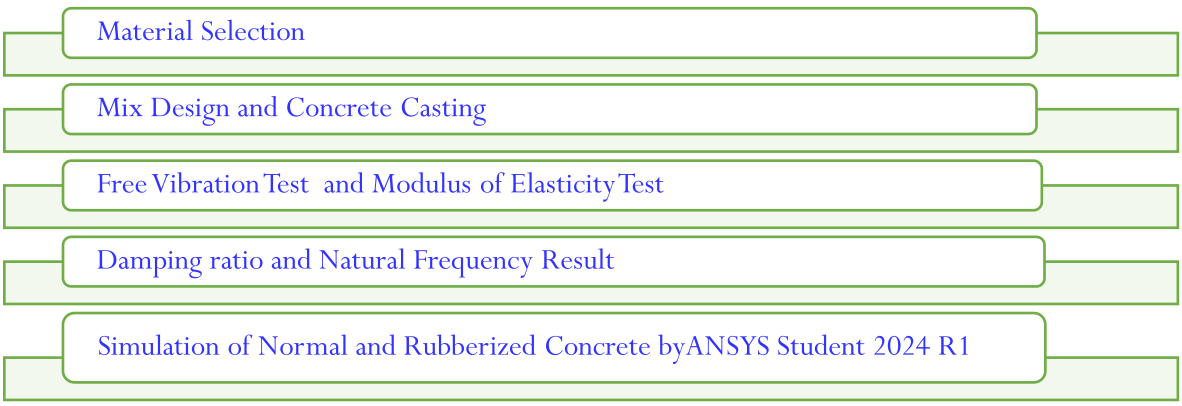

Figure 1. Schematic diagram

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This study analyzed the damping behavior of a cantilever concrete beam using an impact hammer test and an accelerometer to capture vibration data, which was processed in MATLAB Student R2020a using Fast Fourier Transform (FFT). The damping ratio, a key parameter for energy dissipation, was determined using the logarithmic decrement method by evaluating the gradual decay in oscillation amplitude. The schematic diagram is shown in Figure 1.

2.1 Preparing Specimens

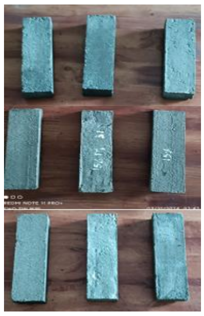
In the experimental study, Ordinary Portland Cement (OPC) was utilized for concrete preparation. Clean laboratory water was used to initiate the hydration reaction in the mixtures. Natural sand and river gravel served as fine and coarse aggregates, respectively. The fineness modulus of the river sand was 2.53 and the crumb rubber was 4.42. For high-quality crumb rubber, the specific gravity was 0.98, and its density was 480 kg/m³. In contrast, for low-quality crumb rubber, the specific gravity was 0.42, and its density was 380 kg/m³. The sand was used in a saturated surface dry (SSD) condition, while crumb rubber particles were pre-treated by soaking in a 5% acetic acid (CH_3COOH) solution, rinsed with tap water, and dried to SSD condition. Table 1 shows the cement, sand, and crumb rubber mix proportions, using a water-cement ratio of 0.38. The mix design followed a volume-based method, with crumb rubber increments of 5% and 10% replacements.

Table 1. Mix proportions of concrete

No	Sample	Cement (lb/yd^3)	Sand (lb/yd^3)	Crumb Rubber (lb/yd^3)	Coarse Aggregate (lb/yd^3)	Water (lb/yd^3)
1	Normal	895	1014	0	1892	340
2	5%HQ	895	964	19	1892	340
3	10%HQ	895	913	38	1892	340
4	5%LQ	895	964	8.1	1892	340
5	10%LQ	895	913	16.2	1892	340

(a)

(b)

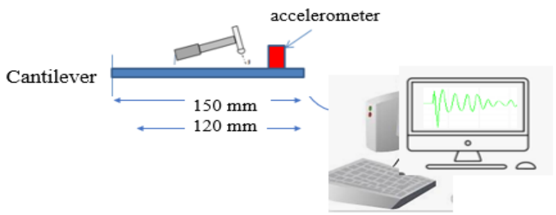


(c)

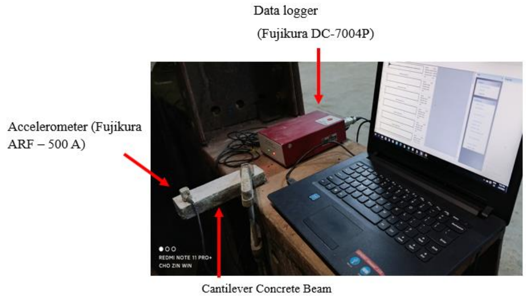
Figure 2. Proportion of rubberized concrete.(a) Treated crumb rubber particles, (b) Mix proportions of cement, sand, aggregate and crumb rubber, and (c) W45 x H25 xL150mm samples

2.2 Experimental procedure

In this study, a cantilever concrete beam (W45 x H25 x L150 mm) was clamped at one end to observe its damping behavior. Before beginning the test, the beam's surface was thoroughly cleaned to ensure sensors adhered effectively. An impact hammer test was carried out for experimental modal analysis, with an accelerometer (Fujikura ARF-500 A) positioned 12 mm from the free end to capture acceleration data. This accelerometer was fixed with adhesive for precise measurements. A Fujikura DC-7004P dynamic data acquisition system recorded the response data, which was then analyzed in MATLAB Student R2020a. Using Fast Fourier Transform (FFT), the acceleration data was converted into the frequency domain to study the beam's dynamic properties.



(a)



(b)

Figure 3. Experimental set up. (a) Schematic diagram of the experimental arrangement, and (b) Free vibration test

2.3 Determination of damping ratio

Damping describes the ability of a structure or subsoil to reduce and dissipate energy during dynamic movements, such as vibrations. Factors like vibration amplitude, material type, mode shape, and the structure's natural vibration period all impact damping levels. The damping ratio (ζ) is an essential parameter that quantifies how effectively a material can minimize vibrations. It reflects the energy dissipation rate of the material under dynamic loading. To determine this damping ratio, wave behavior is analyzed using logarithmic decrement formula, a technique that evaluates the gradual decay in amplitude (Equation (1) and (2)). In this method, the system was set to oscillate freely, and peak amplitudes over n consecutive cycles were recorded. The logarithmic decrement, indicating damping characteristics, is calculated as the natural logarithm of the ratio of these peak amplitudes.

$$\delta = \frac{1}{n} \ln \frac{A_0}{A_n} \text{ if } n = 1,2,3 \tag{1}$$

$$\zeta = \frac{1}{\sqrt{1+\left(\frac{2\pi}{\delta}\right)^2}} \approx \frac{\delta}{2\pi} \tag{2}$$

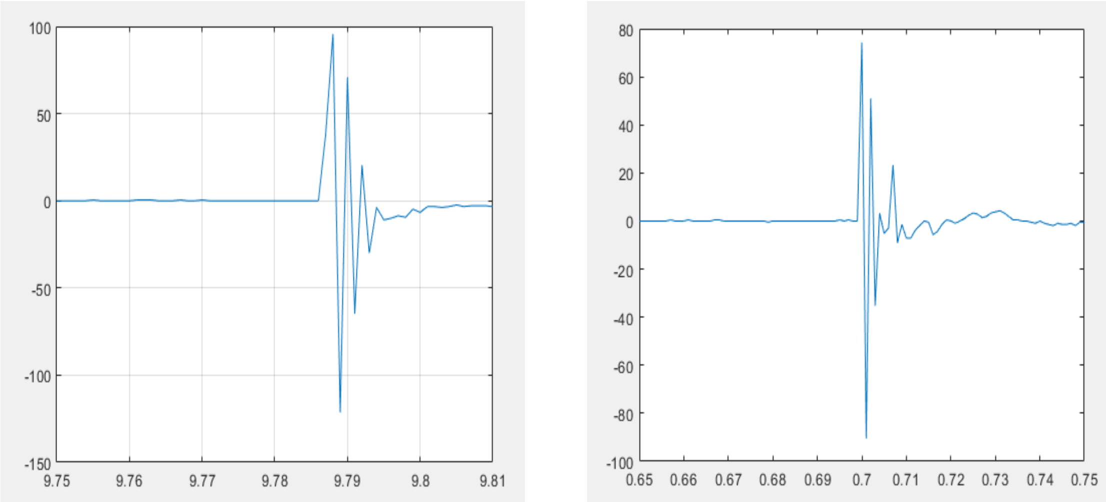
where,

δ= is the damping index,
A_0= the peak amplitude,
A_n = the amplitude after n number of cycles,
ζ= is the damping ratio

3. Results

3.1 Experimental results

To assess damping ratio for concrete cantilever beam at 28 days, free vibration test was conducted to obtain acceleration time history response as shown in following figures.



(a) (b)

Figure 4. Acceleration time history. (a) 5% rubberized concrete, and (b) 10% rubberized concrete

Partially replacing sand with rubber in concrete can significantly improve its energy dissipation properties, particularly by enhancing the damping ratio. The incorporation of rubber modifies the material's response to vibrations, allowing it to absorb and dissipate energy more efficiently. Among the tested specimens, damping ratio is the highest for 10% HQ, indicating superior energy dissipation compared to others. From the Fig.9, the damping ratio increases as the rubber content in the concrete increases. This suggests that higher rubber content enhances the concrete's ability to resist and dampen vibrations, making it potentially useful for applications requiring improved durability and resistance to dynamic loads.

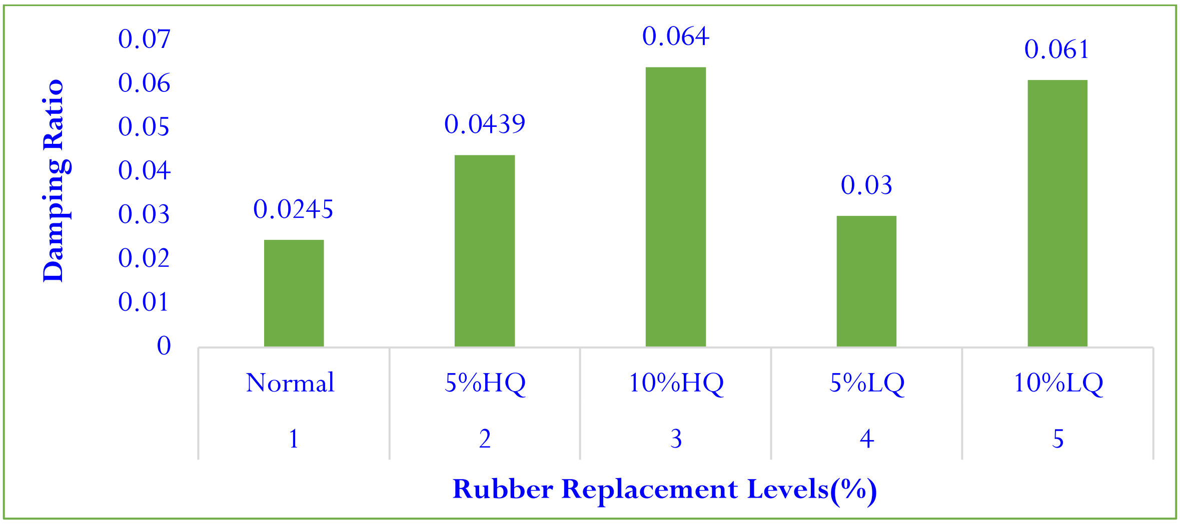


Figure 5. Dynamic damping of crumb rubber concrete

In free vibration, the natural frequency is the frequency at which a system naturally vibrates when disturbed from its equilibrium position and left to oscillate without any external force. It's determined by the system's mass, stiffness, and damping characteristics. The natural frequency governs the rate at which the system oscillates, influencing its behavior and response to external excitations. It can be seen that decreasing natural frequency of low- quality rubberized concrete was more significant than that of high-quality rubberized concrete.

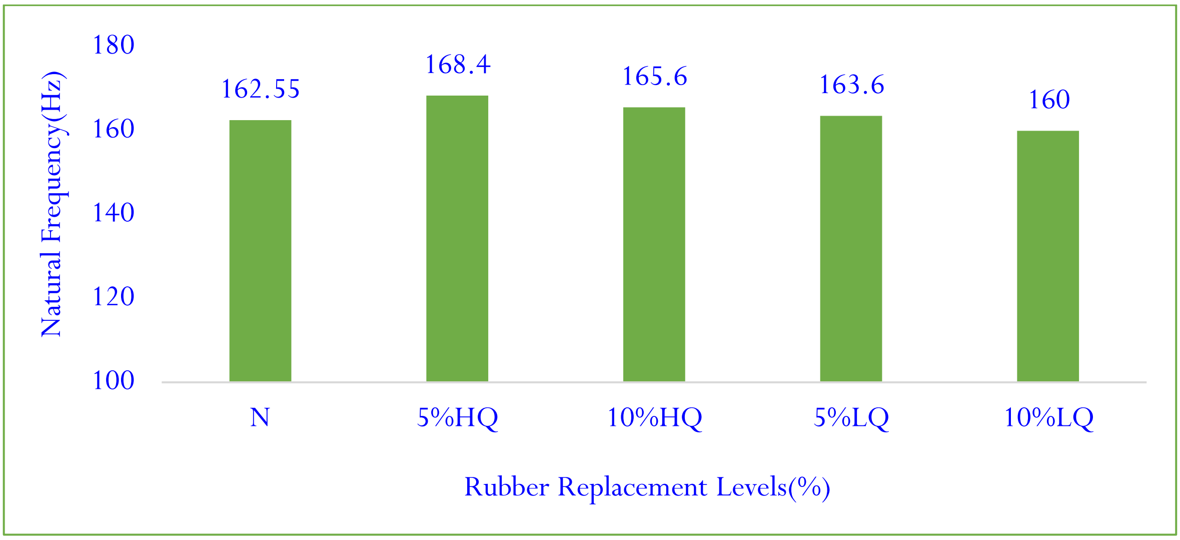


Figure 6. First mode natural frequency value of rubberized concrete (numerical)

3.2 Compressive strength

Concrete cylinders were tested using Maekewa 2000kg Compression Machine. All concrete mixes were prepared under ASTM C192 [19] for compression testing. The study reveals that adding crumb rubber significantly affects the compressive strength and mechanical behavior of concrete. The study reveals that adding crumb rubber, both high-quality (HQ) and low-quality (LQ), significantly affects the compressive strength and mechanical behavior of concrete. Normal concrete achieved a compressive strength of 40 MPa at 28 days, while 5% HQ rubber increased the strength by 11%, reaching 44.4 MPa. In contrast, 5% LQ rubber caused a 5% reduction in strength compared to normal concrete. A 10% HQ rubber replacement improved strength slightly to 41 MPa (2.5% above normal concrete), but the same 10% LQ rubber mix yielded the lowest compressive strength. These results indicate that a moderate 5% HQ replacement optimizes performance, while higher percentages, especially LQ rubber, decrease strength. Additionally, 5% LQ rubber slightly improved over the control mix but was still inferior to HQ rubber. These results are shown in Figure 8.

(a)

(b)

Figure 7. Compression test of specimen. (a) Testing after 28 days curing, and (b) Cracking after compression

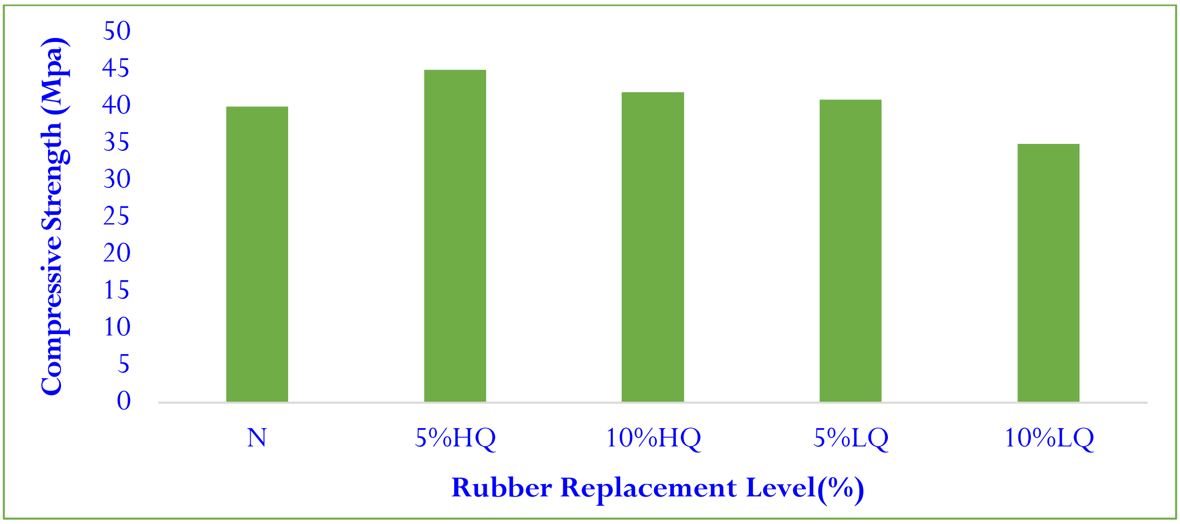
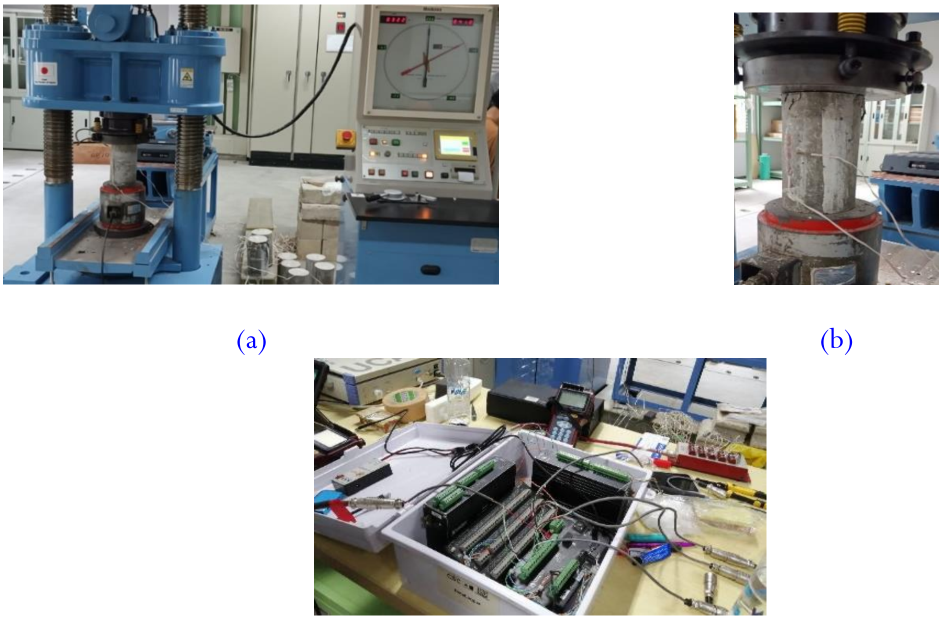


Figure 8. Compressive strength values for normal and rubberized concrete

3.3 Modulus of elasticity test

An elastic modulus test is essential to simulate the rubberized concrete exactly, following ASTM C 469 [20] as shown in Figure 9. For longitudinal and transverse strain values, two strain guages were used. In terms of elasticity and ductility, in Table II, the modulus of elasticity was highest in mixes with 5% HQ rubber, indicating improved stress-strain response. The second highest value of elastic modulus was 10%HQ while 5% LQ was still higher than normal concrete.10%LQ was the lowest elastic modulus among others because elastic modulus depends on the concrete strength. Poisson's ratio, which measures the ratio of transverse to axial strain, increased with the percentage of rubber content. Both 10% HQ and 10% LQ rubber showed higher Poisson ratios than normal concrete, with the highest ratio observed in 10% LQ rubber.



(a) (b)

(c)

Figure 9. Modulus of elasticity test .(a) Maekewa 2000kg compression machine (b)Using strain guage, and (c) Data logger

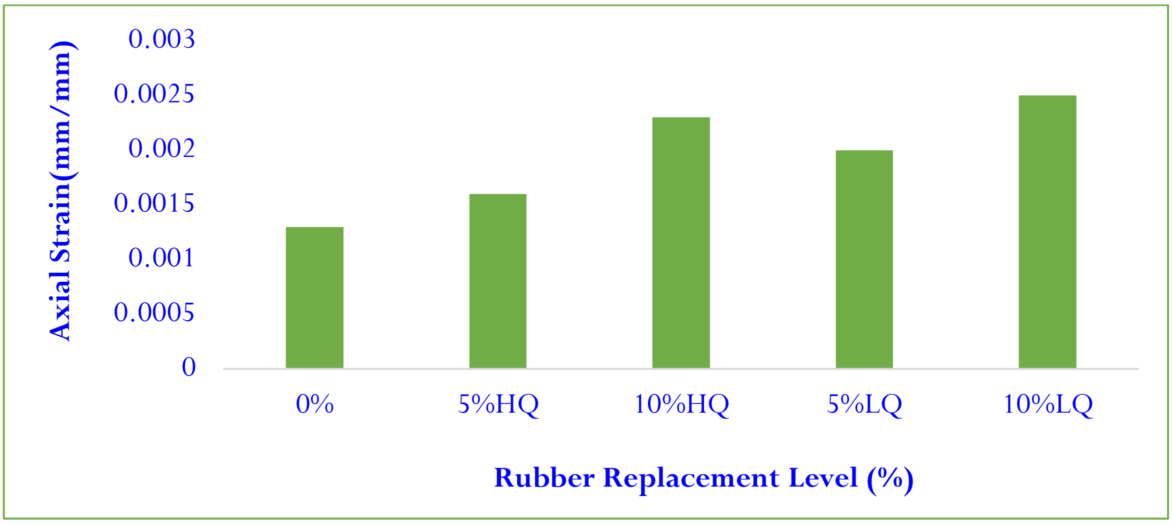


Figure 10. Axial strain values of normal and rubberized concrete

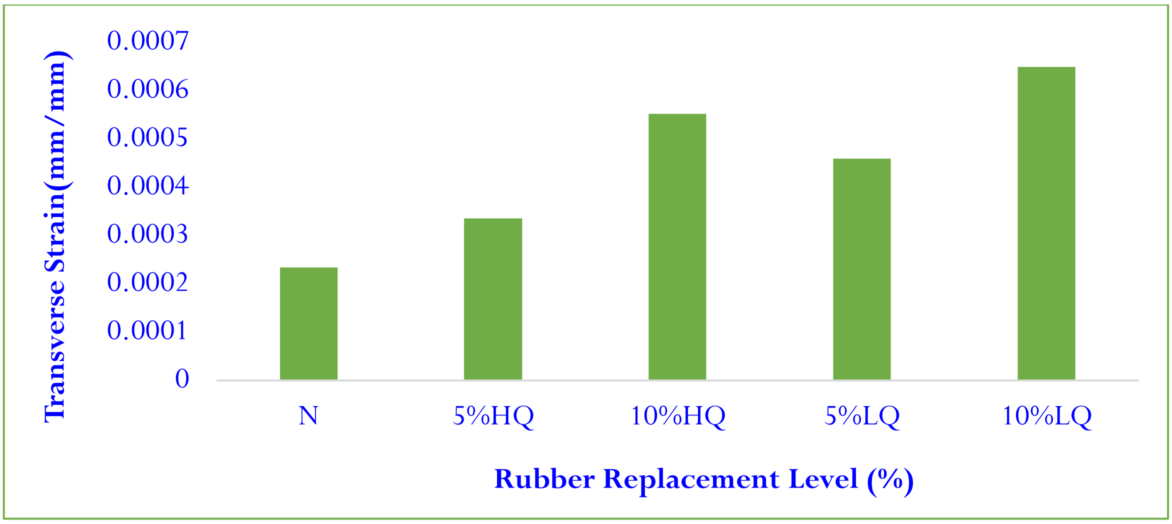


Figure 11. Transverse strain values of normal and rubberized concrete

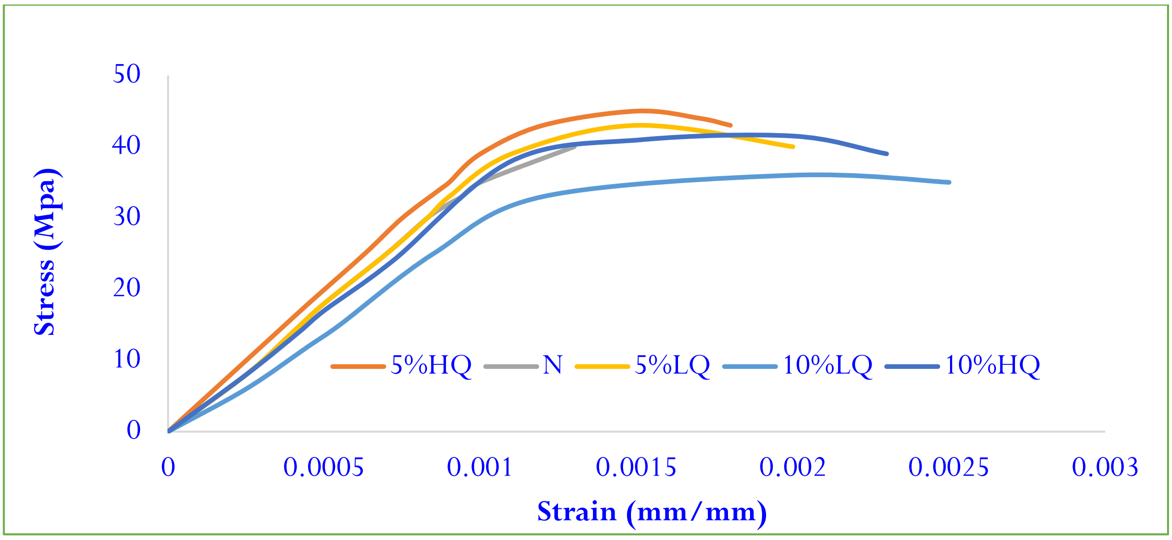


Figure 12. Stress-Strain comparison between normal concrete and rubberized concrete

Rubberized concrete exhibited greater ductility than conventional concrete, especially at 10% LQ replacement, which demonstrated superior performance in stress-strain behavior. Comparisons of stress-strain curves showed that 5% LQ rubber achieved greater ultimate strain than 5% HQ rubber, indicating better crack resistance and flexibility. Overall, the study concludes that crumb rubber, particularly HQ rubber at moderate levels, enhances the mechanical behavior of concrete by improving ductility and elasticity, despite some reductions in compressive strength at higher replacement levels.

3.4 Numerical simulation by ANSYS Workbench

In this research, ANSYS Student 2024 R1 was utilized to analyze the mode shape and natural frequency of normal and rubberized concrete. Modal analysis was performed to study the vibrational behavior of both concrete types under free vibration conditions. The simulation provided insights into how rubber replacement affects the dynamic properties of concrete. Comparing the results helped evaluate the feasibility of rubberized concrete for structural applications. The findings demonstrated variations in mode shape and frequency, emphasizing the influence of rubber particles on stiffness and damping properties. This research contributes to understanding the structural performance of sustainable concrete materials.

To validate the experimental simulation, a rubberized concrete cantilever beam was modeled in ANSYS Student 2024 R1. Essential material properties and strain values were input, and a fixed boundary condition was assigned. The frequency simulation result with ANSYS was only 10% more with experimental results as shown in Figure 14. Overall, the analysis confirms the reliability of ANSYS in predicting the dynamic behavior of rubberized concrete.

Table 2. Material Properties of concrete

Sample	Compressive Strength (Mpa)	Modulus of Elasticity $E=\sigma/\varepsilon_a$ (Gpa)	Poisson Ratio $\mu=\varepsilon t/\varepsilon a$
Normal	40	35	0.18
5%HQ	45	40	0.21
10%HQ	42	38	0.24
5%LQ	41	36	0.23
10%LQ	35	30	0.26

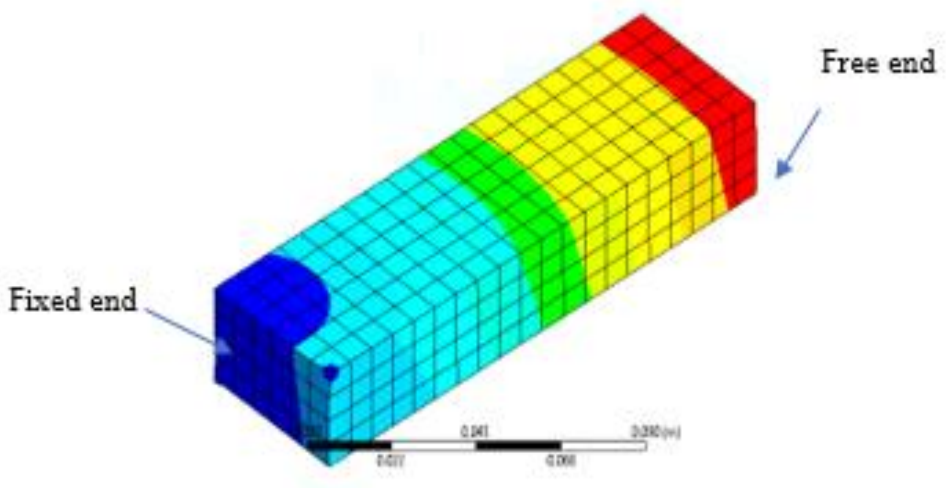


Figure 13. Maximum deflection at the free end of cantilever beam (modal analysis in ANSYS)

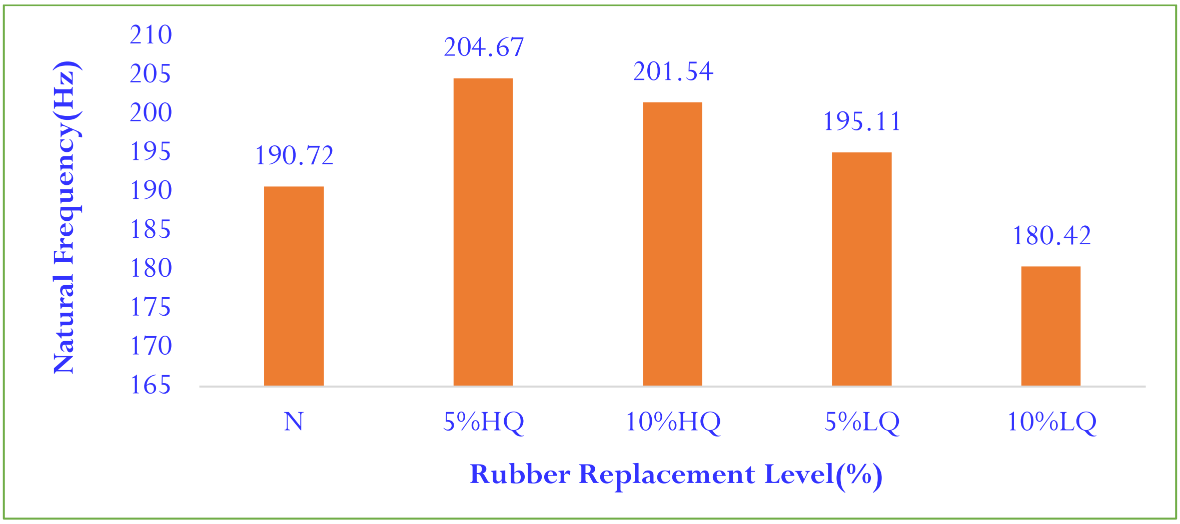


Figure 14. First mode natural frequency value of rubberized concrete (numerical)

4. Discussion

Crumb Rubber Concrete (CRC) has significant interest in residential construction due to its potential for improving flexibility, ductility, and damping properties. Previous research has consistently demonstrated that increasing rubber content reduces compressive strength and density but enhances energy dissipation and damping [8][9][17]. Rubber pre-treatment has been shown to improve workability, but it does not significantly impact the compressive strength of the concrete, as shown in previous studies [11].

However, this research presents a deviation from earlier findings, as it shows that the compressive strength of rubberized concrete increases when CH_3COOH-treated rubber is used as a partial sand replacement. This suggests that the treatment method plays a crucial role in strength loss typically associated with rubber content. The results highlight the importance of selecting the optimal crumb rubber percentage, as balancing the rubber content can enhance both the concrete's mechanical properties and its vibration-damping performance.

While lower replacement levels (such as 5%) of both high-quality and low-quality rubber enhance compressive strength, higher levels (around 10%) improve ductility and damping properties but reduce compressive strength. Damping properties are critical for applications requiring both structural integrity and enhanced vibration control, such as in buildings and infrastructure subjected to dynamic loads. The study recommends a moderate replacement ratio to achieve the best balance between strength, ductility, and damping capacity for effective structural performance.

5. Conclusion

Recycling waste tires into crumb rubber offers a sustainable solution to environmental challenges while improving concrete's energy absorption and reducing brittleness. The research investigated the effects of replacing fine aggregates with 5% and 10% crumb rubber, including low- and high-quality variants treated with CH3COOH solution. Results showed 5% replacement enhances compressive strength and elastic modulus, while workability and damping ratio improve with increased rubber content. Free vibration tests confirmed 10% rubber provides optimal energy dissipation. Simulations in ANSYS showed nearly approximation with experimental values. Incorporating 5% crumb rubber improves compressive strength, damping, and energy absorption, increasing concrete's versatility. This sustainable solution promotes eco-friendly construction for dynamic load applications.

Author's declaration

Author contribution

Cho Zin Win: Conceptualization, methodology, experimentally investigated, writing the manuscript reviewing and editing. **Khin Su Su Htwe**: Methodology, management, supervision, reviewing. **Nyan Myint Kyaw**: Supervision, Evaluating performance and providing feedback.

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Conflict of interest

The authors declare no conflicts of interest associated with this research and its publication that have affected the study's integrity or findings.

Ethical clearance

This research does not involve humans as subjects.

AI statements

This article is the original work of the author without using AI tools for writing sentences and/or creating/editing tables and figures in this manuscript.

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