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Comparative study on energy absorption capacities of normal and rubberized concrete columns under sinusoidal wave

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Abstract: This research explores the use of rubberized concrete composite as an innovative structural material designed to improve energy dissipation and enhance seismic resistance by incorporating recycled rubber crumb into concrete. A reference test model was constructed using normal concrete, while the remaining models were made from concrete in which a portion of the fine aggregates was partially replaced with crumb rubber particles. Lumped mass columns were tested on a shaking table using sine wave excitation to evaluate dynamic behaviour and seismic response with 4 Hz sinusoidal base motion. Acceleration measurements were obtained and analysed in MATLAB using Fast Fourier Transform (FFT), allowing for comparison between normal and rubberized concrete specimens. The results indicated that as the rubber content in the concrete increased, the frequency of the columns decreased under base excitation. Additionally, three-dimensional finite element simulations of lumped mass column models were conducted in ANSYS. Linear dynamic analysis was conducted to assess the system's behaviour when subjected to harmonic loading. In addition, resonance conditions were also considered to assess the dynamic interaction of the column. With higher rubber content, the acceleration response is reduced due to the enhanced damping and energy absorption capabilities of rubberized concrete, leading to a significant decrease in peak acceleration values.

Keywords: rubberized concrete; energy absorption; sinusoidal wave; acceleration response

1. Introduction

Enhancing concrete durability and minimizing waste are key factors in advancing sustainable and eco-friendly construction methods. This approach helps conserve natural resources while managing industrial byproducts effectively (Moolchandani et al., 2024; Oyejobi et al., 2024; Sinkhonde et al., 2023). Concrete has been a vital construction material for centuries, however still vulnerable to seismic forces. Rubberized concrete, made by incorporating recycled tire rubber, has gained attention for its potential to enhance energy dissipation and improve seismic performance (Chen et al., 2025; Elshazly et al., 2020; Kareem et al., 2025). Rubberized concrete has been recognized in studies as an effective approach to repurposing waste tires sustainably. Findings indicate that it enhances both the durability and ductility of structural elements. However, reduced workability and carbonation resistance have been reported (Ahmad et al., 2022; Maeijer et al., 2021; P. Zhang et al., 2023).

Understanding the seismic performance of innovative frame structures is vital. Through shaking table tests and analysis of various experiments, dynamic behaviour under earthquake conditions and proposes evidence-based recommendations were evaluated to improve structural stability, safety, and design practices for enhanced earthquake resilience (Kan et al., 2025). In ground-motion modelling, the integration of densely sampled data is critical for capturing repeatable source, path, and site effects. The study indicates that incorporating detailed non-instrumental data can significantly strengthen ground-motion modelling, leading to more accurate site-specific seismic assessments and improved ShakeMap results (Marcou et al., 2025).

Recent research explored RC's behaviour under static and dynamic loading, analysing varying rubber content (0–30%) and particle sizes (0.1–20 mm). Applying the additive at a 2% content with a 0.5 mm particle size resulted in enhanced mechanical properties and overall material performance. This optimal condition guided the development of predictive tools, including mathematical equations and a neural network model, based on the experimental findings (Du et al., 2024). Machine learning models accurately predicted rubberized concrete strength, identifying rubber content, water-to-cement ratio, and curing time as key factors influencing compressive performance and mix optimization (Zhou & Zheng, 2025). Concrete APS hollow block walls enhanced with SBR rubber and PET flakes were evaluated for vibration response. Testing within the 8–5000 Hz frequency range revealed a significant improvement in damping efficiency—reaching up to 51% higher than that of conventional hollow blocks (Major et al., 2023).

Recycled rubber incorporation in concrete, while reducing workability and strength—especially with finer particles and higher content—significantly enhances impact resistance, presenting a viable solution for sustainable, energy-absorbing construction applications (Abbas et al., 2022). Replacing up to 15% of fine aggregates with rubber in concrete mixes offers notable benefits, particularly improved elasticity and abrasion resistance (Saif, 2025). In addition, rubber fibre-reinforced concrete improved impact resistance with NBR fibres while noting reduced static strength; optimal mixes showed significant enhancement in crack resistance cycles (Abhi et al., 2025; Li et al., 2025). The other study introduces a cost-effective, single-degree-of-freedom shake table for seismic testing, enabling structural evaluation in resource-limited settings by simulating earthquake motions using accessible hardware and PD control (Parajuli et al., 2025). This study used shaking table tests to assess micropyle seismic performance with various casings, showing perforated casings offer similar dynamic benefits to conventional ones. Dynamic testing of PHC (Pre-stressed High-strength Concrete) pipe piles in soft soil revealed notable soil–structure interaction effects. Longer structural periods and higher bending moments, especially under strong ground motions or high peak ground accelerations (PGAs) were included (Mendoza et al., 2025; P. Zhang et al., 2023).

Another study investigates the viability of rubberized concrete made with waste rubber from end-of-life tires by analysing its microstructure and engineering properties through advanced testing methods, revealing its potential for sustainable construction applications such as insulation, dampening, and lightweight structural components (Singh et al., 2025). Changes in the internal structure and surface properties of rubberized concrete create new challenges. Concrete performance is affected by crumb rubber's size and treatment; larger particles weaken strength, crushed rubber serves well as fine aggregate, and treatments significantly improve mechanical properties (Awan et al., 2021; Han et al., 2024; Youssf, Elchalakani, et al., 2022; Youssf et al., 2019; Youssf, Mills, et al., 2022).

Experimental investigations using shaking table tests indicated that premature shear failure in the confined masonry components of hybrid reinforced frame-masonry (HFM) systems significantly degrades lateral stiffness and accelerates frame deterioration, emphasizing the necessity of integrating damage-state-based approaches in seismic design methodologies (H. Zhang et al., 2023). A recent study examined how U-shaped wall specimens made from fibre-reinforced foamed concrete (FRFC) and plain foamed concrete (PFC) respond to seismic activity using shaking table tests. FRFC, reinforced with henequen fibres, demonstrated superior structural integrity and delayed collapse times compared to PFC. Finite element analysis validated the experimental results by indicating lower stress concentrations. The findings suggest FRFC's potential in seismic design, though further validation is needed (Flores-Johnson et al., 2020). Incorporating crumb rubber from waste tires into concrete offers a sustainable solution that improves damping and energy absorption, reducing brittleness. The study found that 5% replacement enhances compressive strength and modulus, while 10% increases energy dissipation, making it suitable for dynamic load applications (Win et al., 2025).

Earlier studies on the dynamic performance of rubberized concrete are scarce, especially regarding its behaviour under shaking table tests. This research aims to explore how both normal and rubberized concrete columns respond to one-directional harmonic loads using shaking table experiments. The experimental results are validated through a three-dimensional finite element analysis conducted in the ANSYS software. The purpose of vibration analysis on the shaking table system is to identify the acceleration response under harmonic excitation. By deepening the understanding of rubberized concrete's dynamic behaviour, this research supports scientific and technological progress, encourages its application in earthquake-resistant structures, and fosters innovation in sustainable and resilient construction materials.

2. Methods

This study investigates the dynamic behaviour of concrete columns incorporating two types of rubber—high-quality and low-quality—under seismic shaking table tests, each modelled as a lumped mass system. This study examines the acceleration response of normal and rubberized concrete columns under unidirectional harmonic using a shaking table, with validation through 3D finite element modelling in ANSYS Student 2025 R1.

In the process of rubberized concrete production, quality of crumb rubber and its surface treatment are described to enhance concrete performance. Crumb rubber, with a fineness modulus of 4.42, was categorized by quality: high-quality crumb rubber had a specific gravity of 0.98, density of 480 kg/m³, and water absorption of 5%, whereas low-quality rubber showed a markedly lower specific gravity of 0.42, density of 380 kg/m³, and water absorption of only 1.3%. To improve interfacial bonding between rubber particles and the cement matrix, the crumb rubber underwent chemical surface modification. This involved soaking in a 5% acetic acid (CH_3COOH) solution, followed by rinsing with tap water and drying to a saturated surface dry (SSD) condition. The acetic acid treatment was theoretically aimed at removing surface contaminants and increasing surface roughness, thus enhancing rubber–matrix adhesion in accordance with interfacial compatibility principles.

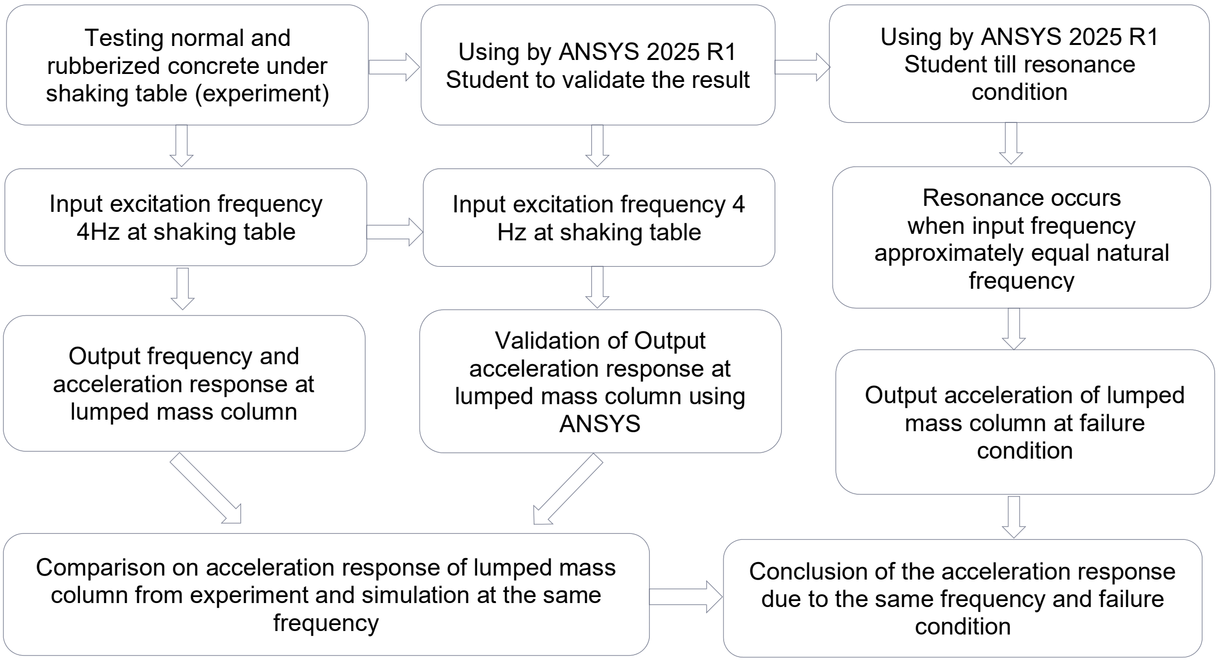
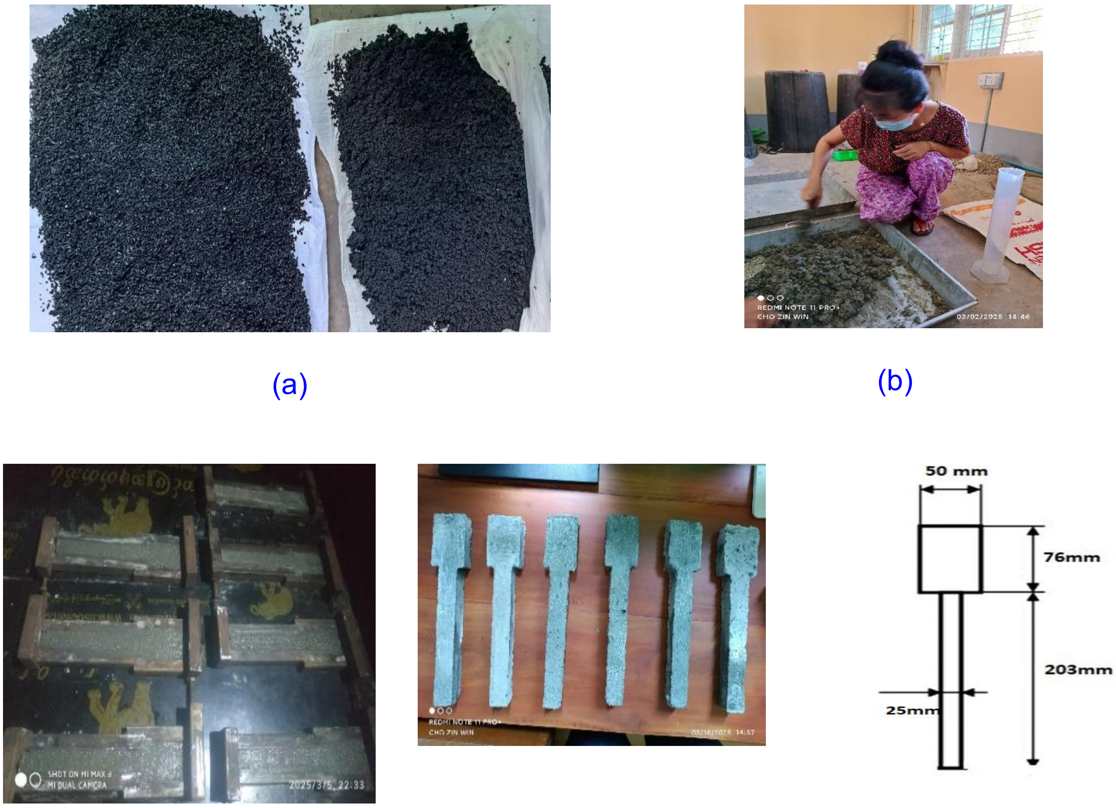


Figure 1. Schematic diagram

In the experiment, a 4 Hz input excitation frequency was applied through the shaking table, and the output frequency and acceleration response were measured at the lumped mass column using accelerometer (Fujikura ARF – 500 A). The same 4 Hz input was used in the numerical simulation using ANSYS to obtain the corresponding acceleration response to validate the experiment. Then, acceleration values of lumped mass columns at 4 Hz excitation for both experimental and numerical simulation are compared. However, due to capacity of the shaking table’s input frequency and payload limitations, input frequencies which equal to the lumped mass column's natural frequency could only be tested in the simulation. As a result, resonance conditions and peak acceleration responses at the natural frequency were observed only in the numerical model.

2.1 Mix proportions

Both rubber types were used to produce normal concrete (NC) and rubberized concrete (RC) specimens with recycled rubber crumb replacing sand at volume ratios of 5% and 10%, while keeping cement content, coarse aggregate, and water-to-cement ratio constant. All specimens were cast using Type 1 Portland cement, and the rubber crumb, with a maximum size of 2 mm, was uniformly mixed into the concrete to evaluate its effect on the seismic response and material properties of RC columns.



(a) (b)

(c) (d) (e)

Figure 2. Process of rubberized concrete production (a) drying CH3COOH treated crumb until SSD condition after washing with water (b) mixing concrete (c) placing concrete (d) normal and rubberized concrete specimens (e) size of specimen

Table 1. Mix proportions of materials

Type of Concrete	Crumb rubber (%)	Cement (lb/yd^3)	Sand (lb/yd^3)	Crumb rubber (lb/yd^3)	Coarse aggregate (lb/yd^3)	Water (lb/yd^3)
Normal concrete	0	895	1014	0	1892	340
High quality rubberized concrete	5	895	964	19	1892	340
	10	895	913	38	1892	340
Low quality rubberized concrete	5	895	964	8.1	1892	340
	10	895	913	16.2	1892	340

2.2 Experimental set up

A shaking table with dimensions of 24 inches in length, 22 inches in breadth, and 12 inches in height was utilized for dynamic testing. The table was driven by a MY1016Z model motor, operating at a rated speed of 3500 revolutions per minute (rpm), with a voltage input of 24V, a current draw of 13A, and an output power of 3600W. Vibrational data was collected using Fujikura ARF – 500 A accelerometer sensor which is small and lightweight and can make high-accuracy measurement with the least interference and its rated output is 0.5 mV/V.

(a) (b) (c)

Figure 3. Test set up. (a) shaking table, (b) measuring acceleration response of specimen, and (c) accelerometer sensor (Fujikura ARF – 500 A)

This study investigates the dynamic behaviour of rubberized concrete columns under cyclic loading conditions. The tested columns, each with a cross-sectional thickness of 25 mm, were subjected to a 4.634 Hz sinusoidal base motion using a shaking table apparatus, as illustrated in the accompanying figures. Acceleration responses were measured using a high-precision accelerometer mounted on the specimens.

2.3 Numerical simulation

This research involves a finite element simulation of a lumped mass column subjected to shaking table excitation using ANSYS Student 2025 R1. The metal shaking table was built to handle moderate loads and acceleration levels. To simulate realistic part interactions, "bonded" and "no separation" contact types were applied between surface of shaking table and specimen. To evaluate the dynamic behaviour of the system, harmonic loads were applied under fixed support conditions. Modal and linear dynamic analyses were carried out to evaluate key parameters such as frequency, and acceleration. Material properties for both the metal shaking table and the concrete superstructure were defined using stress strain value and material parameters. The experimental results of modulus of elasticity, stress and strain values and compressive strength can be applied to simulate numerical simulation as data input in accordance with the same concrete mix proportions, same maximum aggregate size which is limited to 12 mm and same rubber types were used (Win et al., 2025).

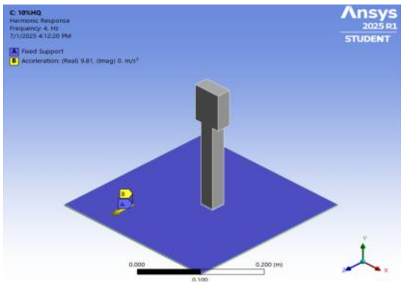


Figure 4. Rubberized concrete under base excitation using ANSYS Student 2025 R1

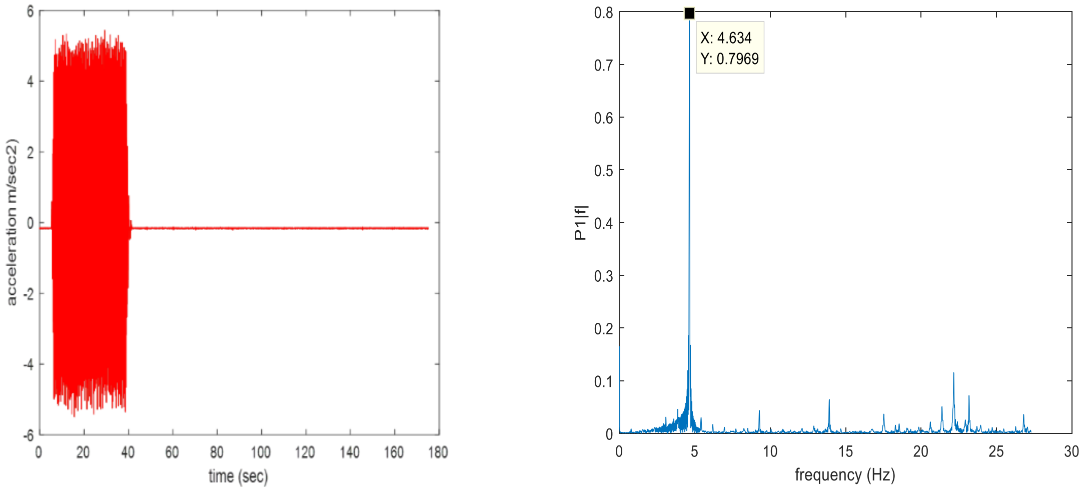
3. Results and discussion

The frequency of the column is obtained through experimental measurements, while the natural frequency is determined via numerical simulation. The frequency due to excitation represents the structural response to an externally applied force, whereas the excitation frequency itself originates from an external input (4 Hz). The natural frequency, determined mainly by its mass and stiffness, represents an inherent dynamic characteristic. Resonance, marked by significantly increased vibration amplitudes, can occur when the excitation frequency aligns closely with this natural frequency. However, if the excitation frequency differs from the natural frequency, the resulting response becomes more complex and is significantly influenced by the system's damping and dynamic behaviour. Therefore, in comparing numerical and experimental results, acceleration response of column is only emphasized.

The discussion in this study is divided into three main sections, each focusing on an essential element of the structure's dynamic performance. Initially, the excitation-induced frequency of the column is evaluated through experimental methods, illustrating the impact of material changes—such as the addition of rubber—on the lump mass column's vibration behaviour. Secondly, the experimental and simulated acceleration responses are compared, highlighting the consistency between measured and predicted results, and validating the accuracy of the numerical model. The last part of the discussion focuses on analysing the acceleration response up to the resonance point, highlighting a notable rise in vibration amplitude as the excitation frequency comes close to matching the system's natural frequency.

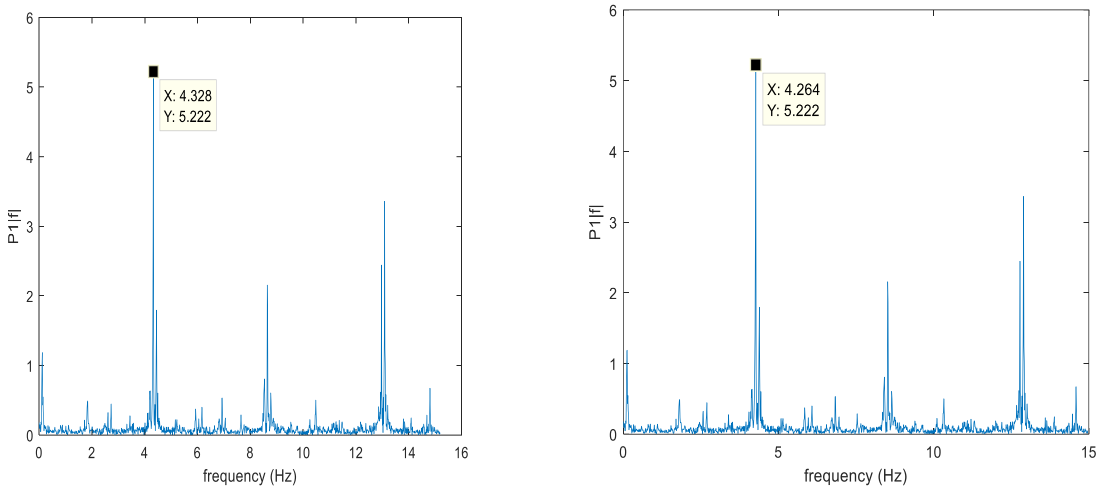
3.1 Testing normal and rubberized concrete under shaking table from experiment

For the variations presented in Figure 5, individual analyses were conducted for each excitation. In Figure 5 (a), time-domain signals corresponding to the applied excitation were processed to compute the Frequency Response Functions (FRFs) in terms of magnitude. The resulting FRF graphs enable detailed analysis of the structural response across a range of excitation frequencies. The transformation from the time domain to the frequency domain was performed using the Fast Fourier Transform (FFT) in MATLAB. The resulting output frequency-domain signals of lumped mass columns for both normal and rubberized concrete are presented in Figure 5(b), Figure 6(c) and Figure 6(d).



(a) (b)

Figure 5. Transformation from the time domain to the frequency domain. (a) base excitation of shaking table, and (b) output frequency of normal concrete



(a) (b)

Figure 6. Transformation from the time domain to the frequency domain (a) output frequency of 5 % HQ rubberized concrete (b)output frequency of 10 % HQ rubberized concrete

In Figure 7, a clear trend of decreasing frequency in the lumped mass column is observed with the addition of rubber into the concrete mix. The control specimen, consisting solely of normal concrete, exhibited the highest recorded frequency at 4.634 Hz which is same value as excitation frequency. Incorporation of 5% high-quality rubber led to a decrease in frequency to 4.328 Hz, and further reduction to 4.264 Hz was observed with 10% high-quality rubber, indicating a direct correlation between rubber content. Similarly, the addition of low-quality rubber also resulted in frequency reductions, with values of 4.306 Hz and 4.200 Hz for 5% and 10% content, respectively. Although both rubber types lowered the frequency, high-quality rubber exhibited a slightly more pronounced effect, suggesting better energy absorption and damping characteristics. These findings highlight the potential of rubber inclusion, especially of higher quality and in greater proportions, to enhance damping performance by reducing dynamic response frequencies in concrete structures.

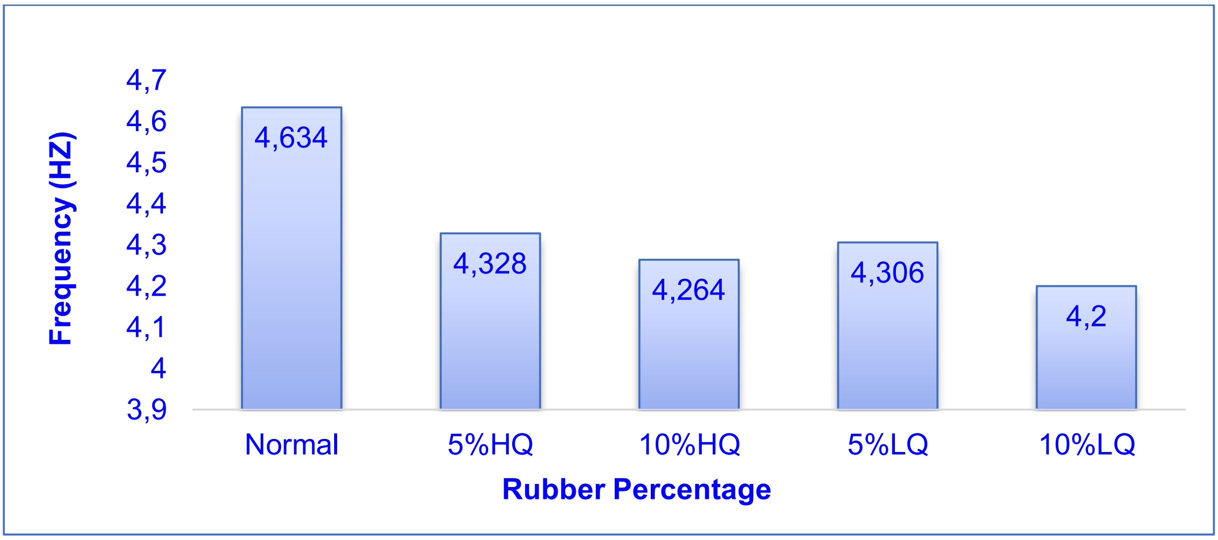


Figure 7. Output frequency of lumped mass column for normal and rubberized concrete

In Figure 8, the experimental investigation examined the acceleration response of a lumped mass column with varying percentages and qualities of rubber inclusion. Results indicate a reduction in acceleration with the addition of rubber, confirming its effectiveness in energy dissipation. The normal specimen exhibited an acceleration of 15 m/sec², while specimens with

5% and 10% high-quality rubber showed reduced responses of 14 m/sec² and 12 m/sec², respectively. Low-quality rubber demonstrated 13.5 m/sec² at 5% and a further decrease to 10 m/sec² at 10%. These findings suggest that while both rubber types enhance damping, low-quality rubber offers superior performance at higher percentages under dynamic loading conditions.

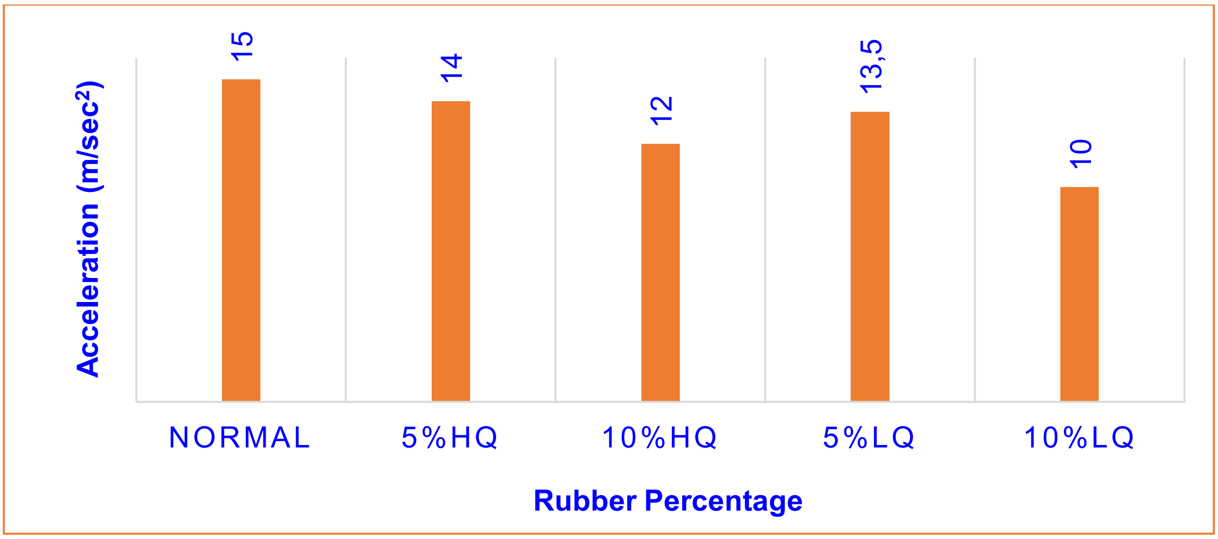


Figure 8. Output acceleration response at lumped mass column

3.2 Validation on acceleration response of lumped mass column by ANSYS

When comparing the dynamic response of rubberized and normal concrete, both experimental and numerical analyses consistently indicate that the incorporation of rubber into concrete mixtures leads to a reduction in acceleration response. In finite element simulations conducted using ANSYS, the peak acceleration observed in normal concrete was approximately 9.3% higher than that of concrete containing 5% rubber, and 14.9% higher than that of concrete with 10% rubber content. Similarly, experimental measurements revealed the acceleration of normal concrete exceeding that of 5% and 10% rubberized concrete by 11.1% and 33.3%, respectively. These findings demonstrate a clear trend of decreasing acceleration and displacement magnitudes as the rubber content increases, highlighting the enhanced energy dissipation capability of rubberized concrete. Another finding is that all acceleration response values are above 9.81 m/sec^2 (1g) for all types of concrete.

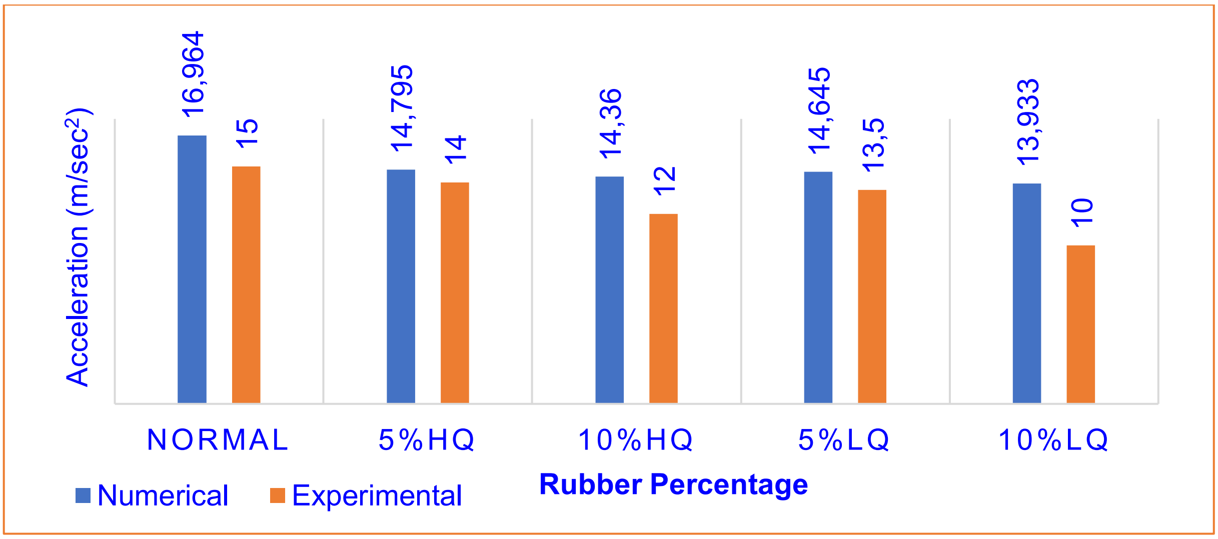


Figure 9. Comparison of acceleration response between normal and rubberized concrete

3.3 Acceleration response from numerical simulation till resonance condition

Resonance occurs when the natural frequency of a structure or system matches the frequency of an external excitation, resulting in a significant increase in vibration amplitude. This condition can lead to excessive deformation, material fatigue, or even structural failure if not properly controlled. Resonance is critical in dynamic analysis as it directly affects the stability and safety of engineering structures. In the context of simulation, the resonance condition is typically identified and studied using modal and harmonic response analyses. ANSYS allows engineers to determine natural frequencies and simulate system responses under dynamic loads. Therefore, resonance condition is most accurately and practically evaluated using ANSYS simulations, where boundary conditions, material properties, and load frequencies can be precisely controlled to observe resonance effects.

3.3.1 Natural frequency from numerical simulation

The dynamic behaviour of concrete elements, particularly natural frequency, is predominantly governed by material properties such as modulus of elasticity, mass density, geometric configuration, and boundary conditions. In numerical simulation, the incorporation of rubber particles into concrete mixtures was investigated to evaluate its impact on natural frequency. When high-quality rubberized concrete was utilized at a 5% replacement level, the observed natural frequency increased to 201.25 Hz, reflecting an 8.17% enhancement relative to conventional concrete. A 10% replacement with high-quality rubber yielded a slightly lower frequency of 197.49 Hz yet still marked a 6.14% improvement over the control specimen. Conversely, the application of low-quality rubber demonstrated a less favourable influence. At 5% replacement, the frequency reached 190.48 Hz, corresponding to a modest increase of 2.39%. However, a further increase to 10% replacement resulted in a significant decline in frequency to 175.45 Hz, representing a 5.70% reduction in comparison to the unmodified concrete. These findings underscore the critical role of rubber quality and content in modulating the dynamic performance of rubberized concrete, with high-quality rubber additives enhancing structural vibrational characteristics at moderate replacement levels.

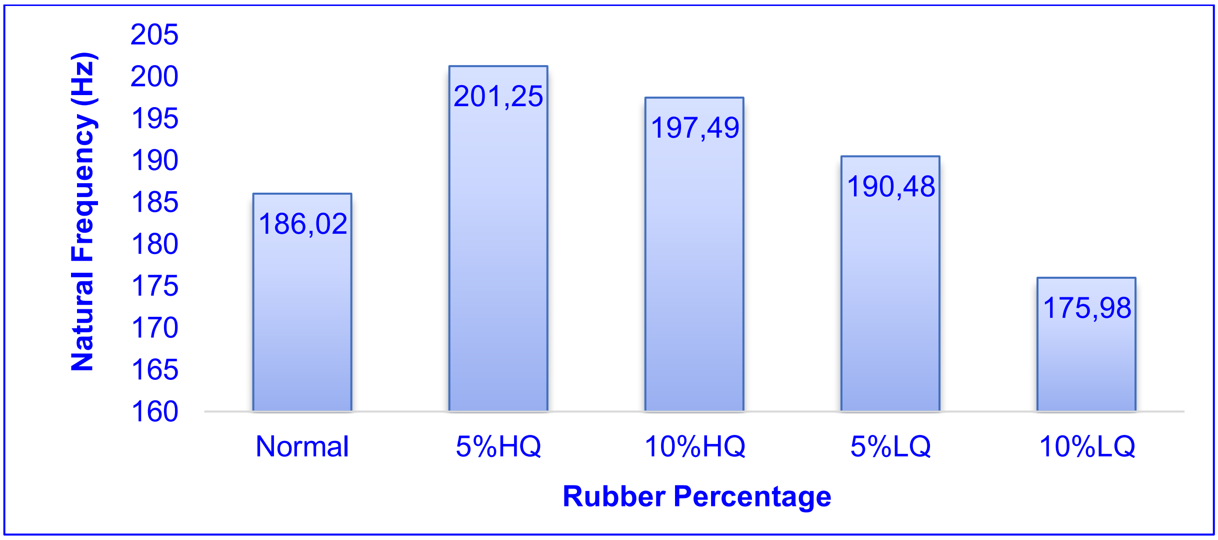
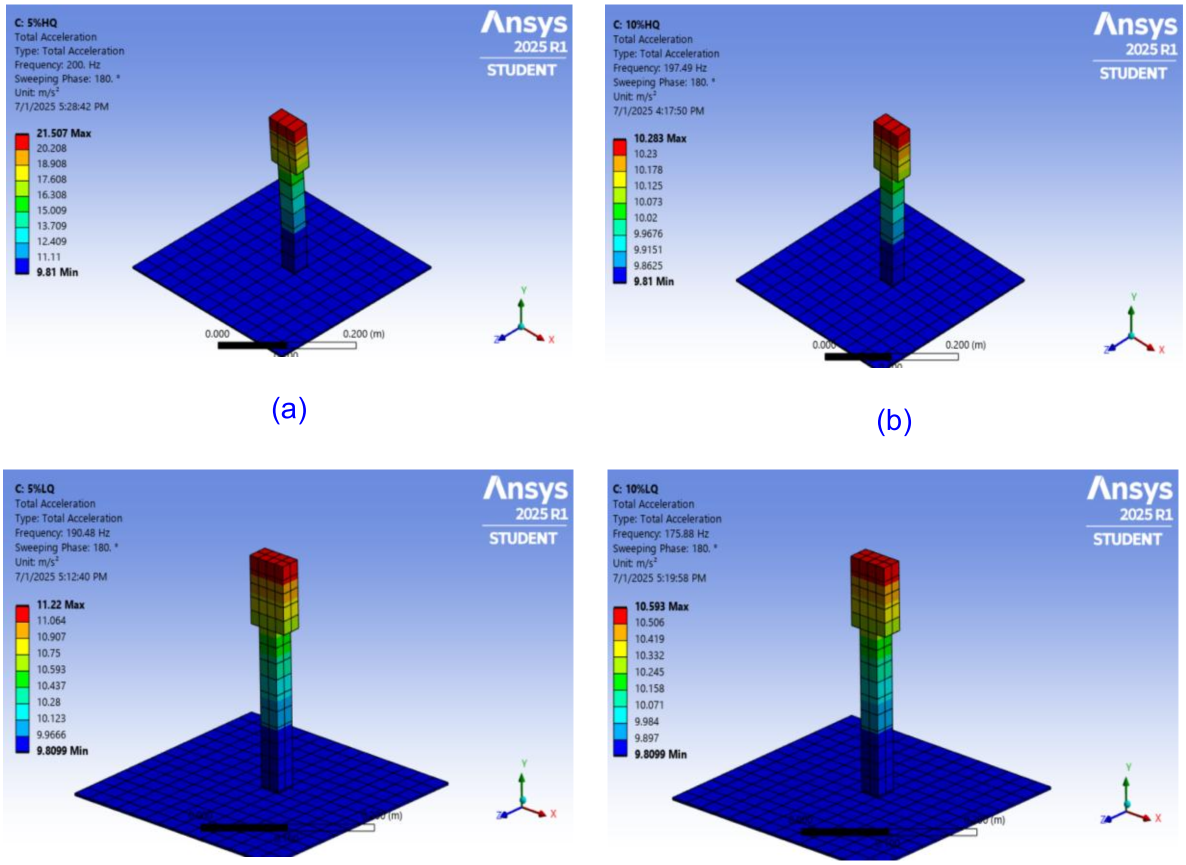


Figure 10. Natural frequency from modal analysis

3.3.2 Acceleration at lumped mass column at resonance condition

The acceleration response of concrete structures under resonance condition is a critical indicator of their vibrational performance and is fundamentally influenced by material damping, mass, stiffness, and energy dissipation properties. In this study, the introduction of rubber particles into concrete was evaluated as a means of enhancing damping characteristics and thus reducing acceleration responses. Baseline measurements for normal concrete yielded an acceleration response of 37.261 m/s². With the inclusion of high-quality rubber particles, a significant reduction in response was observed. At a 5% replacement level, the acceleration decreased to 21.507 m/s², representing a 42% reduction. This attenuation effect was even more pronounced at a 10% replacement, where the acceleration response dropped to 10.283 m/s², indicating a 72.40% reduction compared to the reference concrete.

In the case of low-quality rubberized concrete, although the damping properties were less optimal compared to high-quality rubber, notable reductions in acceleration response were still achieved. Specifically, the 5% replacement yielded an acceleration of 11.22 m/s² (a 68 % decrease), while the 10% replacement exhibited a slightly greater reduction to 10.593 m/s², corresponding to a 71.57% decrease. These findings suggest that the presence of rubber, regardless of its quality, introduces enhanced damping capacity and energy dissipation mechanisms within the concrete matrix, which are primarily responsible for the observed reductions in dynamic acceleration. The results corroborate the hypothesis that increased rubber content leads to improved energy absorption and damping behaviour, thus reducing vibrational amplitudes. However, the data also highlight that rubber quality plays a pivotal role, with high-quality rubber achieving more consistent and pronounced improvements at lower replacement ratios.



(a)

(b)

(c)

(d)

Figure 12. Acceleration response from simulation result at resonance. (a) 5% High quality rubberized concrete, (b) 10% High quality rubberized concrete, (c) 5 % Low quality rubberized concrete, and (d) 10 % Low quality rubberized concrete

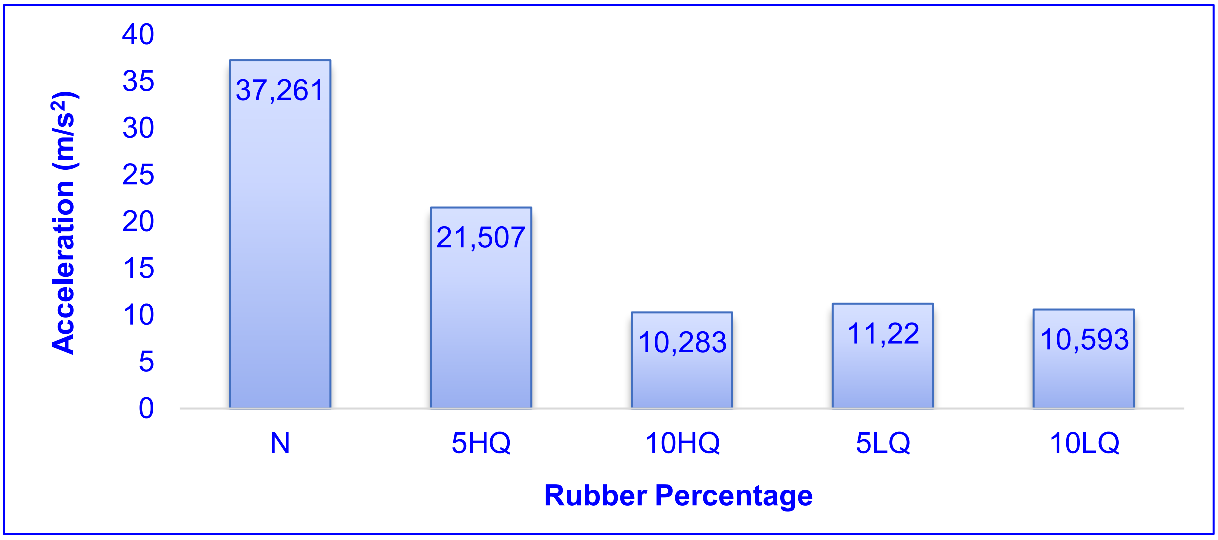


Figure 11. Acceleration response till resonance condition

3.4 Discussion

The experimental and numerical investigations carried out in this study demonstrate that incorporating crumb rubber into concrete significantly enhances its energy absorption and damping capacity. These findings support and expand upon previous research emphasizing rubberized concrete's potential for seismic applications. Previous studies have highlighted the damping advantages of rubberized concrete; for example, Abbas et al. (2022) and Saif (2025) observed that adding rubber enhances energy absorption and impact resistance but typically lowers compressive strength. Win et al. (2025) highlighted 5% replacement enhances compressive strength and modulus due to surface treatment of crumb rubber depending on crumb rubber type whereas 10% crumb rubber replacement as optimal for maximizing damping under free vibration.

In the present study, both the shaking table tests and finite element simulations consistently showed that higher rubber content results in lower peak acceleration. In addition, 72.4% reduction in acceleration at the 10% high-quality rubber level under resonance conditions were observed although the results revealed that normal concrete columns had the highest acceleration response. Interestingly, the study further distinguishes between rubber quality, a nuance not deeply explored in previous studies. This nuanced differentiation emphasizes the importance of material characterization, supporting the findings by Singh et al., (2025), who emphasized the role of microstructure and rubber treatment on dynamic performance. In terms of methodology, this research also contributes uniquely by integrating shaking table experimentation with ANSYS-based numerical simulation, offering cross-validated insights not commonly presented together in previous studies by Kan et al. (2025) and Zhang et al. (2023). This dual-approach strengthens the argument for rubberized concrete's application in earthquake-prone regions, particularly when quality and replacement percentages are optimized.

4. Conclusion

This study investigated the dynamic behaviour of rubberized concrete under vibrational loading, focusing on acceleration response. The results demonstrated that the inclusion of rubber particles, particularly of high quality, enhances damping characteristics and significantly reduces acceleration responses. Experimental and numerical analyses revealed a consistent trend of decreasing output frequency and acceleration response with increasing rubber content, attributed to improved energy dissipation. High-quality rubber at moderate replacement levels proved effective, reducing peak accelerations substantially. Moreover, low-quality rubber also showed benefits and, at higher replacement levels, led to improved vibrational performance. Overall, rubberized concrete, when properly engineered, offers a promising approach to improving the dynamic resilience of structural elements, though further optimization of rubber content and quality is essential for maximizing performance benefits.

In this study, scale effects, typically associated with smaller elements, are not considered. In addition, plain concrete and maximum aggregate size is also limited. However, when reinforcement is included and the aggregate size increases to 25 mm, the structural behaviour may differ slightly due to scale effects, particularly in strength and bond performance. Another fact is that the ACI code recommends using aggregate sizes less than 25 mm in actual construction to ensure better compaction, workability, and adherence to reinforcement spacing requirements.

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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Competing 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 human or animal as subject.

Data availability

The data will be available upon request.

AI statement

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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