

Article

Three-Dimensional Simulation on the Influence of Coated Rubber Chips on Concrete Properties

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Abstract

Rubber chips, when used as a partial replacement for coarse aggregates in concrete, tend to increase ductility, absorb energy, and can be beneficial due to their ability to reduce impact forces and dampen vibrations. However, they lead to a substantial decrease in compressive strength compared to ordinary concrete. Due to the weak bond between rubber particles and the concrete matrix, sand-coating surface treatment was applied to enhance the interfacial properties of the rubber surface. In this research, a detailed numerical analysis was conducted in order to predict the mechanical and dynamic behavior of concrete by incorporating partially replaced coarse aggregates with uncoated and sand-coated rubber chips. The study also seeks to examine the effects of rubber inclusion on key parameters such as damping ratio and compressive strength, thereby providing insights into the effectiveness of using recycled rubber as a sustainable alternative material in concrete production. The compressive strength and damping ratio of concrete were examined through a three-dimensional numerical simulation using ABAQUS/CAE 6.14-1. The results demonstrated that the optimal compressive strength was achieved with a 15% sand-coated rubber replacement, resulting in a 15.67% increment. Furthermore, the maximum improvements in damping ratios were observed to be 48.42% for uncoated rubber chips and 25% for coated ones, when compared to conventional concrete. These enhancements highlight the potential of both coated and uncoated rubber inclusions, due to rubber's high elasticity. Moreover, at optimized levels, improved concrete properties can be achieved while promoting sustainability through material reuse.

Keywords: compressive strength; damping ratio; three-dimensional; numerical analysis; rubber chips; sand coating; ABAQUS/CAE



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1. Introduction

Among the various materials used in modern construction, concrete is one of the most widely used, making it important to investigate its mechanical and dynamic behavior. Given the inherent limitations of conventional concrete in dynamic and demanding structural applications, enhancing its overall performance has become essential [1–4]. Enhancements can be achieved by incorporating supplementary cementitious materials, elastic granular components, and applying various techniques during its production. Moreover, incorporating fibers, polymeric admixtures, or elastic rubber elements can significantly enhance the damping behavior of concrete [4].

Numerous studies have explored the utilization of waste tire rubber chips as a replacement for natural coarse aggregates in the production of rubberized concrete [1–7]. Rubber materials exhibit distinctive properties, including low thermal conductivity, low density, high dynamic modulus, high damping capacity, and a very low rate of water absorption [2,7–9]. Owing to these characteristics, rubber enables efficient energy dissipation and contributes to improved damping behavior. Consequently, incorporating rubber chips into concrete improves its overall damping capacity [4,7,9].

Several studies have shown that utilizing waste tire rubber as a substitute for coarse aggregate in concrete leads to a reduction in the tensile, compressive, and flexural strengths of the resulting rubberized concrete [10–19]. However, it improves the damping capacity of concrete [4,7,19–21].

In a study conducted by Garrick et al. [19], the utilization of waste tire rubber chips as a partial replacement for coarse aggregates in concrete resulted in a reduction in compressive strength. This reduction was primarily attributed to the debonding of rubber particles from the concrete matrix. A key contributing factor for this reduction was the weak interfacial bonding between the hardened cement paste and the rubber surface [1,17,21,22].

The poor bond between rubber particles and the hardened cement paste has been identified as a key factor contributing to the reduction in the mechanical properties of rubberized concrete. Improving this bond could significantly enhance the performance of such concrete. One effective approach to achieving this improvement is by applying surface treatments to the rubber chips using various coating or mixing solutions.

Various studies have reported different surface treatment techniques applied to rubber particles to strengthen the interfacial bond between the rubber and the cement matrix, including sand coating [4,9], the use of oxidizing solutions [23,24], zinc stearate [25], use of solvents [26], soaking in water [27], silica fume coating [28] or other solutions.

Gebre et al. [9], conducted an experimental investigation on the use of sand-coated rubber chips in concrete. Their test results demonstrated that the compressive strength reaches its optimal at a 15% replacement level with sand-coated rubber chips, showing a 12.5% increase compared to the conventional concrete. Beyond this replacement level, the compressive strength starts to decline.

Mohammadi et al. [27] studied the effects of rubber treatment using a water-soaking method on the fresh and hardened properties of rubberized concrete. Their findings revealed that rubber treated with this method contributed to higher flexural and compressive strengths than untreated rubber and improved bonding between the rubber particles and the cement paste [27]. Additionally, waste tire rubber chips were subjected to chemical pretreatment using oxidizing agents, including water, 20% sodium hydroxide, and 5% calcium hypochlorite solutions. The effects of these treatments were evaluated on concrete mixtures with 8% rubber aggregates. Test results showed that calcium hypochlorite pretreatment outperformed both water and sodium hydroxide, leading to improved compressive and tensile strengths, along with reduced water permeability, when compared to concrete made with untreated rubber chips [23].

Research has also been conducted on the replacement of coarse aggregates with rubber chips to investigate the damping ratio of concrete. For instance, concrete containing rubber exhibited a higher damping ratio compared to conventional concrete. The results showed that the damping ratio increased with rubber content up to 30%, but beyond this point, further increases in rubber content caused the damping ratio to decrease [20]. Additionally, Gebre et al. [9], found that the damping ratio of concrete increased as the proportion of rubber aggregates in concrete increased, up to a 20% replacement level. The damping ratio remained higher than that of the conventional concrete beyond 20%, but it showed a declining trend.

The partial replacement of coarse aggregates with rubber chips has been found to significantly enhance the damping ratio of concrete [7]. Additionally, rubberized concrete

absorbed more energy than the control mix, thereby improving its toughness. These findings indicate that rubberized concrete has a strong ability to absorb dynamic loads [19].

In addition to experimental investigations, many researchers have explored the mechanical and dynamic behavior of concrete through advanced simulation and modeling software such as Virtual Cement and Concrete Testing Laboratory (VCCTL-v9.5), ABAQUS/CAE 6.14-1 and ANSYS (APDL)-17.0. For instance, concrete with coated aggregates was simulated using ABAQUS on a 2D concrete beam, predicting the damping ratio of concrete [29]. A summary of key findings from studies employing these simulation techniques to investigate concrete properties is presented below.

A study by [4] employed VCCTL-v9.5 software to simulate the compressive strength of concrete that had been partially replaced with uncoated and sand-coated rubber chips at replacement levels ranging from 0% to 25%. The findings showed that for sand-coated rubber chips, the optimal compressive strength was achieved at a 15% replacement level, but declined beyond this level. In contrast, concrete containing uncoated rubber chips exhibited a reduction in compressive strength.

Concrete mixtures with water-to-cement ratios varying from 0.4 to 0.55 were selected, and experimental tests were conducted to compare the compressive strength and modulus of elasticity predicted by the VCCTL-v9.5 software. The results showed that at water-to-cement ratios of 0.4 and 0.45, the software makes reasonable predictions for the modulus of elasticity compared to the specimens tested in the laboratory. However, for a w/c ratio of 0.5 and higher, the model slightly overestimated the elastic modulus of concrete [30].

In the numerical study conducted by [31], heavy core lead coatings combined with silicone, natural rubber, and nylon were used to examine the damping characteristics of concrete. The models incorporated coating thicknesses varying between 0.5 and 3 mm, with randomly generated aggregates having a maximum size of 24 mm. Modal and harmonic analyses were performed using software packages ANSYS (APDL)-17.0 and MATLAB R2019a, applying both harmonic and impact loading. The results demonstrated that coatings of silicone, natural rubber, and nylon improved the damping ratio compared to uncoated concrete. Notably, the highest damping ratio was achieved with a 1.0 mm thick rubber coating.

A study by [4] employed ABAQUS 6.14-1 simulation tools to perform Frequency Response Function (FRF) analysis on a 2D concrete beam, predicting the damping ratio of concrete that had been partially replaced with uncoated and sand-coated rubber chips at replacement levels varying from 0% to 25%. The findings demonstrated that the optimal damping ratio of concrete with uncoated rubber chips was achieved at the 25% replacement level. Meanwhile, concrete containing sand-coated rubber chips showed an improved damping behavior compared to conventional concrete but exhibited a lower damping ratio than the mix with uncoated rubber chips.

Recent advancements in numerical modeling have enabled detailed three-dimensional (3D) simulations to capture the heterogeneous and nonlinear behavior of concrete at the meso-scale [32–35]. Unlike two-dimensional (2D) or simplified analytical approaches, such as those presented in [4,29,36], three-dimensional simulations can explicitly represent the spatial distribution, shape, and interfacial characteristics of aggregates within the cementitious matrix. This allows for a more realistic evaluation of local stress transfer, crack propagation, and damage evolution under various loading conditions.

In this study, a detailed 3D modeling approach using ABAQUS is employed to explore the effects of partially replacing coarse aggregates with rubber aggregates in concrete mixtures, and to provide deeper insights into the resulting compressive strength and damping ratio in comparison with experimental observations. To enhance the bond between the rubber particles and the surrounding cement paste, a sand-coating surface treatment was

applied to the rubber chips. The effectiveness of this treatment was evaluated through finite element-based numerical analysis, focusing on two key parameters: compressive strength and damping ratio. Various replacement levels of uncoated and sand-coated rubber chips, up to 25%, were considered to assess both the structural integrity and energy absorption capacity of the modified concrete.

2. Numerical Modeling Using ABAQUS

The Finite Element Method (FEM) and Smoothed Particle Hydrodynamics (SPH) are both numerical techniques used to simulate concrete fracture; however, they differ fundamentally in terms of formulation and application. FEM is highly effective for problems with well-defined geometries and boundary conditions, whereas SPH is a mesh-free, particle-based method in which the material is represented by discrete particles.

For instance, the researchers [37] developed an enhanced SPH framework to model hydraulic fracturing in meso-structured concrete, effectively capturing crack initiation and propagation without the mesh dependency issues typical of conventional methods. Similarly, Yu et al. [38] employed a coupled thermo-hydro-mechanical damage SPH model to investigate frost-induced cracking mechanisms, highlighting the significant influence of aggregate distribution and pore structure on freeze–thaw durability. These studies demonstrate the capability of SPH to simulate extreme deformations and intricate fracture processes, offering a valuable complement to the FEM, which remains more efficient for conventional structural and controlled loading analyses [38].

In the present study, the FEM was employed using ABAQUS 6.14-1 software to determine the compressive strength and damping ratio of concrete with uncoated and sand-coated rubber aggregates.

2.1. Model Geometry and Aggregate Representation

The model comprises a 3D rectangular block matrix containing randomly distributed, non-overlapping solid spheres covered by spherical shells representing coating layers. To investigate the effect of coated spherical inclusions (representing rubber aggregates) on concrete behavior, a numerical procedure was developed using Python 3.12.4 scripting in ABAQUS/CAE to generate spheres and shells.

In this study, the rubber chips were modeled as perfect spheres, primarily to reduce computational complexity and to facilitate the generation of non-overlapping, randomly distributed inclusions within the concrete matrix. This simplification enables efficient meshing and ensures numerical stability throughout the simulation process.

It is acknowledged that actual aggregates exhibit irregular and angular shapes, which can influence local stress distribution and interfacial bonding behavior. However, several previous numerical studies [32–34] have also adopted spherical aggregates representations, demonstrating that this simplification provides reasonably accurate overall responses in terms of stiffness, strength, and damping characteristics.

2.2. Generate Spherical Rubber Aggregates

A Python script was developed to generate a rectangular block, non-overlapping solid spherical particles, and concentric shells. The sizes of the spherical particles, volume fractions, and coating shells vary as needed. The thickness of the shell corresponds to the coating thickness. These components—non-overlapping spherical particles and concentric shells—are generated randomly within a rectangular block and used to simulate the beam's behavior in 3D simulations.

With each iteration, a solid sphere is generated by selecting a random radius and a random center position (x_i , y_i , z_i) within the defined 3D spatial boundaries. A new

sphere is then generated, with its center at $(x_{i+1}, y_{i+1}, z_{i+1})$. Next, a function utilizing the 3D Euclidean distance formula is employed to ensure the newly created sphere does not overlap with any previously placed spheres. Once a non-overlapping solid sphere is generated, a concentric spherical shell is created around it to represent the coating layer with desired thicknesses.

2.2.1. Aggregate Size Distribution

The Fuller ideal grading curve is used for aggregate size distribution. The curve ensures that the concrete mix attains optimal aggregate strength and compaction [33,39].

2.2.2. Steps to Generate Random Spherical Aggregates

The numerical modeling procedure for generating random spherical aggregates and a concentric spherical shell (coating layer) within a rectangular block using Python script is presented below.

1. A prismatic beam with specified dimensions was created to serve as the domain into which spherical aggregates and concentric spherical shells were generated.
2. A solid sphere is generated by selecting a random radius and a random center position (x_i, y_i, z_i) within the defined boundaries (rectangular prism).
3. A new sphere is generated with its center at $(x_{i+1}, y_{i+1}, z_{i+1})$
4. To ensure that the newly generated spheres did not overlap, the distance between the centers of any two spheres was set to be greater than the sum of their radii.
5. Continue generating solid spheres until the specified volume of spheres is reached.
6. Each solid sphere was encapsulated in a hollow spherical shell of uniform thickness (thickness of coating materials), simulating a coated particle.
7. At each iteration, verify that all specified conditions are satisfied, including the total volume of aggregate, the minimum spacing between adjacent spheres, and the non-overlapping requirement.
8. Repeat the process until all spherical aggregates and their corresponding concentric spherical shells are generated and accurately positioned within the defined boundaries of the block.

2.3. Rubber Chip Size and Coating Thickness

In the simulation, spherical aggregates and concentric spherical shells were randomly generated within a rectangular block. Rubber chips having a size range of 12–25 mm and a uniform coating thickness of 2.0 mm were incorporated as partial replacements for coarse aggregates in concrete mixtures. These specific dimensions were selected to closely match with the actual aggregate sizes in concrete mixtures, ensuring realistic modeling and consistent interaction with the surrounding cement matrix during numerical analysis. Figure 1 shows the randomly generated spherical aggregates, while Figure 2 presents a solid sphere with a coating layer.

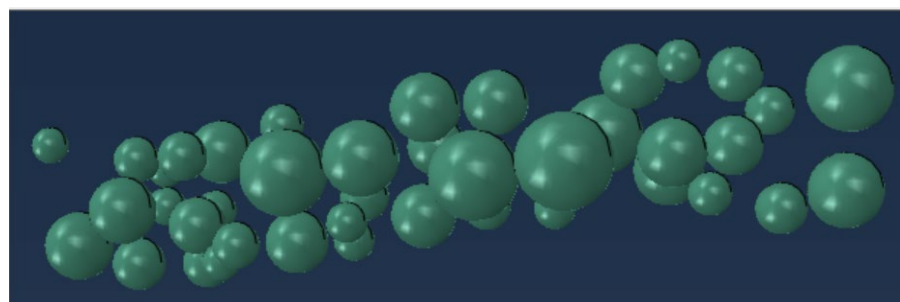


Figure 1. Randomly generated spherical aggregates with dimensions 12–25 mm.

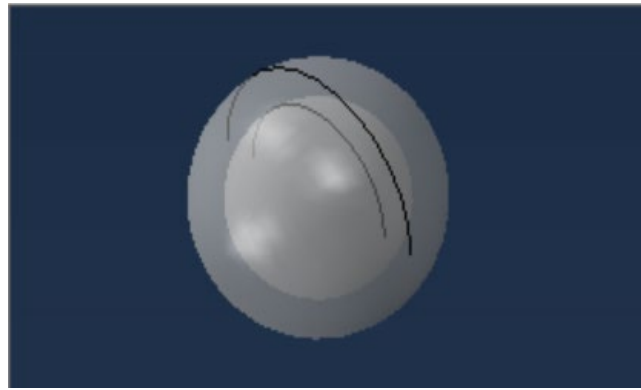


Figure 2. Sphere with coating layer (shell) of 2.0 mm.

2.4. Notation

In the numerical simulation, concrete mixes with coarse aggregates partially replaced by coated and uncoated rubber chips are assigned specific model codes. The conventional concrete model is designated as CCM-0, the concrete model with uncoated rubber chips as RM-n, and the concrete model with sand-coated rubber chips as SCRM-n. The replacement level is indicated by the letter n. (e.g., SCRM-5 represents concrete model with a 5% replacement of coarse aggregate by sand-coated rubber chips).

2.5. Numerical Simulations

To begin the simulation, a Python script was developed to generate randomly distributed spherical aggregates and concentric spherical shells within a rectangular block. The script is then imported into ABAQUS to perform the simulations. Once the material properties are assigned, then the created parts are assembled and meshed, to analyze the compressive strength and damping ratio of concrete.

The material properties of the concrete, standard sand, and rubber chips used in the numerical simulations are listed in Table 1 [4,29].

Table 1. Material properties.

Material	Density (kg/m ³)	Young's Modulus (GPa)	Poisson's Ratio ν
Concrete	2400	30	0.20
Standard sand	1130	1.0	0.35
Rubber	725	10	0.45

3. Determination of Compressive Strength and Damping Ratio

3.1. Determination of Compressive Strength

In order to predict the compressive strength of concrete using ABAQUS/CAE, a finite element analysis (FEA) model of a cube (150 mm × 150 mm × 150 mm) concrete specimen is developed, and randomly generated solid spheres and coating layers (spherical shells) are created to realistically simulate the actual compression test conducted in laboratories.

The appropriate material properties for concrete, standard sand, and rubber chips, such as Poisson's ratio, elastic modulus, and density are assigned. The Concrete Damaged Plasticity (CDP) model is used to represent the nonlinear, inelastic behavior of concrete under compression. In this part, the f_{b0}/f_{c0} ratio is approximately 1.16 (represents the biaxial to uniaxial compressive strength), the parameter K is taken as 0.667, and a viscosity parameter is set as 0 [40]. Additionally, a dilation angle of 40° was used in the model because different dilation angles in the CDP model have been reported in the literature.

For instance, dilation angles ranging from 20° to 40° have been suggested by [41], while analyses with dilation angles between 10° and 56.3° were used in [42].

Moreover, key damage parameters such as the compressive behavior (stress–strain data), which describes the inelastic deformation behavior of concrete under compression, and the tensile behavior (stress–strain data), which describes the cracking response of concrete, are obtained from the experimental investigation.

Figure 3 illustrates randomly distributed spherical aggregates within the cube model used for numerical simulation.

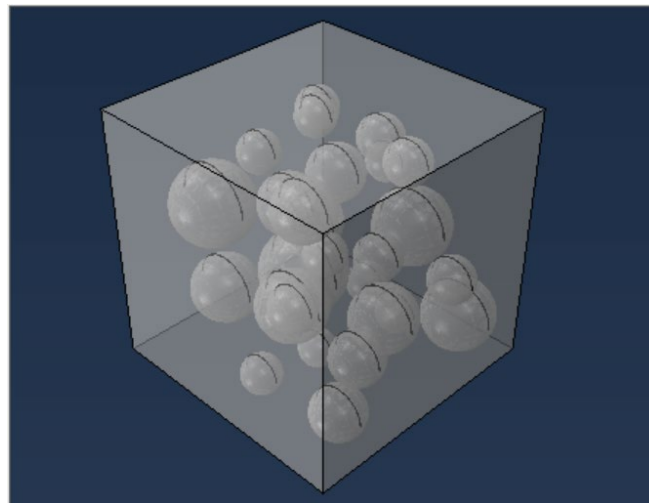


Figure 3. Randomly generated spherical aggregates.

3.1.1. Assembly

The three parts—a 150 mm cubic block, spherical aggregates, and concentric shells—are instantiated into the global coordinate system using the assembly module.

3.1.2. Meshing

For meshing, solid elements such as C3D8R, 8-node brick elements with reduced integration are used to accurately model the concrete.

3.1.3. Boundary Conditions

Boundary conditions are applied to imitate how the concrete specimen is physically held and loaded during an actual compression test in the laboratory, where one end of the specimen is fixed at the base, and free at the top (free to move only in the vertical direction).

3.1.4. Loading Conditions

Displacement-controlled loading is used in the simulations until failure to capture the post-peak behavior of concrete, with a 5 mm displacement applied at the top to simulate compression. In the simulation, the 5 mm displacement loading corresponds to an approximate loading rate that is consistent with the experimental conditions.

3.2. Determination of Damping Ratio

3.2.1. Assembly

The three parts—a 500 mm $\times$ 100 mm $\times$ 100 mm rectangular block, spherical aggregates, and concentric shells—are instantiated into the global coordinate system using the assembly module. Each part is meshed separately when it is independent, while a dependent part instance inherits the mesh configuration of the original part [43]. Figure 4 shows the randomly generated spherical aggregates within the rectangular block.

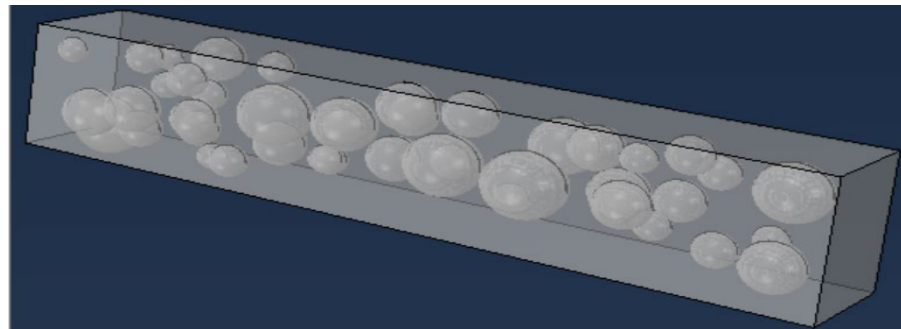


Figure 4. Randomly generated spherical aggregates within rectangular block.

3.2.2. Meshing

In the finite element model, a global seed size of 10 mm is applied, and the model is discretized using a free meshing technique with quadratic tetrahedral elements (C3D10). The mesh of the beam model is presented in Figure 5.

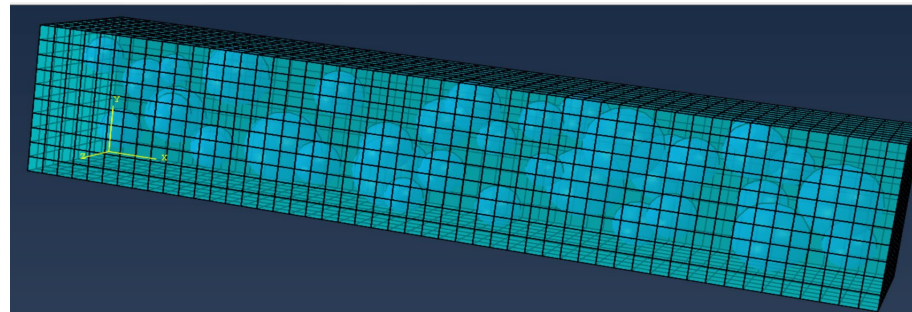


Figure 5. Mesh of the beam model.

3.2.3. Boundary Conditions

To develop a numerical model beam that corresponds to the experimental test setup, the modeled cantilever beam is fixed at the one end and free at the other end, with a point load applied at the free end.

3.2.4. Frequency Response Function (FRF) Analysis

The Frequency Response Function (FRF) analysis is carried out using a two-step procedure. In the first step, a modal analysis is performed to determine the natural frequencies and corresponding mode shapes of the structure. The results from this step are used to define the frequency range and the number of frequency points to be considered between successive modes. In the second step, the steady-state dynamic (modal) analysis option is selected. Within this step, the defined frequency range is applied, and a harmonic point load with an amplitude of 1 N is applied at the free end of the cantilever beam to determine the frequency response.

3.3. Validation of Numerical Simulation

The model was validated using experimental test results obtained from the findings of a previous study, ref. [9]. In the study [9], the mechanical and damping behavior of concrete, in which coarse aggregates were partially replaced by uncoated and sand-coated rubber chips at different volume fractions, was investigated experimentally.

The experimental investigation was carried out in the Materials Testing Laboratory of Addis Ababa University (AAU)—College of Technology and Built Environment (CTBE, formerly AAiT), School of Civil and Environmental Engineering (SCEE). The compressive strength and damping ratio predicted by the numerical simulations were compared with

the values obtained from physical tests [9]. A summary of the comparison between the experimental results and the corresponding simulation data is provided in Table 2.

Table 2. Validation of simulation results.

Notation	Compressive Strength (MPa)		Damping Ratio %		Ratio (Compressive Strength: Simulation/Expt.)	Ratio (Damping Ratio: Simulation/Expt.)
	Expt. (1)	ABAQUS (2)	Expt. (3)	ABAQUS (4)		
CCM-0	45.12	41.88	4.95	4.75	0.93	0.96
RM-5	46.95	43.56	5.54	5.07	0.93	0.92
RM-10	44.15	40.03	5.86	5.43	0.91	0.93
SCRM-10	49.09	45.64	5.47	5.25	0.93	0.96
SCRM-25	38.49	40.05	6.09	5.88	1.04	0.97

As shown in Table 2, the variation in the experimentally measured values and the predicted compressive strength of concrete obtained from ABAQUS simulation ranges from 4% to 9%. Moreover, experimental measurements and the predicted damping ratio of concrete with rubber and sand-coated rubber chips using ABAQUS simulation vary between 3% and 8%. The observed variabilities in compressive strength and damping ratio are mainly attributed to the random spatial distribution of aggregates and coating layers in the numerical model, as well as minor experimental uncertainties such as material heterogeneity and specimen preparation, which collectively influence stress transfer and energy dissipation mechanisms, resulting in the observed range of variability.

This lower variability between the experiment and simulation results can be considered good for numerical simulations. The level of agreement between the experimental data and the simulation demonstrates that the model is reliable for predicting the compressive strength and damping behavior of concrete with rubber and sand-coated rubber chips under the given conditions.

3.4. Results and Discussion

This study utilizes a 3D finite element modeling approach to predict the compressive strength and damping ratio of concrete with sand-coated and uncoated rubber chips. The simulation allows for more manageable analysis. As a result, the numerical simulation offers significant understanding of the concrete properties under various conditions, including natural frequencies, displacement response, stress distributions, and more. The results of the compressive strength and damping ratio of concrete are discussed in the following subsections.

3.4.1. Compressive Strength

The stress distribution and the force–displacement plot obtained from the simulation are presented in Figures 6 and 7, respectively. Moreover, from the force–displacement curves once the peak force is obtained for each simulation, the compressive strength of concrete with uncoated and sand-coated rubber chips is determined accordingly. The computed results are summarized in Table 3.

Table 3. Compressive strength and damping ratio of concrete.

Notation	Compressive Strength (MPa)	Standard Deviation	Damping Ratio (%)	Standard Deviation
CCM-0	41.88	0.112	4.75	0.123
RM-5	43.56	0.092	5.07	0.132

Table 3. Cont.

Notation	Compressive Strength (MPa)	Standard Deviation	Damping Ratio (%)	Standard Deviation
RM-10	40.03	0.106	5.43	0.098
RM-15	37.54	0.095	6.27	0.130
RM-20	37.59	0.101	6.92	0.107
RM-25	33.13	0.113	7.05	0.125
SCRM-5	45.97	0.123	4.97	0.106
SCRM-10	45.64	0.144	5.25	0.114
SCRM-15	47.75	0.142	5.87	0.125
SCRM-20	45.93	0.114	6.01	0.137
SCRM-25	40.05	0.131	5.88	0.129

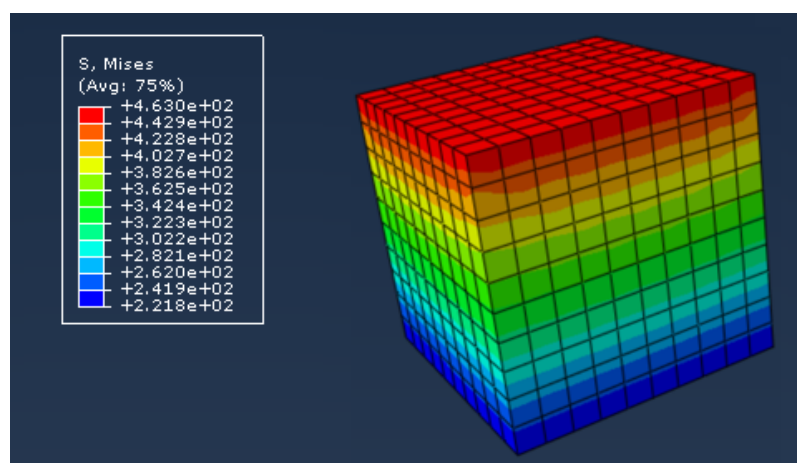


Figure 6. Von Mises stress distribution in RM-5.

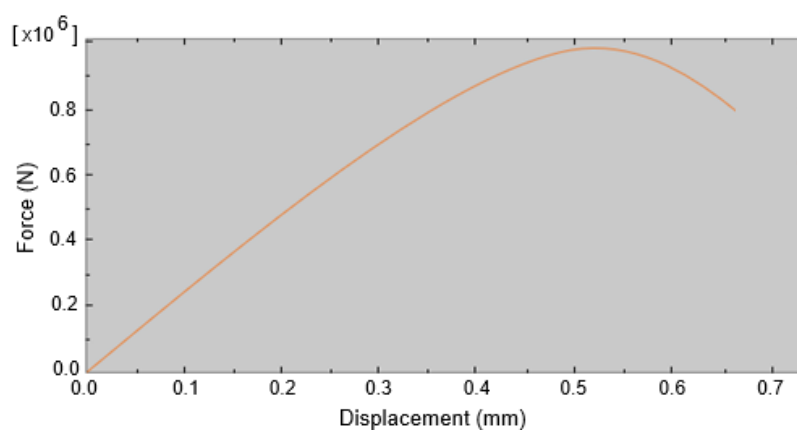


Figure 7. Force–displacement response of RM-5.

For example, Figure 7, which shows the force–displacement curve for the RM-5 concrete model obtained from the simulation, the peak force is approximately 0.98×10^6 N. The concrete cube has a cross-sectional area of $22,500 \text{ mm}^2$, and using the fundamental relation, the compressive strength is calculated as 43.56 MPa.

3.4.2. Damping Ratio

The damping behavior of a material is typically represented by the damping ratio, which can be evaluated by analyzing wave responses using techniques like the logarithmic decrement [44,45] and the half-power bandwidth methods [46]. However, in this study, the damping ratio was determined from the frequency response data in accor-

dance with the ASTM E756-05 standard [47], using the half-power bandwidth method, as expressed in Equation (1).

$$\xi = \frac{f_2 - f_1}{2f_0}, \quad (1)$$

where ξ is the damping ratio, f_0 is the resonance frequency, f_1 and f_2 are the frequencies on the either side of f_0 at which the vibration amplitude drops to 0.707 of the peak amplitude.

After the FRF analysis is performed, the frequency response data is obtained, in the form of amplitude versus frequency plots. From the plot, f_1 and f_2 are identified, and the damping ratio is subsequently calculated using Equation (1). This calculation involves identifying the resonance frequency and the corresponding half-power points, which are essential for determining the energy dissipation capacity of the concrete specimen [46].

The compressive strength and damping ratio of concrete, obtained through numerical simulations with coarse aggregates, are partially replaced by uncoated and sand-coated rubber chips, are illustrated in Figures 8 and 9, and summarized in Table 3.

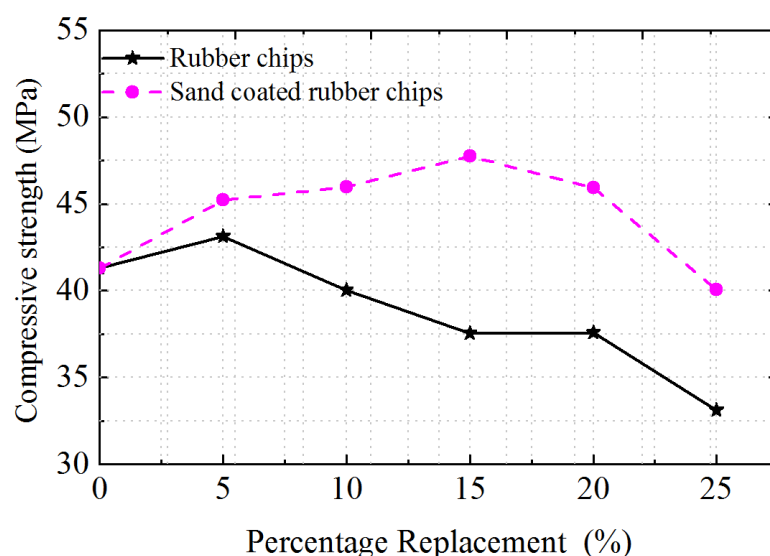


Figure 8. Compressive strength (MPa).

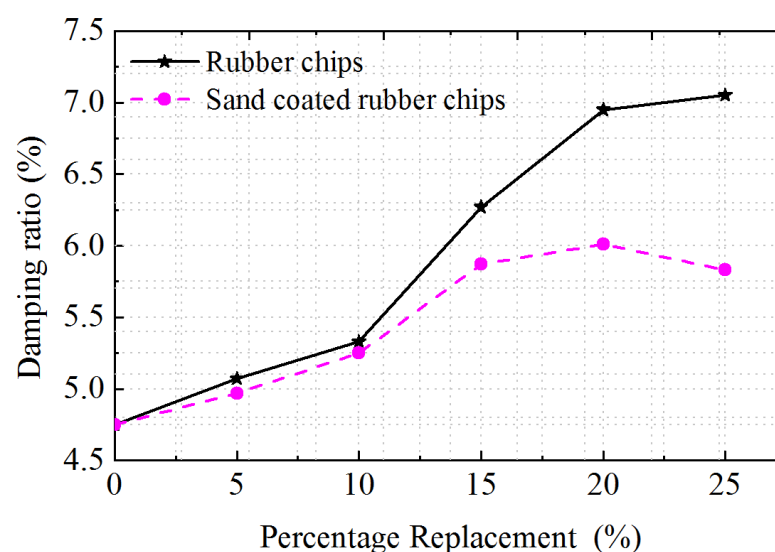


Figure 9. Damping ratio (%).

As indicated in Figure 8, for the concrete model with RM-5, the compressive strength was slightly increased by 4.48%, but a further increase beyond this replacement level

resulted in a reduction in compressive strength as compared to the conventional concrete model. This reduction is primarily attributed to the lower stiffness, low elastic modulus, and high deformability of rubber particles. These findings are consistent with previous studies conducted by Gebre et al. [9], Vijayan et al. [16], Siddiqui et al. [17], Banerjee et al. [18], Liu et al. [21], and Thiruppathi et al. [22], all of which reported that increasing the content of rubber chips in concrete results in a reduction in compressive strength of concrete. However, the simulation results show that the optimal compressive strength was achieved at a 15% replacement level of sand-coated rubber chips, yielding a 15.67% increase compared to the conventional concrete model.

Moreover, as presented in Figure 9, it was observed that an increase in rubber content in concrete causes a higher damping ratio compared to conventional concrete. It was also observed that the damping ratio of concrete increases with the percentage of sand-coated rubber chips, reaching its maximum at a 20% replacement level with an optimal damping ratio of 6.01%. Exceeding this proportion may negatively affect the concrete's damping properties. The reduction in damping ratio for sand-coated rubber beyond the 20% replacement level is attributed to the improved bond between the rubber and the concrete matrix due to the sand coating, which increases stiffness and strength by providing a rough interface but reduces energy dissipation at the interface by constraining the viscoelastic deformation of the rubber particles. A similar trend was observed in the previous study conducted by [9].

A maximum 48.42% increment in damping ratio was achieved for the uncoated rubber, while a 26.53% increase was reached for sand-coated rubber aggregates. With 20% sand-coated rubber aggregates, concrete is promised to have improved damping properties without affecting its compressive strength. Thus, enhancing damping properties can help to absorb and dissipate vibrations for concrete structures subjected to dynamic loads including wind, vehicular impacts and seismic forces. Moreover, concrete with uncoated and sand-coated rubber aggregates is suitable for sound barriers, industrial floors, bridges, or railway sleepers.

The result indicates that the damping ratio increases as the percentage content of rubber chips in the concrete mix increases. Comparable results were also reported by Sete et al. [7], Gebre et al. [9], Lin et al. [14], and Zheng et al. [20], who observed similar trends in their investigations. This highlights the potential of rubber chips to improve the energy dissipation capacity of concrete structures.

As shown in Table 3, the statistical evaluation of the simulation results demonstrates that the standard deviation of the compressive strength of concrete samples with uncoated and sand-coated rubber chips ranges from 0.092 to 0.144, while the damping ratio of concrete lies between 0.089 and 0.137. These relatively low standard deviations demonstrate that the variability across repeated simulations is minimal and consistent for each scenario, implying that the model consistently generates reliable results for specific volume fractions of aggregates and coating materials.

In conclusion, the low standard deviation values confirm the stability and dependability of the numerical simulation outcomes, providing a strong foundation for analyzing the effect of uncoated and sand-coated rubber chips on the compressive strength and damping characteristics of concrete. The consistency of the repeated simulations, even with changes in input parameters like aggregate distribution and coating patterns, underscores the robustness of the simulation framework.

4. Conclusions

Based on the numerical simulation findings, the key conclusions are summarized as follows:

- An increase in compressive strength of concrete is obtained with an optimal replacement level of 5% of rubber chips. Beyond this optimal level, a reduction in compressive strength was noticed, when compared to the conventional concrete model. This is mainly due to a large difference in elastic modulus between the rubber particles and other concrete ingredients. Thus, cracks appear along the contact zone of rubber and concrete matrix.
- Up to 20% replacement of coarse aggregates with sand-coated rubber chips, results in improvement in compressive strength. This shows coating the surface of rubber particles with sand results in a rough texture, which enhances the bond at the interface between the rubber and the concrete matrix. This improved interfacial bonding contributes to an increase in the compressive strength of concrete.
- Concrete with rubber chips, as well as concrete with sand-coated rubber chips up to 20% demonstrate enhanced damping capacity. This enhancement is attributed to rubber's high deformability under large loading, which helps in vibration reduction and impact resistance. This indicates its promising potential for use in structures, such as bridges and buildings, to minimize the risk of structural damage from dynamic and impact loads.
- To improve the damping properties of conventional concrete, partial replacement of natural coarse aggregates by chipped rubber and sand-coated rubber chips is suggested.
- Rubberized concrete demonstrates promising potential for various nonstructural applications, including acoustic insulation barriers, interior partitions, vibration-isolation pads, and lightweight wall construction. In practical applications, it has been successfully implemented in highway noise barrier panels to mitigate traffic-induced sound transmission, in interior partitions of office and industrial buildings, and in vibration-isolating floor systems or machinery foundations to reduce mechanical vibrations.
- Utilizing waste tire rubber chips as a partial replacement for coarse aggregates in concrete production offers a sustainable construction solution and contributes to environmental conservation by reducing the ever-growing demand for naturally sourced coarse aggregates.
- Unlike previous 2D or VCCTL-based studies, the 3D model captures the full three-dimensional distribution of spherical uncoated and coated rubber aggregates, including interactions between neighboring inclusions. This allows more realistic prediction of stress distribution, damping behavior, and the effect of coating layers.
- Numerical computational tools enable detailed analysis of concrete performance under various conditions, offering a cost-effective and efficient alternative to traditional laboratory testing.

5. Future Works

This study focused mainly on the mechanical properties and damping characteristics of concrete incorporating coated and uncoated rubber inclusions. In the future, this study can be extended by incorporating more advanced numerical models that capture the microstructural behavior of the interfacial transition zone between rubber chips and cement paste to improve prediction accuracy. Additionally, modeling the response of concrete with rubber inclusions under various dynamic loading scenarios, such as seismic or impact conditions, would provide deeper insight into its performance.

However, long-term durability aspects such as freeze–thaw resistance, water absorption, and permeability were not addressed in the present study. Future research should therefore extend this work to investigate these durability-related properties through combined experimental and numerical approaches, providing a more comprehensive un-

derstanding of the performance of concrete incorporating uncoated and coated rubber chips. Moreover, future work may incorporate more realistic, irregular particle geometries derived from image-based or stochastic modeling techniques to further refine interfacial behavior predictions.

Scaling up the simulations to analyze full structural elements and integrating multi-physics approaches to assess durability under environmental conditions are also promising directions for further numerical investigation.

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Abbreviations

The following abbreviations are used in this manuscript:

2D	Two-Dimensional
3D	Three-Dimensional
AAiT	Addis Ababa Institute of Technology
AAU	Addis Ababa University
ANSYS	Analysis System
APDL	ANSYS Parametric Design Language
ASTM	American Society for Testing and Materials
CAE	Complete ABAQUS Environment
CCM	Conventional Concrete Model
CDP	Concrete Damaged Plasticity
CTBE	College of Technology and Built Environment
DAAD	Deutscher Akademischer Austauschdiens
DFG	Deutsche Forschungsgemeinschaft
FEA	Finite Element Analysis
FEM	Finite Element Method
FRF	Frequency Response Function
RM	Rubber Chips Model
SCEE	School of Civil and Environmental Engineering
SCRM	Sand-Coated Rubber Chips Model
SPH	Smoothed Particle Hydrodynamics
VCCTL	Virtual Cement and Concrete Testing Laboratory

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