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Comparative Analysis of the Mechanical Properties of Cortical–Trabecular Bone Materials and Calcium Silicate Materials for Bone Tissue Engineering Applications

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ABSTRACT

Biomechanical modeling of bone is a crucial component of bone tissue engineering, as it enables a deeper understanding of the mechanical behavior of natural bone and substitute materials under physiological loading conditions. This study aims to compare the mechanical properties of cortical–trabecular bone as a tissue-supporting environment with calcium silicate ($CaSiO_3$) as an engineered artificial substitute, using the finite element method. A long-bone phantom model in the form of a hollow cylindrical structure was developed by separating cortical and trabecular regions and analyzed using ANSYS Workbench. The applied loading scenarios included lateral bending with a load of 500 N and axial compression with a load of 1000 N. The analyzed mechanical parameters were total deformation and equivalent (von Mises) stress. Simulation results show that cortical–trabecular bone is able to distribute stress more adaptively, with greater deformation occurring in the trabecular region and stress concentration in the cortical layer. Meanwhile, calcium silicate exhibits higher stiffness with smaller deformation but comparable maximum stress values. These findings indicate that the compatibility of mechanical properties between scaffold materials and natural bone significantly affects the effectiveness of bone tissue engineering applications.

1. INTRODUCTION

Biomechanical modeling of bone is an important approach in biomechanics and tissue engineering as it provides quantitative insights into how bone responds to mechanical loads under physiological and pathological conditions. Bone is not a simple homogeneous structure but a hierarchical composite material composed of cortical (compact) bone and trabecular (porous) bone, each having distinct functional and mechanical roles in supporting body loads. The microstructure and material composition determine bone strength, stiffness, and fracture resistance, which directly influence fracture risk and the response to implants and tissue-engineered scaffolds (Wang et al., 2022). Biomechanical modeling approaches, particularly the finite element method (FEM), are extensively employed to simulate the mechanical behavior of bone under diverse loading conditions and to predict stress and strain distributions at both tissue and organ levels. This approach is also essential for understanding bone remodeling processes influenced by mechanical stimuli, osteogenic cells, and the mechanostat mechanism in living bone (Boccaccio et al., 2011).

Material properties play a fundamental role in governing the mechanical response of bone tissue and scaffold structures in implant or substitute material design. Parameters such as elastic modulus, Poisson's ratio, and density are critical in determining a material's ability to transfer mechanical loads effectively without inducing stress shielding or premature structural failure (Niu et al., 2023). Cortical bone exhibits a substantially higher elastic modulus and density than trabecular bone due to its compact structure dominated by inorganic mineral content and well-organized collagen fibers. In contrast, trabecular bone, characterized by its porous architecture, displays lower stiffness but efficiently dissipates mechanical loads through its complex trabecular lattice network (Barak, 2024). FEM-based bone tissue modeling demonstrates that variations in material properties, including elastic modulus and microstructural heterogeneity, strongly influence stress distribution and overall mechanical response predictions.

In the context of bone tissue engineering, substitute materials such as calcium silicate ($CaSiO_3$) have been extensively explored as bioactive scaffolds capable of supporting new bone growth and biological integration. Calcium silicate materials are known for their high bioactivity and biocompatibility, as well as their ability to bond with bone tissue through the formation of a surface mineral phase. However, the mechanical properties of pure calcium silicate tend to be more brittle and mechanically weaker than compact bone, especially when used in porous 3D ceramic forms (Liu et al., 2023). Material modification strategies, such as ion doping or composite reinforcement, have been developed to improve mechanical properties while maintaining bioactivity. Differences in elastic modulus and mechanical response between natural bone tissue and scaffold materials such as $CaSiO_3$ remain a major issue, as mechanical mismatch can negatively affect healing effectiveness and implant durability (Min et al., 2024).

Based on these considerations, this study aims to perform a biomechanical comparison between natural bone materials (cortical and trabecular) as an environment for tissue support and calcium silicate ($CaSiO_3$) as an engineered artificial substitute in scaffold or implant design. The main focus is to evaluate differences in mechanical properties such as elastic modulus, Poisson's ratio, and density, with the goal of providing a stronger mechanical and design foundation for the development of optimal bone scaffolds and realistic in silico modeling. This comparative approach is expected to provide a comprehensive understanding of the advantages and challenges associated with each material in clinical bone tissue engineering applications.

2. METHOD

The phantom model used in this study represents a simplified long bone shaft resembling the diaphysis of the femur. The geometry consists of a hollow cylindrical structure composed of two main regions: a cortical layer as the outer shell and a medullary cavity in the inner region. The primary geometric dimensions of the bone phantom were specified as a total length of 300 mm, an outer diameter of 30 mm, and a cortical thickness of 5 mm, producing a medullary cavity with an approximate diameter of 20 mm. A simplified trabecular region was incorporated at the proximal section, modeled as a homogeneous porous cylindrical structure with a diameter of 18 mm and a length of 40 mm, representing an idealized trabecular bone configuration. The cortical and trabecular regions were geometrically separated to allow the assignment of different material properties in the finite element analysis software. The geometric model was created using SolidWorks and imported into ANSYS for biomechanical simulation. ETS materials were modeled as linear elastic, isotropic materials using realistic mechanical parameters commonly reported in biomechanical bone modeling literature.

Cortical bone was represented as a rigid material characterized by an elastic modulus (E) of 17 GPa, a Poisson's ratio (ν) of 0.30, and a density (ϱ) of 1900 kg/m^3, reflecting typical mechanical properties of human cortical bone in the longitudinal direction. The trabecular region was modeled as a more compliant porous material, with an elastic modulus (E) of 0.5 GPa, a Poisson's ratio (ν) ranging from 0.20 to 0.30, and a density (ϱ) between 800 and 1200 kg/m^3. These values reflect the mechanical characteristics of trabecular bone, which strongly depend on density and microarchitecture but remain within realistic ranges reported in the literature (Kaur et al., 2019). As a comparative engineered substitute to natural bone materials, calcium silicate ($CaSiO_3$) was employed as a bioceramic scaffold material with mechanical properties specified by an elastic modulus (E) in the range of 20–30 GPa, a Poisson's ratio (ν) between 0.22 and 0.25, and a density (ϱ) of 2800–3000 kg/m^3. The elastic modulus of $CaSiO_3$ lies within the range of bioactive ceramic materials and may approach or exceed that of cortical bone, although it exhibits higher brittleness.

2.1. Loading Scenarios, Boundary Conditions, and Modeling Assumptions

2.1.1 Loading Scenarios and Boundary Conditions

Two wo primary loading conditions were implemented to assess the mechanical response of the bone phantom and the comparison material. In the lateral bending condition, a 500 N load was applied perpendicular to the longitudinal axis of the bone. The proximal end of the phantom was fully constrained (all degrees of freedom restricted), while the load was applied at the mid-shaft to induce maximum bending effects. This condition was designed to evaluate peak stress in the lateral cortical region and the maximum deflection resulting from bending. In the axial compression condition, a compressive load of 1000 N was applied along the longitudinal axis of the bone. The proximal end was fixed, and the load was applied at the distal end to analyze the von Mises stress distribution, axial deformation, and the differences in mechanical response between natural bone and calcium silicate materials.

2.1.2 Modeling Assumptions

Numerical simulations were performed using ANSYS Workbench (Static Structural module). The meshing strategy employed solid tetrahedral/hexahedral elements with an initial element size of 0.5 mm, refined to 0.01 mm in critical regions such as the cortical wall, cortical–trabecular transition zone, and load application areas. All materials were assumed to be linear elastic, isotropic, and subjected to small deformations. Viscoelasticity, plasticity, and material damage were not considered. This approach was chosen to enable a controlled numerical comparison of mechanical responses between biological materials and engineered materials.

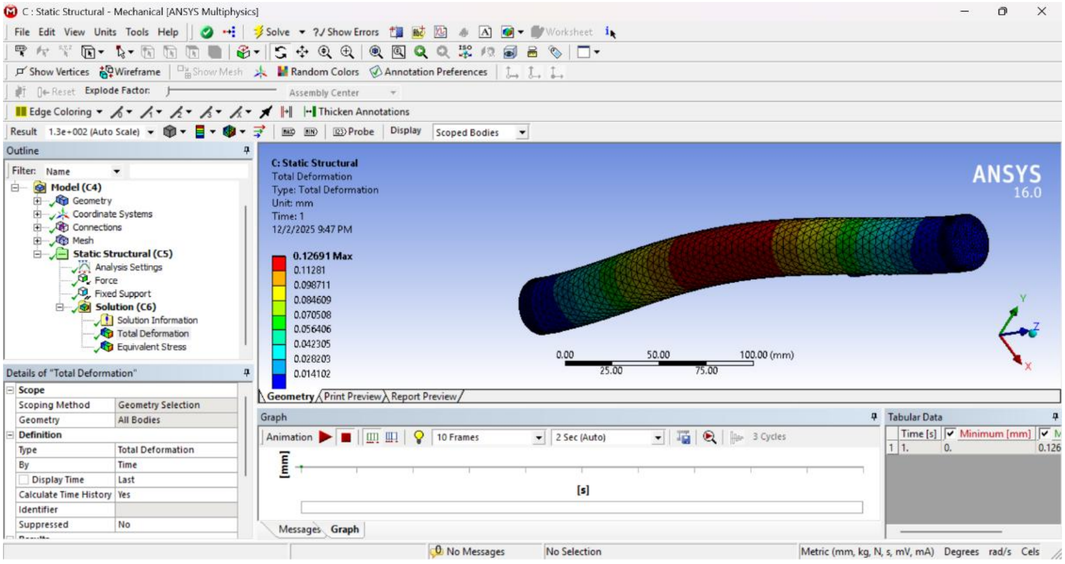
3. RESULTS AND DISCUSSION

3.1. Simulation Results for Cortical–Trabecular Bone Material

Numerical analysis was conducted using ANSYS Mechanical – Static Structural to evaluate the mechanical response of the bone implant phantom composed of trabecular and cortical bone, modeled as linear elastic isotropic materials. The cylindrical phantom model was subjected to fixed support at one end and applied loads at the opposite end to represent physiological loading conditions. Cortical bone, with its higher elastic modulus, acts as the primary load-bearing component, while trabecular bone serves as a more flexible supporting structure.

The total deformation results show that the maximum displacement occurs at the free end of the phantom, while the minimum deformation is located at the fixed support. As illustrated in Figure 1, the total deformation of the cortical–trabecular material under a 500 N load is 0.12691 mm, and in Figure 2, under a 1000 N load, it reaches 0.25383 mm. The increase in maximum deformation from 0.12691 mm to 0.25383 mm with increasing load indicates a linear relationship between the applied force and the deformation response. The trabecular region exhibits greater deformation due to its lower elastic modulus, while the cortical layer constrains the overall deformation and preserves structural stability.

The equivalent (von Mises) stress distribution reveals that the highest stress concentrations are localized within the cortical layer, particularly near the fixed support and at the trabecular–cortical interface. As shown in Figure 3, the maximum von Mises stress for the cortical–trabecular material under a 500 N load is 14.723 MPa, while in Figure 4, under a 1000 N load, it reaches 29.447 MPa. This indicates an increase in maximum stress from 14.723 MPa to 29.447 MPa with increasing load, whereas the trabecular region exhibits lower stress levels but higher deformation. These findings demonstrate that the cortical–trabecular composite structure effectively distributes mechanical loads and provides a realistic representation of human bone biomechanical behavior under elastic conditions.



C : Static Structural - Mechanical [ANSYS Multiphysics]

Result 1.3e+002 (Auto Scale)

Display Scoped Bodies

C: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
12/2/2025 9:47 PM

0.12691 Max
0.11281
0.098711
0.084609
0.070508
0.056406
0.042305
0.028203
0.014102

Details of "Total Deformation"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Total Deformation
By	Time
☐ Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No

Tabular Data

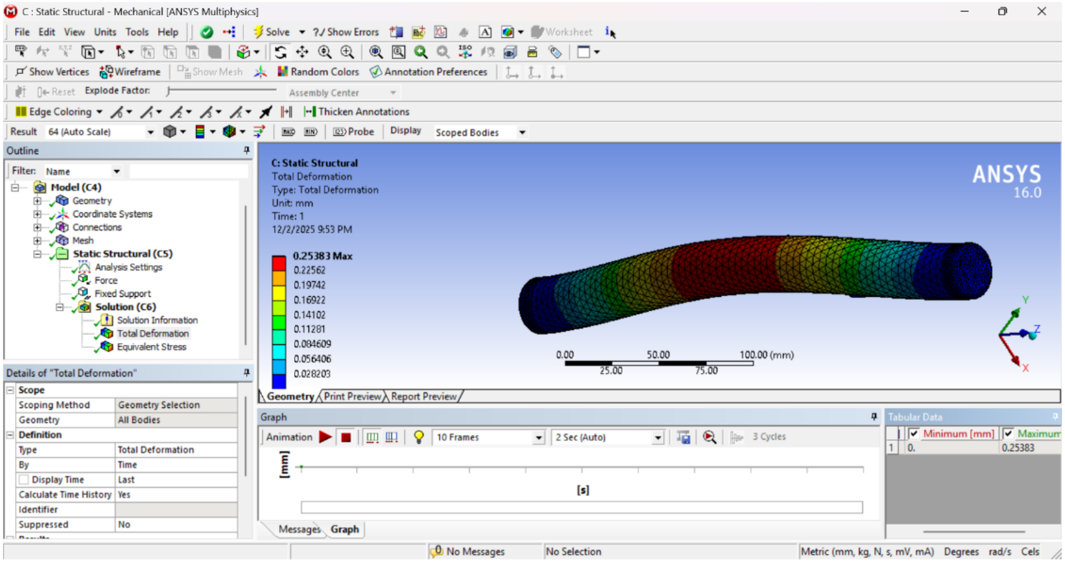
	Time [s]	☑ Minimum [mm]	☑ M
1	1.	0.	0.126

0 No Messages

No Selection

Metric (mm, kg, N, s, mV, mA) Degrees rad/s Celsius

Figure 1. Total Deformation Distribution of Cortical–Trabecular Material under a 500 N Load



C : Static Structural - Mechanical [ANSYS Multiphysics]

Result 64 (Auto Scale)

Display Scoped Bodies

C: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
12/2/2025 9:53 PM

0.25383 Max
0.22562
0.19742
0.16922
0.14102
0.11281
0.084609
0.056406
0.028203

Details of "Total Deformation"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Total Deformation
By	Time
☐ Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No

Tabular Data

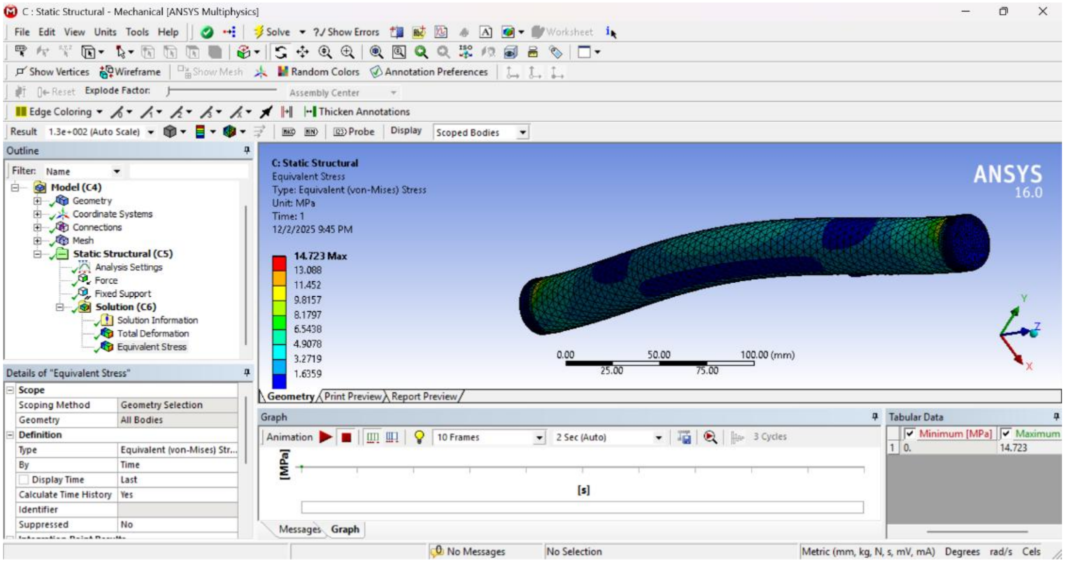
	☑ Minimum [mm]	☑ Maximum
1	0.	0.25383

0 No Messages

No Selection

Metric (mm, kg, N, s, mV, mA) Degrees rad/s Celsius

Figure 2. Total Deformation Distribution of Cortical–Trabecular Material under a 1000 N Load



C : Static Structural - Mechanical [ANSYS Multiphysics]

C: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
12/2/2025 9:45 PM

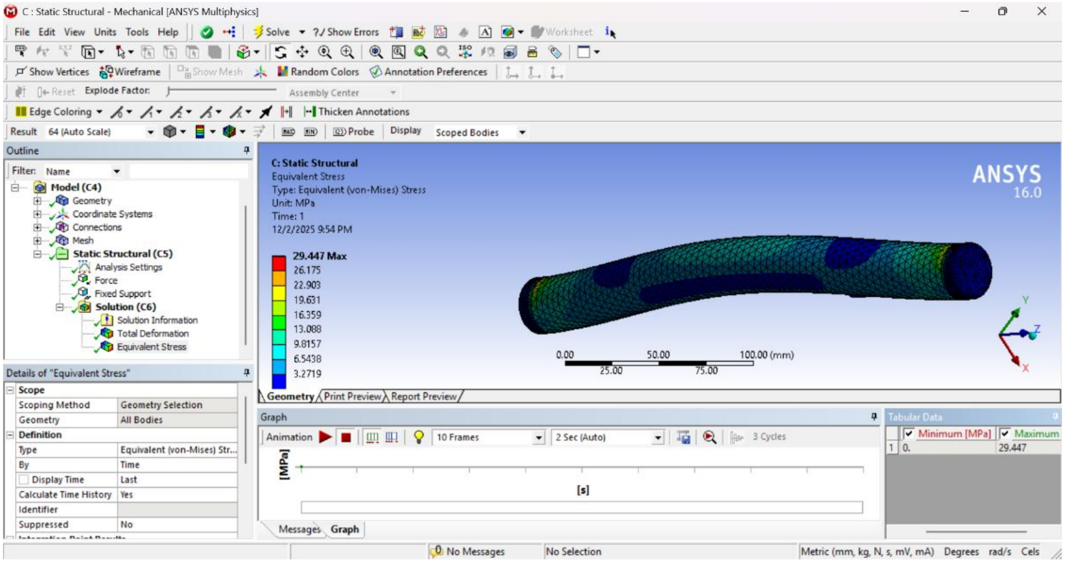
Details of "Equivalent Stress"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Equivalent (von-Mises) Str...
By	Time
Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No

Tabular Data

	Time [s]	☑ Minimum [MPa]	☑ Maximum
1	1.	0.	14.723

Figure 3. Equivalent (von Mises) Stress Distribution of Cortical–Trabecular Material under a 500 N Load



C : Static Structural - Mechanical [ANSYS Multiphysics]

C: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
12/2/2025 9:54 PM

Details of "Equivalent Stress"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Equivalent (von-Mises) Str...
By	Time
Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No

Tabular Data

	Time [s]	☑ Minimum [MPa]	☑ Maximum
1	1.	0.	29.447

Figure 4. Equivalent (von Mises) Stress Distribution of Cortical–Trabecular Material under a 1000 N Load

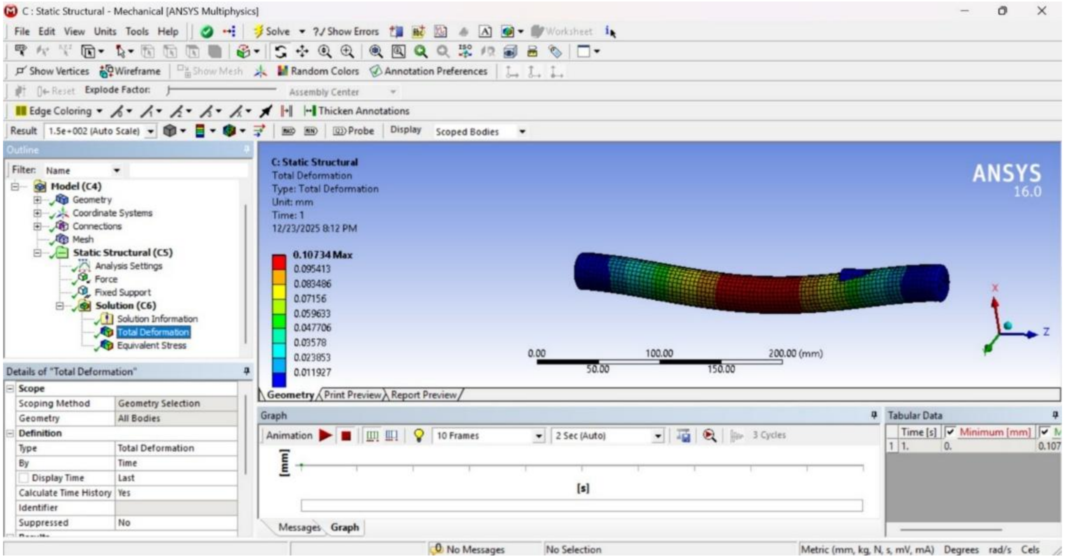
3.2. Simulation Results for Calcium Silicate Material

Numerical simulations were performed using ANSYS Mechanical – Static Structural to investigate the mechanical response of a bone implant phantom composed of cortical and trabecular bone, both modeled as linear elastic isotropic materials. The cylindrical phantom was subjected to a fixed boundary condition at one end and external loading at the opposite end to represent physiological loading conditions. Due to its higher elastic modulus, cortical bone functioned as the primary load-bearing component, whereas trabecular bone acted as a more compliant supporting structure.

The simulation results indicate a maximum total deformation of 0.10734 mm under a 500 N load, as presented in Figure 5, and 0.21468 mm under a 1000 N load, as shown in Figure 6, with the minimum deformation occurring at the fixed support. The highest deformation is concentrated in the central region of the phantom, represented by the red contour zone, which reflects the region of maximum bending-induced deflection. These deformation magnitudes remain relatively small compared to the overall geometric dimensions, demonstrating that the structure possesses sufficient stiffness to sustain the applied mechanical loads.

The equivalent (von Mises) stress distribution exhibits a maximum value of 15.245 MPa under a 500 N load, as shown in Figure 7, and 30.49 MPa under a 1000 N load, as presented in Figure 8, while the minimum stress approaches 0 MPa. The maximum stress is concentrated in the middle region and near the transition to the support area, which is a critical region due to the tensile and compressive stresses occurring simultaneously during bending. This stress distribution pattern is consistent with classical mechanics of materials theory, where the maximum stress in a bent beam occurs at the outer fibers in the region of maximum bending moment. Increasing the load directly increases the magnitude of the internal stress without significantly altering its distribution pattern, confirming that the response remains within the linear elastic regime.

Overall, the simulation results indicate that calcium silicate material in the bone implant phantom can withstand mechanical loading with relatively uniform stress and deformation distributions and without extreme stress concentration. The maximum stress values remain below the commonly reported failure limits of calcium silicate materials, suggesting their potential suitability as bone implant or scaffold candidates under static loading conditions.



C : Static Structural - Mechanical [ANSYS Multiphysics]

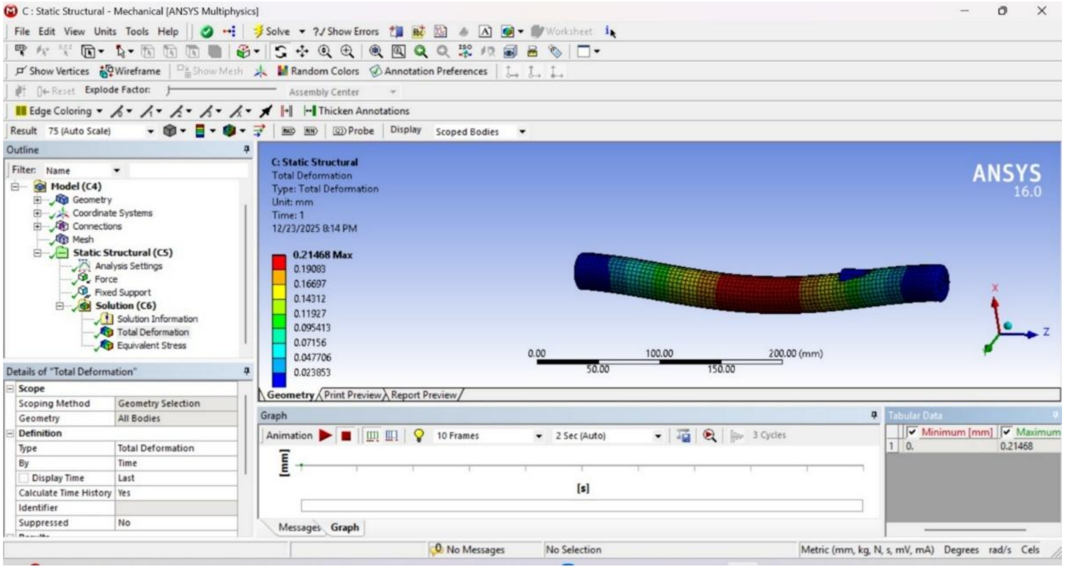
Result: 1.5e+002 (Auto Scale)

C: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
12/23/2025 8:12 PM

Details of "Total Deformation"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Total Deformation
By	Time
☐ Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No

Figure 5. Total Deformation Distribution of Calcium Silicate Material under a 500 N Load



C : Static Structural - Mechanical [ANSYS Multiphysics]

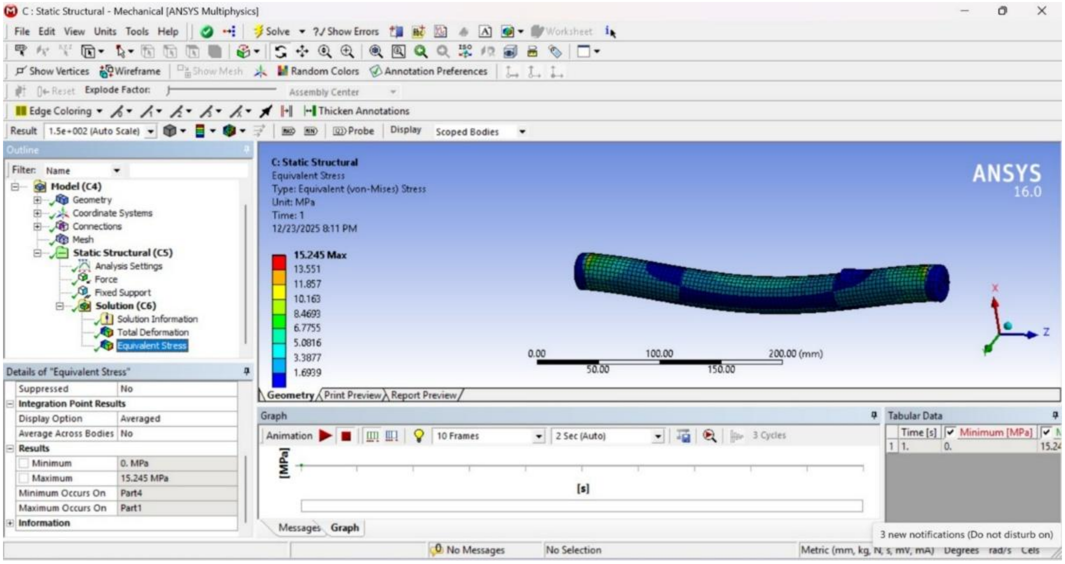
Result: 75 (Auto Scale)

C: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
12/23/2025 8:14 PM

Details of "Total Deformation"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Total Deformation
By	Time
☐ Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No

Figure 6. Total Deformation Distribution of Calcium Silicate Material under a 1000 N Load

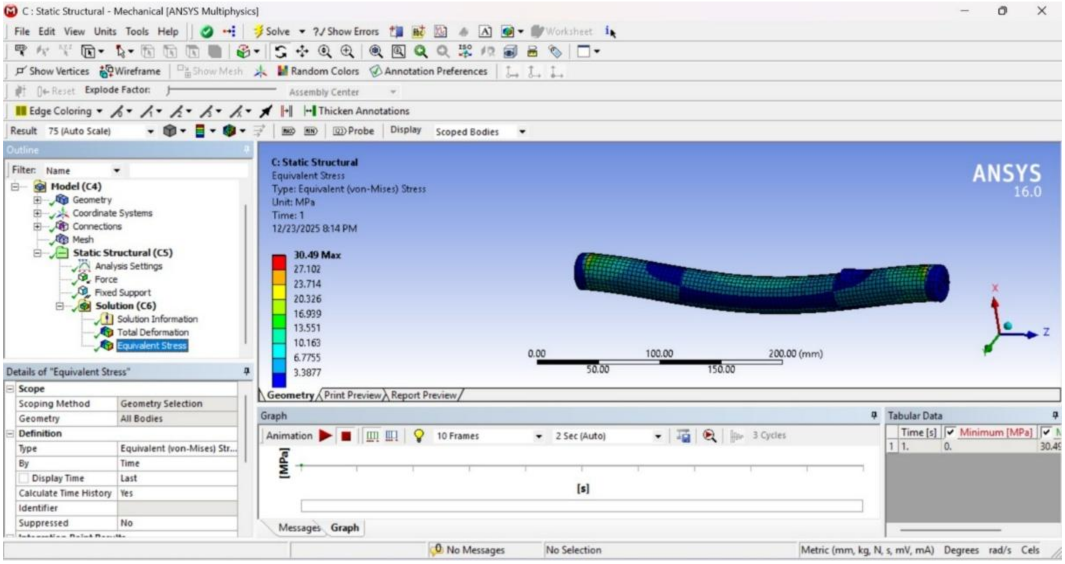


C: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
12/23/2025 8:11 PM

Details of "Equivalent Stress"

Suppressed	No
Integration Point Results	
Display Option	Averaged
Average Across Bodies	No
Results	
Minimum	0. MPa
Maximum	15.245 MPa
Minimum Occurs On	Part4
Maximum Occurs On	Part1
Information	

Figure 7. Equivalent (von Mises) Stress Distribution of Calcium Silicate Material under a 500 N Load



C: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
12/23/2025 8:14 PM

Details of "Equivalent Stress"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Equivalent (von-Mises) Str...
By	Time
Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No

Figure 8. Silika Equivalent (von Mises) Stress Distribution of Calcium Silicate Material under a 1000 N Load

4. CONCLUSION

This study successfully conducted a comparative analysis of biomechanical responses between cortical–trabecular bone as a natural material and calcium silicate as an engineered material using the finite element method. Simulation results demonstrate that cortical bone plays a dominant role in load-bearing with higher stress concentrations, while trabecular bone functions as a more flexible supporting structure with greater deformation. Their combined structure results in effective stress distribution that closely resembles the physiological biomechanical behavior of human bone.

Calcium silicate material shows less deformation due to its higher elastic modulus of 20 GPa, indicating good stiffness under static loads. However, differences in mechanical properties between $CaSiO_3$ and natural bone can lead to mechanical mismatch if not optimally designed, emphasizing the importance of matching the scaffold's mechanical properties with bone tissue to avoid stress shielding.

The limitations of this study include the assumption of linear elastic isotropic material behavior and the exclusion of viscoelastic effects and material degradation. Future studies are recommended to develop nonlinear models, incorporate scaffold pore structures, and validate simulation results with experimental data to achieve more realistic biomechanical modeling.

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