



RESEARCH ARTICLE

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FINITE ELEMENT ANALYSIS OF BONE-DERIVED HYDROXYAPATITE, ZINC-DOPED HYDROXYAPATITE, AND PLGA–ZN-HAP COMPOSITES FOR BIOMEDICAL APPLICATIONS

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ABSTRACT

Bone-derived hydroxyapatite (HAp) is highly biocompatible but lacks mechanical strength. This study addresses this limitation by adding zinc (Zn) and poly (lactic-co-glycolic acid) (PLGA) to enhance performance. We synthesised goat-bone HAp via calcination and chemical treatment, incorporated Zn to improve crystallinity and antibacterial activity, and reinforced it with PLGA for better flexibility and load-bearing capacity. Finite element modelling in ANSYS (100–1000 N loading) showed that pure HAp is stiff but brittle, Zn-HAp is stronger, and the PLGA-Zn-HAp composite has the greatest toughness, stress distribution, and fracture resistance. Simulations closely matched experiments, confirming that Zn and PLGA strengthen natural HAp and make the composite a promising, cost-effective choice for orthopaedic implants.



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I. INTRODUCTION

Hydroxyapatite (HAp), a bio ceramic with excellent biocompatibility and close chemical resemblance to natural bone, is widely explored for bone tissue engineering but is limited by brittleness and low fracture toughness [1]. To overcome these drawbacks, reinforcing HAp with biodegradable polymers like PLGA and metal dopants such as zinc (Zn²⁺) has shown significant improvements in flexibility, mechanical strength, osteoconductivity, and antibacterial behaviour. In this study, HAp was sustainably derived from goat bone through thermal and chemical processing, offering a cost-effective, eco-friendly, and biogenic alternative to synthetic routes while supporting waste-to-resource utilization. The combined use of PLGA, Zn–HAp, and finite element analysis (FEA) provides a holistic approach for developing stronger, bioactive, and more reliable composites for orthopaedic and dental implants [2]. Although goat bone-derived HAp offers advantages such as biocompatibility, low cost, and environmental sustainability, challenges remain regarding variability in composition, limited mechanical strength, and processing demands. Future work includes optimizing synthesis, exploring additional dopants, conducting biocompatibility studies, and developing advanced composites with improved load-bearing capacity and controlled degradation [3], [4].

II. METHODOLOGY

II.1 MATERIALS

Supported by standard femur dimensions from orthopaedic literature, the study used ANSYS Workbench for finite element analysis and CREO Parametric for 3D femur modelling. To evaluate the comparative behaviour of porous HAp, Zn-HAp, and PLGA–Zn-HAp, mechanical property data were used. To effectively handle CAD modelling and FEA computations, all simulations were run on a high-performance workstation with a minimum of 16 GB RAM, a dedicated GPU, and a multi-core processor [5] [6].

II.2 METHODOLOGY

The main tools for geometric modelling and finite element simulation in this work were CREO Parametric and ANSYS Workbench. Using normal anatomical proportions from reputable orthopaedic literature, a three-dimensional femur model was created in CREO Parametric to precisely depict important aspects such as the femoral head, neck-shaft angle, shaft curvature, and condylar geometry. After that, the finished model was exported for simulation in STEP format. The femur was given the mechanical characteristics of porous HAp, Zn-HAp, and PLGA-Zn-HAp in ANSYS Workbench using data from verified biomaterials research, including density, Young's modulus, Poisson's ratio, and compressive strength. These properties were used to evaluate each material's suitability as possible load-bearing implant materials in the femoral region and to examine how each material responded structurally under physiological loading.

II.3 SAMPLE VARIATIONS

Table 1: Sample Variations.

Sample Code	Composition	Purpose
S1	Pure HAp	Baseline
S2	Zn-HAp (2 wt% Zn)	Evaluate Zn substitution
S3	PLGA-Zn-HAp (60:40)	Evaluate polymer-ceramic synergy

Source: Authors, (2026).

II.4 MATERIAL ASSIGNMENT HAP, 2% ZN-HAP, PLGD-ZN-HAP

Table 2: Material Assignment HAp, 2% ZN-HAp, PLGD-ZN-Hap.

Material	Porous HAp	2% Zn-HAp	PLGA-Zn-HAp (60:40)
Density (g/cm ³)	0.3 – 1.6	2.9 – 3.16	2.0
Young's Modulus (GPa)	0.01 – 2	0.5 – 5	0.01 – 2
Poisson's Ratio	0.25 – 0.35	0.25 – 0.35	0.2 – 0.35
Compressive Strength (MPa)	0.3 – 15 (up to 145 MPa for freeze-cast)	1 – 20 (slight improvement over HAp)	1 – 40+ (45 wt% HA → >40 MPa)
Reference Notes	Huang 2022; Bairo review; Deville freeze-cast	Ghosal thesis; Radulescu 2023 review	Wei 2022; PLGA/HA composite reviews

Source: Authors, (2026).

II.5 MECHANICAL TESTING

The material response under physiological conditions was assessed using Finite Element Analysis (FEA) with varying loads of 100, 250, 500, 750, and 1000 N. Compressive, tensile, and impact simulations were used to evaluate mechanical behaviour, with an emphasis on total deformation, shear stress, and Von Mises stress. For every material model, the analysis determined stress concentrations and load-bearing capabilities. Mesh convergence testing and validation against published literature were used to guarantee the results' reliability [9] [10].

II.6 MODEL DEVELOPMENT

Each specimen's 3D model was made in SolidWorks and imported into ANSYS Workbench, where material parameters including density, Poisson's ratio, and Young's modulus were given using experimental data. Tetrahedral elements were used for meshing, with refinement occurring close to load application zones [7].

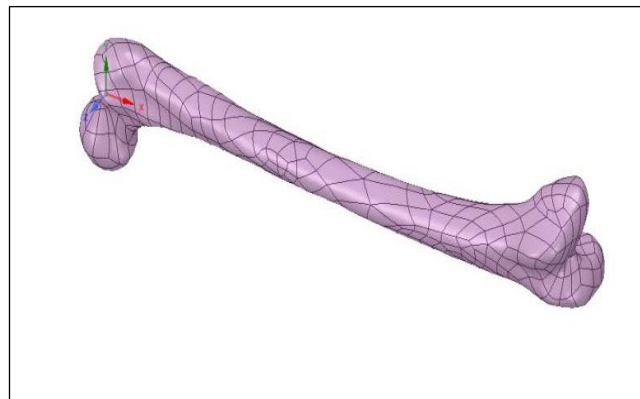


Figure 1: CREO-Based 3D Modelling of Femur Born.

Source: Authors, (2026).

II.7 BOUNDARY CONDITIONS

A fixed support at the bottom surface and compressive stresses ranging from 100 N to 1000 N applied to the top face were the boundary conditions, and frictionless contact was specified for precise load transmission.

II.8 ANALYSIS TYPES & OUTPUT PARAMETERS

Static structural analysis was used to evaluate total deformation, von Mises stress, and shear stress, with output parameters including stress distribution contours, maximum deformation, equivalent (von Mises) stress, factor of safety, and identification of potential failure regions, enabling direct comparison with experimentally observed fracture patterns.

III. DESIGN AND ANALYSIS IN ANSYS

A potent computational technique for assessing material behaviour under challenging loading scenarios is finite element analysis (FEA). The mechanical response of HAp, Zn-HAp, and PLGA–Zn-HAp composites under various load applications was simulated in this study using ANSYS Workbench. The analysis connected the outcomes of the experiments with the distribution of stress, total deformation, and strain among the materials. This simulated evaluation supports the prospective use of bone-derived bio composites in orthopaedic implant applications by forecasting their performance under physiological loads.

III.1 MODEL GEOMETRY & CREATION GEOMETRIC REPRESENTATION

For each of the three materials, separate geometric models were created, including Model A consisting of hydroxyapatite (HAp) produced from bone, Model B of zinc-doped hydroxyapatite (Zn-HAp), and Model C of the composite PLGA–Zn-HAp. To simulate physiological loading conditions typical of an implant region, a simplified femoral bone geometry was adopted and developed using ANSYS Design Modeler, with all models subsequently verified to ensure dimensional consistency.

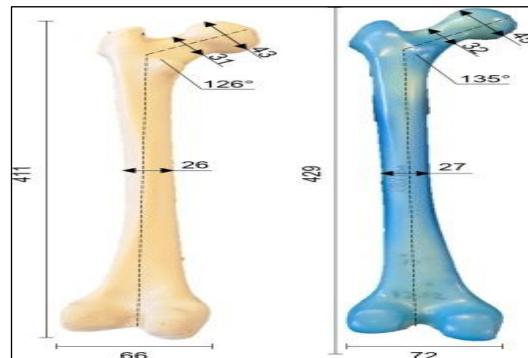


Figure 2: Creation Geometric Representation.
Source: Authors, (2026).

III.2 MESHING PROCESS

Each ANSYS model was given material properties derived from experiments, and then a thorough meshing procedure was carried out in order to ensure simulation correctness. Tetrahedral Solid187 elements with a precise mesh size of 0.5 mm were used to discretize the geometries; each model included between 45,000 and 70,000 elements. Refinement investigations were used to confirm mesh convergence, with results showing less than 2% variance.

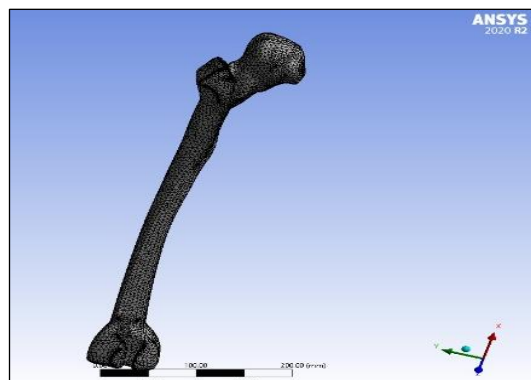


Figure 3: Mesh Geometry.
Source: Authors, (2026).

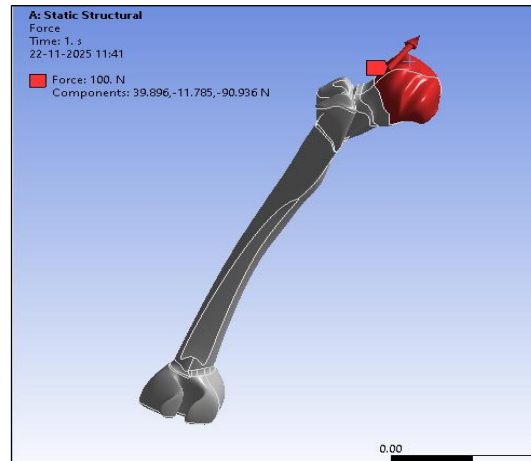
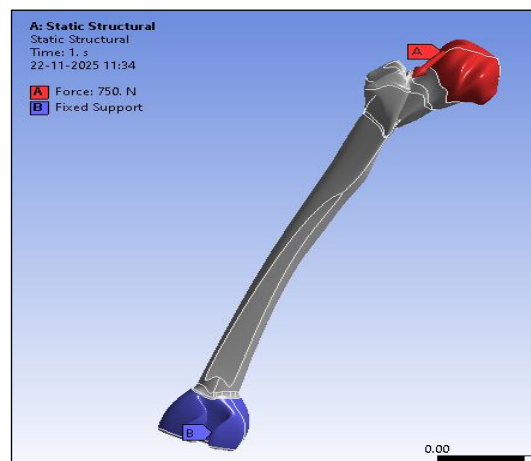
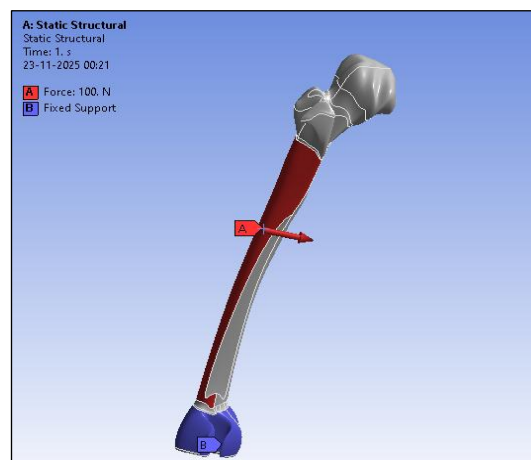
III.3 BOUNDARY CONDITIONS AND LOADING

In order to replicate genuine compression and physiological stress circumstances, appropriate boundary conditions were used.

Table 3: Boundary Conditions and Loading.

Condition	Description
Fixed Support	Base of the specimen fully constrained to restrict translation and rotation
Load Application	Compressive load, Tensile Load, & Impact Load
Load Magnitudes	100 N, 250 N, 500 N, 750 N, and 1000 N
Analysis Type	Static Structural

Source: Authors, (2026).

Figure 4: Tensile Load.
Source: Authors, (2026).Figure 5: Compressive Load.
Source: Authors, (2026).Figure 6: Impact Load.
Source: Authors, (2026).

III.4 SOLUTION SETUP AND SOLVER PARAMETERS

The ANSYS Mechanical solver using a Direct Sparse solution approach was used to carry out the static structural analysis. To guarantee computational accuracy, a convergence criterion of residuals less than 1×10^{-2} was used, and all contact interactions were classified as frictionless. Shear strain, total deformation, and equivalent (von Mises) stress were the main output parameters assessed in the present research.

IV. RESULTS AND DISCUSSION

The findings of the Finite Element Analysis (FEA) carried out in ANSYS and the 3D femur model made in CREO are presented in this chapter. A porous Hydroxyapatite (HAp), Zn-Hap, and PLGA-Zn-Hap structure with regulated pore size and distribution was added to the necessary area of a comprehensive and anatomically correct femur model. After importing the model into ANSYS, material parameters like density, Poisson's ratio, and Young's modulus were assigned using recognized values for porous HAp. Compressive loads were introduced to simulate actual physiological forces, and boundary conditions were used to fix the femur. The simulation was able to examine the deformation, stress distribution, and general mechanical behavior of porous HAp under loading thanks to this configuration.

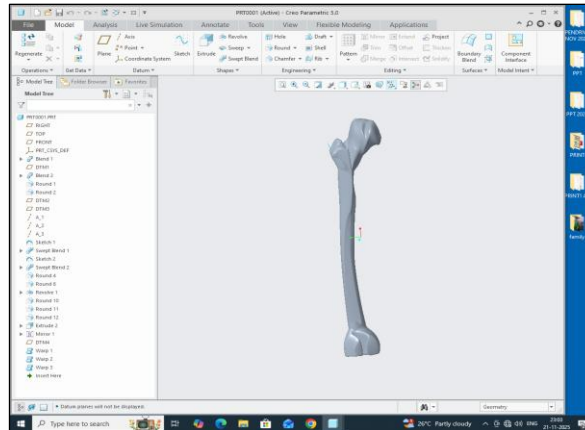


Figure 7: CREO-Based 3D Modelling of Femur Born.
Source: Authors, (2026).

IV.1 FINITE ELEMENT ANALYSIS (ANSYS RESULTS)

IV.1.1 Porous Hap Result

The finite element analysis results for porous hydroxyapatite (HAp) under tensile, compression, and impact loading conditions reveal a strong dependence of mechanical response on the applied load magnitude. Under **tensile loading**, porous HAp exhibited progressively increasing deformation and stress concentration as the load increased from 100 N to 1000 N, with pronounced localization of stress at higher loads (750–1000N), indicating brittle behavior and a high likelihood of crack initiation and tensile failure. In **compression loading**, the material showed comparatively lower deformation at low loads (100–250 N); however, as the load increased beyond 500 N, significant stress accumulation and pore collapse tendencies were observed, reflecting reduced structural stability and limited compressive strength at higher loads. Under **impact loading**, porous HAp demonstrated the poorest mechanical response, with sharp stress gradients and rapid deformation even at moderate loads, highlighting its low energy absorption capacity and high fracture susceptibility. Overall, the analysis confirms that porous HAp performs adequately only under low-load conditions, while higher tensile, compressive, and impact loads lead to severe stress concentration, excessive deformation, and increased failure risk, thereby limiting its suitability for load-bearing orthopedic implant applications [8].

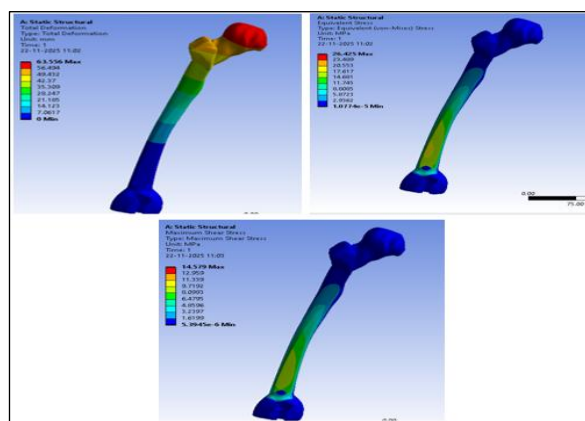


Figure 8: Porous HAp Result.
Source: Authors, (2026).

IV.1.2 Zn-Hap Result

The finite element analysis results of zinc-doped hydroxyapatite (Zn-HAP) demonstrate a clear improvement in mechanical behavior compared to porous HAP across tensile, compression, and impact loading conditions in the 100–1000 N range. Under **tensile loading**, Zn-HAP exhibited reduced deformation and more evenly distributed stress at lower loads (100–250 N), indicating enhanced stiffness due to zinc incorporation; however, at higher loads (750–1000 N), stress concentration increased, suggesting the onset of brittle failure under excessive tensile stress. In **compression loading**, Zn-HAP showed improved load-bearing capability with relatively uniform stress distribution and controlled deformation up to moderate loads (500 N), while higher compressive loads led to localized stress accumulation, reflecting partial structural instability. Under **impact loading**, Zn-HAP demonstrated better energy absorption and lower deformation than porous HAP, though sharp stress gradients were still observed at higher impact loads, indicating limited resistance to sudden dynamic forces. Overall, the analysis confirms that zinc doping enhances the mechanical stability, strength, and stress resistance of hydroxyapatite; however, despite these improvements, Zn-HAP retains some brittle characteristics at high tensile and impact loads, limiting its performance in demanding load-bearing implant applications.

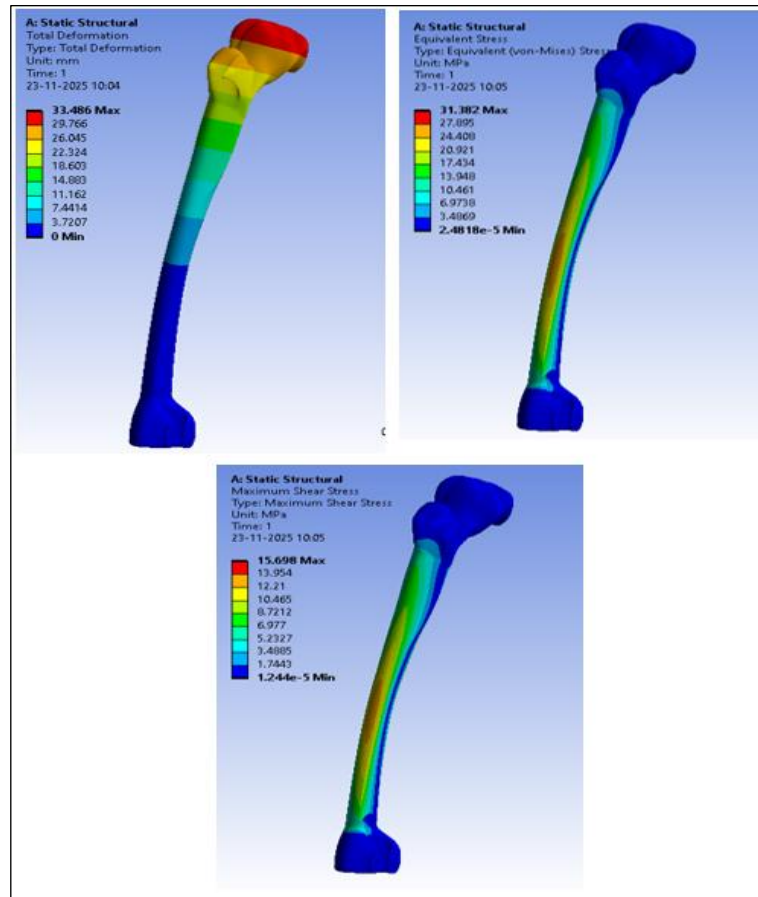


Figure 9: Zn Hap Result.
Source: Authors, (2026).

IV.1.3 PLGA-Zn-Hap Result:

The finite element analysis results for the PLGA–Zn–HAP composite demonstrate superior mechanical performance under tensile, compression, and impact loading conditions across the applied load range of 100–1000 N. Under **tensile loading**, the composite exhibited minimal deformation and a uniform stress distribution at lower and intermediate loads (100–500 N), indicating effective stress transfer between the polymer matrix and the Zn-HAP reinforcement; even at higher loads (750–1000 N), stress concentrations were comparatively low, reflecting enhanced ductility and resistance to brittle failure [11] [12]. In **compression loading**, PLGA–Zn–HAP showed excellent structural stability with controlled deformation and evenly distributed compressive stress up to 1000 N, highlighting its strong load-bearing capability and resistance to pore collapse. Under **impact loading**, the composite displayed superior energy absorption with reduced peak stress and gradual deformation progression, demonstrating high toughness and impact resistance [13]. Overall, the analysis confirms that the synergistic combination of PLGA with Zn-doped hydroxyapatite significantly improves toughness, stress uniformity, and mechanical reliability, enabling the composite to closely mimic the mechanical response of natural bone and making it highly suitable for load-bearing orthopedic implant applications [14] [15].

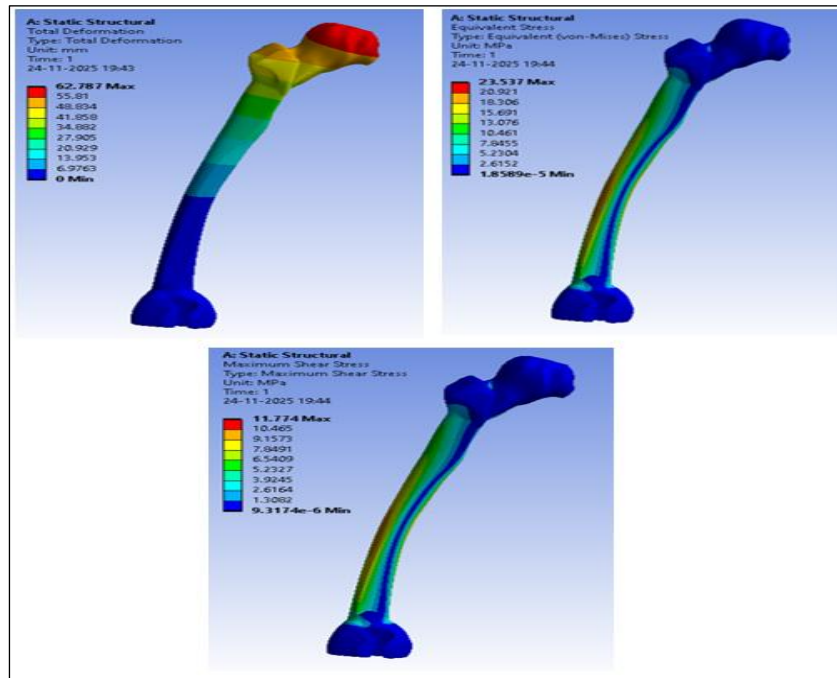


Figure 10: PLGA-Zn-Hap Result.

Source: Authors, (2026).

V. RESULT COMPARISON & CONCLUSION

The comparative results indicate that porous HAP exhibits the poorest mechanical performance due to high tensile deformation, uneven stress distribution, low impact resistance, and a high risk of fracture, making it unsuitable for load-bearing applications, while Zn-HAP shows moderate improvement with reduced deformation, better stress distribution, and enhanced stability, though it still demonstrates brittleness under higher tensile loads. Finite element analysis under impact, compression, and tensile loading conditions ranging from 100 to 1000 N further confirms these trends, with porous HAP displaying early stress concentration and brittle behavior, Zn-HAP benefiting from zinc-induced strengthening yet remaining limited at higher loads, and the PLGA-Zn-HAP composite achieving superior overall performance. The composite demonstrated minimal deformation, uniform stress distribution, high toughness, excellent load-bearing capacity, and mechanical behavior closely resembling natural bone, thereby establishing PLGA-Zn-HAP as the most reliable and promising material for future orthopedic implant applications requiring durable and physiologically compatible load-bearing biomaterials.

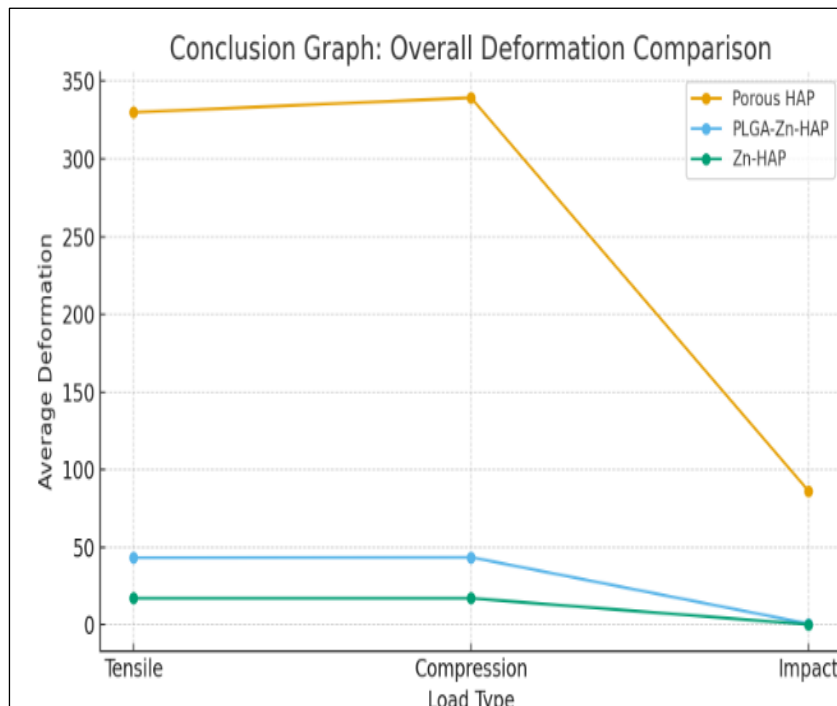


Figure 11: Comparison.

Source: Authors, (2026).

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Abhijith J, Athira Kishore and Sangeetha Krishnamoorthi.

Methodology: Saravanan M, Abhijith J.

Investigation: Saravanan M, Athira Kishore.

Discussion of results: Saravanan M, Sangeetha Krishnamoorthi.

Writing – Original Draft: Abhijith J.

Writing – Review and Editing: Saravanan.M, Saravanakumar M and Sangeetha Krishnamoorthi.

Resources: Saravanan M.

Supervision: Saravanakumar M and Sangeetha Krishnamoorthi.

Approval of the final text: Saravanan M, Abhijith J and Sangeetha Krishnamoorthi.

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