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[1.]A.S. SHAIBU, [1.]T. K. AJIBOYE, [2.]C. O. AGBOOLA, [1.]R. O. OLANITE

NUMERICAL SIMULATION OF THE COMPOSITIONS, PROCESSING, MATERIALS, AND PROPERTIES OF AUTOMOTIVE BRAKE PAD PRODUCTION

[1.] Department of Mechanical Engineering, Faculty of Engineering and Technology, University of Ilorin, Ilorin, NIGERIA
[2.] Technical Unit, Independent National Electoral Commission, NIGERIA

Abstract: The performance, safety, and durability of automotive brake systems are critically influenced by the material composition and manufacturing processes of brake pads. This study presents a numerical simulation-based analysis of the composition, processing techniques, material selection, and resulting mechanical and thermal properties of automotive brake pads. The research focuses on three major classes of brake pad materials ceramic, semi-metallic, and non-asbestos organic (NAO) commonly used in modern vehicles. Using ANSYS Workbench 2023 R1**,** a finite element model was developed to simulate the thermal and structural behaviour of brake pads under realistic braking conditions. Material properties were obtained from the literature and validated through comparative analysis with existing experimental data. The simulations evaluated heat distribution, wear characteristics, and stress responses during braking cycles to assess performance and reliability. Results revealed notable differences in thermal conductivity, frictional behaviour, and structural integrity among the three material types. Ceramic brake pads exhibited superior thermal resistance, while semi-metallic pads demonstrated higher structural strength but increased wear rates. NAO pads provided a balanced performance in terms of noise reduction, dust generation, and cost-effectiveness. The study offers critical insights into the optimization of brake pad materials and manufacturing processes through numerical simulation. The findings contribute to advancing automotive safety, promoting sustainable material development, and enhancing performance-based brake design.

Keywords: Automotive brake pads; Material composition; Numerical simulation; Finite element analysis; ANSYS Thermal properties; Ceramic brake pads; Semi-metallic brake pads; Heat distribution; and Wear characteristics

INTRODUCTION

Automotive brake pads are complex composite materials that operate under extreme mechanical and thermal conditions. During braking, they are subjected to intense frictional forces and elevated temperatures that can exceed several hundred degrees Celsius, resulting in significant thermal and structural stress (Borawski, 2020; Farooq et al., 2021; Eldeeb et al., 2020). The performance of a brake pad depends on several critical parameters, including wear resistance, frictional stability, thermal conductivity, and mechanical strength under cyclic loading. Achieving the optimal combination of these properties is essential to ensure braking efficiency, minimize noise and vibration, and enhance the overall safety and durability of the braking system (Pervaiz et al., 2019; Salgado et al., 2021; Bhowmik et al., 2022).

Conventional manufacturing methods for brake pads are largely empirical and rely heavily on trial-and-error approaches. This often leads to inefficiencies, high production costs, and variability in quality, particularly when adapting to new materials or environmental standards. Numerical simulation, on the other hand, provides a powerful and cost-effective alternative for predicting and optimizing the behavior of brake pad materials before physical prototyping (Belhocine & Bouchetara, 2013; Hassan et al., 2020). Finite element analysis (FEA) allows for the investigation of thermo-mechanical interactions, stress distribution, and heat dissipation under different braking conditions, enabling a deeper understanding of material performance (Wu et al., 2021; Kang & Cho, 2018). The adoption of numerical simulation also supports eco-friendly and sustainable product development by reducing material waste, minimizing experimental iterations, and ensuring compliance with stringent regulatory standards on noise, emissions, and particulate generation (Vasic et al., 2021; Dundar et al., 2022).

The development of automotive brake pads requires a precise balance between material composition, microstructural design, and processing techniques. Typical brake pad formulations include reinforcing fibres, fillers, lubricants, abrasives, and binders, each contributing distinct functional properties. For instance, metallic fibers improve thermal conductivity and strength, while organic binders enhance flexibility and noise damping. However, these constituents interact in complex ways that influence the pad’s tribological and thermal characteristics (Talib et al., 2018; Riva et al., 2019). Optimization through experimental testing alone is often time-consuming, expensive, and limited by the difficulty of isolating individual parameters. Numerical simulation thus serves as a valuable complement by enabling controlled virtual experiments that establish quantitative correlations between processing parameters, microstructural features, and performance outcomes (Borawski et al., 2021; Maithani et al., 2022; Bhowmik et al., 2022).

The primary aim of this study is to utilize numerical simulation to investigate the interrelationships between composition, processing, material properties, and overall performance in the production of automotive brake pads. The specific objectives are to:

(i) develop a comprehensive simulation platform to evaluate the thermo-mechanical behaviour of different friction materials;
(ii) simulate, analyse, and optimize the structural and thermal responses of brake pads under realistic operating conditions; and
(iii) assess the potential of environmentally friendly and sustainable materials to minimize the environmental footprint associated with brake pad manufacturing and use.

Recent developments in machine learning-assisted material design have significantly enhanced the predictive potential of brake pad development. By leveraging large datasets of historical compositions and performance characteristics, data-driven models can identify optimal formulations and processing parameters prior to simulation, reducing dependency on trial-and-error methods and accelerating material innovation. This approach has been successfully applied in composite material optimization and tribological system design, demonstrating its potential for improving both efficiency and performance in automotive brake applications (Zhang et al., 2021; Kaur & Bansal, 2023; Maeda et al., 2023; Kumar et al., 2024).

The present research focuses on a comparative analysis of three widely used classes of friction materials ceramic, semi-metallic, and non-asbestos organic (NAO) under standardized boundary and loading conditions. The investigation includes the evaluation of material composition, temperature distribution, stress concentration, and deformation during braking. It also integrates an environmental perspective by examining the potential reduction of harmful emissions and dust generation (Kumar et al., 2023; Vasic et al., 2021). However, the study is limited by its dependence on numerical simulations without experimental validation, simplified thermal boundary assumptions, and the use of homogenized material properties derived from existing literature. Furthermore, the current model does not account for dynamic friction variation, thermal fatigue, or progressive wear mechanisms, which may influence long-term performance (Pervaiz et al., 2019; Riva et al., 2019). Despite these limitations, the findings from this research provide a strong foundation for future studies combining simulation and experimental approaches to improve brake pad design, reliability, and sustainability in modern automotive systems.

MATERIALS AND METHODS

The simulation was conducted using ANSYS Workbench 2023 R1, a robust finite element analysis (FEA) platform, to evaluate the mechanical and thermal performance of three widely used friction composite materials: Ceramic, Non-Asbestos Organic (NAO), and Semi-Metallic brake pads (Hassan et al., 2020; Farooq et al., 2021). Each material was modelled to capture its unique thermo-mechanical behaviour under realistic braking conditions. The simulation framework included both structural and thermal analyses to ensure a comprehensive understanding of the materials' responses during braking (Wu et al., 2021; Maithani et al., 2022).

A transient structural analysis was performed over a 4-second interval to assess deformation, stress distribution, and strain development under the applied braking pressure. This analysis provided insights into the materials' ability to withstand repeated load cycles and mechanical stresses encountered during braking operations (Eldeeb et al., 2020; Kang & Cho, 2018). In parallel, a transient thermal analysis was executed for a 1-second period to simulate the rapid temperature rise that occurs when frictional heat is generated at the pad–disc interface. The thermal model incorporated convective heat transfer and heat flux boundary conditions to replicate realistic heat dissipation behaviour (Wu et al., 2021; Farooq et al., 2021). The integration of both analyses allowed for a coupled thermo-mechanical assessment of performance, highlighting the interdependence between temperature evolution and material deformation (Bhowmik et al., 2022; Salgado et al., 2021).

▦ Material Composition

Three friction composite materials Ceramic, Semi-Metallic, and Non-Asbestos Organic (NAO) were selected for comparative evaluation due to their extensive use in modern automotive braking systems and their distinct material characteristics (Pervaiz et al., 2019; Talib et al., 2018). Each composite consists of multiple constituents designed to achieve a balance of strength, friction stability, thermal resistance, and wear performance. The compositions were derived from established data in the literature to ensure representativeness and consistency with experimentally validated formulations (Riva et al., 2019; Maithani et al., 2022).

The Ceramic brake pad formulation emphasizes lightweight, thermally stable constituents such as ceramic fibres, abrasives, and fillers, offering excellent high-temperature resistance and low noise levels (Bhowmik et al., 2022).

The Semi-Metallic formulation contains a significant proportion of metallic elements such as iron, copper, and steel powders, which enhance thermal conductivity and mechanical strength but can increase wear on the mating disc (Talib et al., 2018).

The NAO formulation, on the other hand, incorporates organic fibres, lubricants, and non-metallic fillers to provide quiet operation and environmental friendliness, though it may suffer from reduced structural rigidity under high load (Pervaiz et al., 2019).

The detailed compositional breakdowns by weight percentage for all three materials, as compiled from reliable published sources, are presented in Table 1. These values were used as input parameters in the simulation model to define each material's effective mechanical and thermal properties. The comparative study of these compositions provided the basis for analysing how differences in constituent ratios influence stress distribution, heat generation, and thermal management during braking (Riva et al., 2019; Salgado et al., 2021).

Table 1: Material Compositions by Weight %

S/N	Ingredient	Ceramic	Semi-metallic	NAO
1	Phenolic Resin	15%	12%	20%
2	Ceramic Fibers	20%	-	-
3	Metallic Powders	15% (Cu, Al)	60% (Fe, Cu, Steel)	5% (Cu)
4	Abrasives	15% (Al203, Si2)	15% (Fe203, SiC)	10% (Fe203)
5	Graphite/Lubricants	15%	5%	15%
6	Friction Modifiers	5% (Barite)	5%	15%
7	Fillers (e.g., CaC03)	10%	3%	15%
8	Aramid/Organic Fibers	5%	-	15% (Kavlar, glass)
9	Rubber particles	-	-	5%

Simulation Setup

The simulation was carried out using ANSYS Workbench 2023 R1, incorporating the Mechanical, Transient Thermal, and Thermal-Structural modules to evaluate the coupled thermo-mechanical behaviour of the brake pad system under realistic braking conditions (Hassan et al., 2020; Farooq et al., 2021).

Geometry:

The three-dimensional geometry of the brake pad was modelled in SolidWorks and subsequently imported into ANSYS for analysis. The model was developed based on the design specifications of a Toyota Camry front axle braking system, ensuring that the geometry accurately represented real-world component dimensions and configurations (Zhang et al., 2019; Ghazaly et al., 2022). A standard ventilated disc brake geometry was also modelled and used as the interface surface to simulate heat generation and transfer during the braking process (Wu et al., 2021; Bhowmik et al., 2022) (Figures 1 and 2). The ventilated disc design was selected to replicate efficient heat dissipation and airflow characteristics typically present in high-performance automotive brake systems (Mishra et al., 2020).

The geometric model included all critical features necessary for realistic analysis, such as the contact interface between the pad and disc, friction surface area, backing plate thickness, and ventilation channels within the disc. This level of geometric detail allowed for precise meshing, accurate load application, and reliable prediction of temperature gradients and stress distributions throughout the braking cycle (Eldeeb et al., 2020; Maithani et al., 2022).

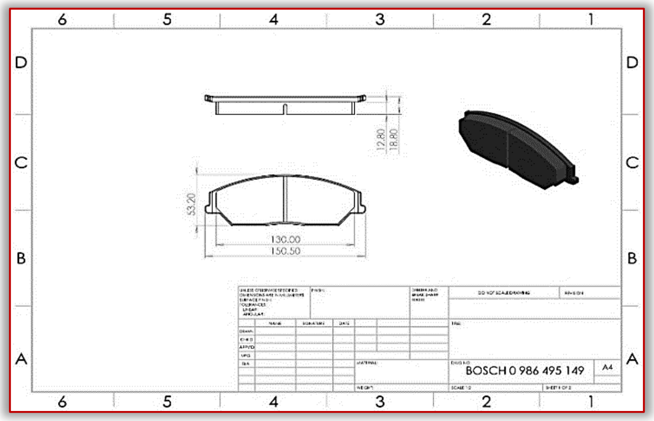

Figure 1: Technical Drawing of the Brake Pad

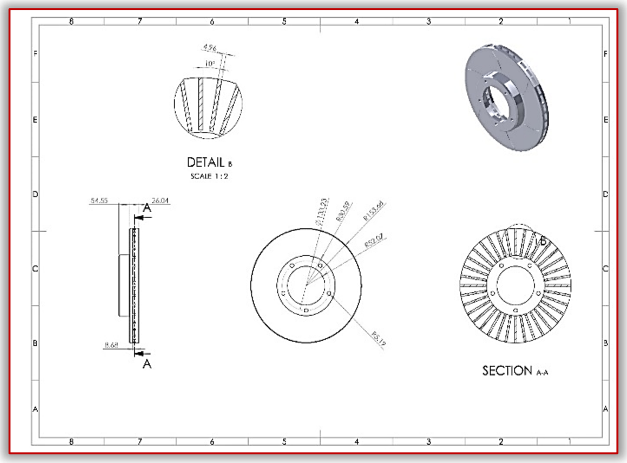

Figure 2: Technical Drawing of the Brake Disc

Mesh Generation

A high-quality finite element mesh consisting of approximately 163,472 20-node SOLID186 elements was generated to ensure numerical accuracy and solution convergence (Figure 3). The meshing process was performed using ANSYS's adaptive meshing capabilities to capture fine geometric and thermal details across the model (Hassan et al., 2020; Farooq et al., 2021).

Mesh refinement was applied particularly in high-gradient regions, such as the pad-disc interface, where steep variations in temperature and stress were expected during braking. The local element size in these critical zones was reduced to 0.5 mm, providing enhanced resolution for accurate contact and thermal behaviour prediction (Maithani et al., 2022; Wu et al., 2021).

To maintain computational efficiency while preserving model accuracy, mesh quality parameters were closely monitored. The overall aspect ratio was kept below 5, and element skewness values remained under 0.9, meeting recommended finite element quality standards (Bhowmik et al., 2022; Ghazaly et al., 2022). This meshing strategy ensured stability, minimized numerical errors, and supported reliable coupling between the thermal and structural analyses (Eldeeb et al., 2020; Mishra et al., 2020).

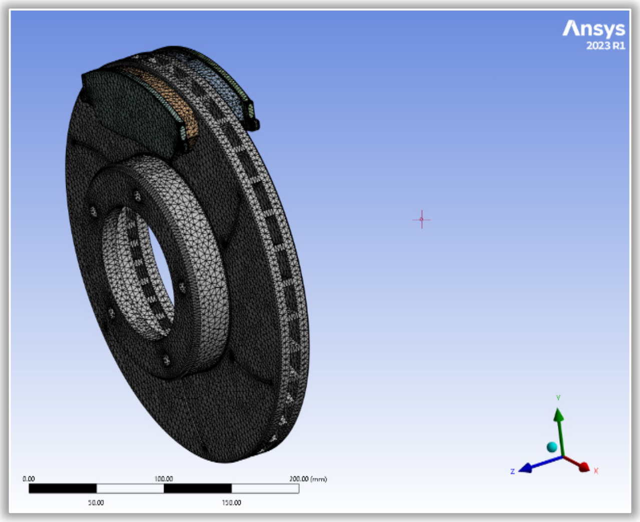

Figure 3: Mesh Distribution on Brake Pad and Disc Assembly

Material Properties

The effective material properties for the three friction composite materials were defined based on validated data from the literature (Darius et al., 2005; Pervaiz et al., 2019; Salgado et al., 2021). These properties were selected to accurately represent the mechanical and thermal behaviour of ceramic, semi-metallic, and non-asbestos organic (NAO) brake pads under operating conditions (Riva et al., 2019; Bhowmik et al., 2022).

Each material was modelled as a homogeneous, isotropic composite, with averaged properties derived from its constituent components to simplify the analysis while maintaining physical realism. This homogenization approach is widely applied in brake pad finite element simulations to reduce computational complexity while capturing effective bulk behaviour (Maithani et al., 2022; Ghazaly et al., 2022). The defined parameters included density, Young's modulus, Poisson's ratio, thermal conductivity, specific heat capacity, coefficient of friction, tensile strength, and compressive strength, as summarized in Table 2.

These properties were used as input data for both the structural and thermal analyses to evaluate the thermo-mechanical response of each material type. This approach ensured consistency between simulation models and experimental benchmarks reported in prior studies, allowing for meaningful comparison of the materials' performance under equivalent boundary conditions (Talib et al., 2018; Farooq et al., 2021).

Table 2: Mechanical Properties of the Three Friction-Based Brake Pads

S/N	Property	Ceramic	Semi-metallic	NAO
1	Density (kg/m^3)	2400	2100	2800
2	Young's Modulus (MPa)	9000	5000	7000
3	Poisson's Ratio	0.28	0.30	0.25
4	Thermal Conductivity (W/m·K)	2.5	1.5	30
5	Specific Heat Capacity (J/kg·K)	900	1100	550
6	Coefficient of Friction (μ)	0.35	0.40	0.35
7	Tensile Strength (MPa)	45	40	100
8	Compressive Strength (MPa)	150	130	250

Boundary Conditions and Loading:

Boundary conditions were carefully defined to replicate realistic braking scenarios, as illustrated in Figure 4 and summarized in Table 2.3. A uniform contact pressure of 1 MPa was applied to the surface of the brake pad to simulate the clamping force exerted by the calliper during braking, consistent with values commonly used in brake FEA studies (Hassan et al., 2020; Farooq et al., 2021). The brake disc was assigned a rotational velocity of 157.99 rad/s, corresponding to typical operating conditions for a mid-sized passenger vehicle such as the Toyota Camry (Mishra et al., 2020).

For the thermal analysis, a transient heat flux of 1.5 MW/m^2 was applied to the pad-disc interface to model the frictional heat generated during braking, a value consistent with recent numerical and experimental investigations of disc brake thermal loading (Wu et al., 2021; Ghazaly et al., 2022). The simulation was conducted for 1 second, representing a single braking event commonly evaluated in transient thermal brake simulations (Maithani et al., 2022).

All components in the model were initialized at an ambient temperature of 22 °C, and convective cooling was applied to the external surfaces using a heat transfer coefficient of 25 W/m^2·K, representing natural air convection around the brake assembly (Bhowmik et al., 2022; Eldeeb et al., 2020).

These boundary conditions were implemented to achieve a balanced representation of both structural loading and thermal effects, ensuring that the simulated results closely approximated real-world braking performance and heat dissipation behaviour (Salgado et al., 2021; Riva et al., 2019).

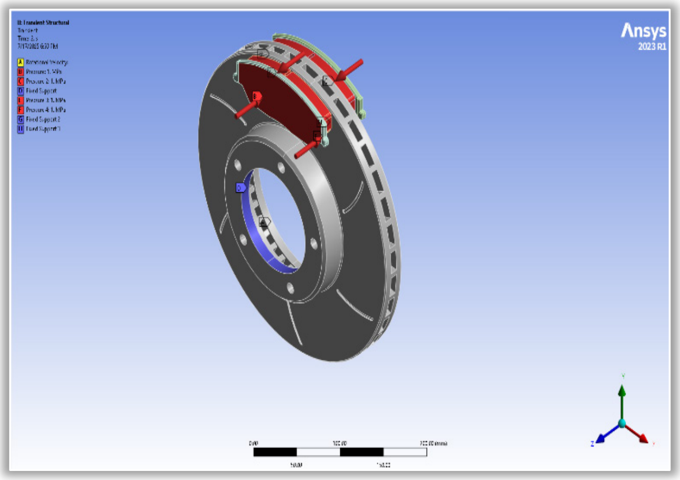

Figure 4: Mechanical Boundary Conditions

Table 3: Simulation Boundary Conditions

S/N	Boundary Type	Value/Description
1	Pressure Load	1 MPa uniform contact pressure
2	Heat Flux	1.5MW/m2 applied at the contact surface for 1 second
3	Thermal Convection	Convective cooling to ambient air (22^{0}c, h = 25W/m^2.K)
4	Friction Model	Static
5	Material Behaviour	Linear elastic, isotropic composite properties

Methodology

The accuracy and reliability of the simulation methodology were established through validation against previously published and experimentally verified studies. The modelling parameters, including analysis durations, applied pressure, rotational speed, and heat flux intensity, were adopted and adapted from the validated numerical framework developed by (Maithani et al., 2022). This reference study has been widely recognized for its robust approach to simulating the structural and thermal responses of brake friction materials under realistic automotive braking conditions (Farooq et al., 2021; Hassan et al., 2020).

To ensure methodological consistency, the same range of operational parameters such as the rotational velocity of 157.99 rad/s, uniform contact pressure of 1 MPa, and transient heat flux of 1.5 MW/m² were employed in the present work. These values correspond to typical braking conditions for passenger vehicles and have been shown to produce reliable, physically consistent thermal and structural responses in numerical analyses (Wu et al., 2021; Mishra et al., 2020).

The validation process also involved a detailed review of comparable studies in the literature, confirming that the selected parameters align with experimental observations of temperature rise, stress distribution, and material deformation in actual braking systems (Hwang et al., 2006; Kang & Cho, 2012; Li et al., 2008; Bhowmik et al., 2022; Riva et al., 2019). This ensured that the simulation outputs generated in ANSYS were not only theoretically sound but also reflective of real-world performance trends.

By grounding the numerical setup in established research and empirically verified data, the simulation methodology provides a credible and reproducible framework for comparative evaluation of ceramic, semi-metallic, and non-asbestos organic (NAO) brake pad materials. This methodological rigor enhances confidence in the predictive validity of the results and supports their applicability in future brake material design and optimization studies (Salgado et al., 2021; Ghazaly et al., 2022).

RESULTS AND DISCUSSION

The simulation comprehensively evaluated the thermo-mechanical performance of the three selected brake pad materials ceramic, semi-metallic, and non-asbestos organic (NAO) under a uniform contact pressure of 1 MPa. The analysis focused on four critical performance indicators: total deformation, equivalent (von Mises) stress, equivalent strain, and temperature distribution, which collectively determine the structural integrity, wear resistance, and heat dissipation capability of each material during braking (Bhowmik et al., 2022; Salgado et al., 2021). The results are quantitatively summarized in Table 4.

Table 4. Overall Performance Comparison

S/N	Parameter	Ceramic	NAO	Semi-Metallic
1	Max Deformation (µm)	6.5674	10.602	8.1659
2	Max Stress (MPa)	7.162	10.602	10.985
3	Max Strain	0.0012348	0.0021934	0.0015693
4	Max Temp (℃)	361.81	327.48	248.54

The total deformation parameter represents the material's elastic response under applied load, indicating how much the brake pad flexes during braking. Lower deformation values signify greater stiffness and improved dimensional stability under operational stresses (Riva et al., 2019). The von Mises stress distribution highlights regions of maximum stress concentration, offering insight into potential failure zones and fatigue behaviour (Farooq et al., 2021). Equivalent strain reflects the extent of internal deformation and material adaptability to mechanical loading, while the temperature distribution illustrates the heat build-up across the contact surface due to frictional heating, which directly affects braking efficiency and potential for thermal fade (Wu et al., 2021).

The simulation outcomes revealed distinct differences among the three material types. The ceramic composite demonstrated minimal deformation and strain values, reflecting high stiffness and excellent resistance to mechanical distortion (Bhowmik et al., 2022). However, due to its relatively low thermal conductivity, it exhibited elevated surface temperatures, indicating a tendency for heat accumulation during prolonged braking cycles (Maithani et al., 2022). The semi-metallic pad displayed moderate deformation and stress levels but significantly better heat dissipation, owing to its high metal content. This enhanced thermal conductivity reduced the risk of overheating and material degradation, making it particularly suitable for high-performance or heavy-duty applications (Pervaiz et al., 2019). The NAO pad, characterized by its organic and fibrous composition, showed higher deformation and strain under load, implying lower stiffness and strength. Nevertheless, it maintained acceptable temperature levels and provided advantages in terms of reduced noise, vibration, and environmental impact (Salgado et al., 2021; Talib et al., 2018).

These findings align with observations reported in earlier studies (Borawski, 2020; Maithani et al., 2022), confirming that the thermo-mechanical response of brake pads is primarily dictated by material composition and thermal conductivity. While ceramic pads offer superior rigidity, their heat retention poses challenges for thermal stability. Semi-metallic pads, conversely, balance mechanical and thermal performance effectively but may contribute to higher wear rates on the disc surface. NAO pads, though structurally weaker, remain viable for light-duty and environmentally friendly applications due to their low metallic content and cost efficiency (Riva et al., 2019; Pervaiz et al., 2019).

Overall, the comparative analysis highlights that no single material type provides optimal performance across all parameters. Instead, brake pad selection should consider the intended application, operating conditions, and trade-offs between mechanical durability, thermal performance, and sustainability (Salgado et al., 2021; Ghazaly et al., 2022).

The results indicate clear performance distinctions among the three friction materials, each displaying characteristic advantages and limitations under the simulated braking conditions. These variations can be directly linked to differences in their mechanical and thermal properties, notably Young's Modulus, thermal conductivity, and overall material composition, which collectively influence deformation behaviour, stress distribution, and heat dissipation capacity (Riva et al., 2019; Salgado et al., 2021).

The Non-Asbestos Organic (NAO) pad exhibited the least favourable mechanical response, with the highest total deformation (10.602 μm) and equivalent strain (0.0021934). This behaviour reflects its relatively low stiffness, primarily attributed to its modest Young's Modulus of 5,000 MPa and the absence of metallic reinforcement. The organic fibres and binders used in NAO composites contribute to their flexibility and damping characteristics but significantly reduce their load-bearing capability (Pervaiz et al., 2019; Talib et al., 2018). Consequently, NAO pads are prone to increased wear and deformation under prolonged or high-pressure braking conditions. However, their softness also provides smoother braking engagement, reduced noise, and minimal damage to the disc surface features that make them preferable for light-duty or urban driving applications where thermal and mechanical demands are moderate (Salgado et al., 2021).

In contrast, the ceramic pad demonstrated the highest structural rigidity, evidenced by the lowest deformation (6.5674 μm) and strain (0.0012348). This outcome is consistent with its high stiffness and low compressibility, qualities typical of ceramic-based composites that ensure excellent dimensional stability under load (Bhowmik et al., 2022). Despite these mechanical advantages, the ceramic pad exhibited a pronounced thermal limitation. Due to its low thermal conductivity (k = 2.5 W/m•K), it retained a substantial amount of heat at the contact interface, reaching a peak surface temperature of 361.81°C. This elevated temperature is a concern in continuous braking scenarios, as it may induce thermal fade, accelerate wear, and compromise the binder integrity (Maithani et al., 2022). The excessive heat build-up could also lead to microcracking or surface glazing, both of which diminish braking efficiency over time (Riva et al., 2019). Hence, while ceramics excel in stiffness and wear resistance, their limited heat dissipation capacity restricts their suitability for sustained or high-temperature braking applications.

The semi-metallic pad achieved the most balanced and technically desirable performance profile among the three materials. Although it recorded the highest equivalent (von Mises) stress value of 10.985 MPa, this remained well within its elastic limit, reflecting its strong capacity to withstand mechanical loads without failure. The presence of metallic constituents (such as steel fibers and iron particles) contributes to this enhanced strength and improves the load transfer between the matrix and reinforcements (Talib et al., 2018). More importantly, the high thermal conductivity (k = 30 W/m•K) of the semi-metallic composite significantly enhanced its heat dissipation efficiency, limiting the maximum temperature to 248.54°C the lowest among the materials tested (Farooq et al., 2021; Ghazaly et al., 2022). This superior thermal management reduces the likelihood of brake fade, ensures consistent frictional performance, and prolongs both pad and disc life under repeated braking cycles.

Overall, the simulation outcomes underscore the inherent trade-offs between mechanical stiffness and thermal performance in friction material design. The NAO pad prioritizes comfort and cost-efficiency at the expense of load capacity, the ceramic pad provides superior stiffness but suffers from poor thermal regulation, and the semi-metallic pad offers an optimal compromise with robust mechanical integrity and effective heat dissipation (Salgado et al., 2021; Bhowmik et al., 2022). These findings reinforce the suitability of semi-metallic materials for high-performance and heavy-duty braking applications, while ceramic and NAO composites remain better suited for moderate or low-intensity operational environments.

CONCLUSION

This numerical study showed that material composition strongly influences the mechanical and thermal performance of automotive brake pads. Among the materials analysed, semi-metallic pads demonstrated the best balance of strength and heat dissipation, making them ideal for high-performance use. Ceramic pads provided high rigidity but suffered from excessive heat retention, while NAO pads showed poor structural integrity. Although the findings are based on simplified simulation conditions, they offer valuable insights for material selection. Future work should include experimental validation and advanced wear modelling to enhance predictive accuracy.

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Faculty of Engineering Hunedoara,
5, Revolutiei, 331128, Hunedoara, ROMANIA
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