Enhancement of Stiffness and Thermal Behaviour of Polyamide-6 (Pa6) Featured With Carbon Nanotube and Silicon Dioxide Nanoparticles

R Meenakshi Reddy1, M Jegadeeswaran2, M Maran3, M Karthick4,a), S Karvendhan5, B N Deepak Kumar6, R Suresh Balaji7, Senthil Kumar Vishnu8, N Karthikeyan9

1 Department of Mechanical Engineering, G.Pulla Reddy Engineering College, Kurnool, 518007, Andhra Pradesh, India

2Department of Agricultural Engineering, Rathinam Technical Campus, Coimbatore,Tamil Nadu 64102, India

3 Department of Mechanical Engineering, Velammal College of Engineering and Technology, Madurai. 625009, Tamil Nadu, India.

4 Department of Mechanical Engineering, Erode Sengunthar Engineering College, Thuduppathi, 638057, Tamil Nadu, India.

5 Department of Mechanical Engineering, Velalar College of Engineering and Technology, Erode, 638102, Tamil Nadu, India.

6 Department of Mechanical Engineering, Dayananda Sagar Academy of Technology and Management, Bengaluru, 560082, Karnataka, India.

7Department of Mechanical Engineering, Karpagam Academy of Higher Education, Coimbatore, Tamil Nadu, India.

8Centre for Sustainable Materials Research, Department of Mechanical Engineering, Academy of Maritime Education and Training (AMET)Deemed to be University, Kanathur, Chennai 603112, Tamil Nadu, India.

9Department of Mathematics, Kongunadu College of Engineering and Technology, Trichy, 621215 Tamil Nadu,India

**Corresponding author:** a)[*mkarthickmech1992@gmail.com*](mailto:mkarthickmech1992@gmail.com)

**Abstract:** To improve mechanical and thermal properties of Polyamide 6 this work explores reinforcing it using silicon dioxide 30 nm nanoparticles and carbon nanotubes 1-3 mm. Compression molding was used to create composites utilizing several filler combinations such as 2–5% CNT and 1-3 weight percent SiO₂. Significant gains in flexural strength, thermal stability and impact resistance were demonstrated by mechanical and thermal studies, especially for the sample that contained 2 weight percent CNT and 1 weight percent SiO₂. Silica nanoparticles acted as stress dissipators and heat barriers whereas this hybrid combination synergistically increased stiffness. According to the findings these composites are good options for automotive door panel applications since they provide lightweight, high performing substitutes for conventional polymers filled with glass or talc.

# Introduction

Researchers are looking more and more into using nanofillers to get over these restrictions. Because of their remarkable tensile strength of 60 GPa approximately and Young's modulus 1 TPa approximately, carbon nanotubes are perfect for reinforcing polymer matrices. As physical barriers to heat conduction and matrix deterioration silicon dioxide nanoparticles (SiO₂, ~30 nm) are thermally stable ceramics that increase stiffness and heat resistance [1-3].

The revolutionary effect of nanoscale reinforcements on the mechanical, functional and thermal performance of engineered thermoplastics like polyamide-6 has been highlighted by recent developments in polymer research. Among these, silica nanoparticles and carbon nanotubes have become the most promising options for improving composite behavior under thermal and structural loads [4-6].

By further describing the interactions between ultra-high molecular weight polymer matrices and a wide range of nanoparticles, such as CNTs and oxides Padhy and Kandasubramanian (1) established the fundamental framework for comprehending polymer nanocomposites. Their review demonstrates how high-performance thermoplastics' stiffness, fracture resistance and multifunctionality can be significantly improved by nanofillers. To broaden this perspective, investigated the application of short-cut carbon fibers in fused deposition modelling fabricated PA6 composites exhibiting concurrent enhancements in tensile strength, toughness and lightweighting essential attributes for automotive and aerospace engineering [7-9].

By using a polyurethane-based surface scaling approach to incorporate nano-SiO₂, improved the interface engineering of 3D-printed PA6 composites. Their research demonstrated a notable improvement in fiber-matrix adhesion resulted in increased interfacial shear and tensile strength [10-14]. Research [15] contextualised the wider range of nanosilicates and oxides such as SiO₂, for enhancing load transfer efficiency and thermal endurance in semicrystalline polyamides in their thorough assessment of nanoclay reinforced polymers.

Research [16] assessed the selective laser sintering (SLS) of CNT-reinforced PA6 composites and found that even small loadings of MWCNTs greatly increased yield strength and tensile modulus, indicating that CNTs can function as effective stress-transfer conduits inside the matrix. By examining inorganic nanoparticle-modified polymers, Diez-Pascual (6) further supported this conclusion and highlighted how SiO₂, TiO₂ and other oxides improve strength as well as electrical, thermal and UV resistance making them useful in PA6 based multifunctional applications.

In order to achieve a desirable compromise between impact strength and stiffness, Research [17] optimized hybrid PA6 composites including both short glass fibers and MWCNTs using response surface methods. For industrial-scale applications where process-property optimization is crucial, their statistically guided methodology is invaluable. In the meantime, Research [17] addressed interfacial engineering by improving interfacial shear strength through the application of CNT-based surface sizing to basalt fibers. This principle is directly applicable to PA6/CNT systems, where composite efficiency is determined by matrix-fiber load transmission. CNTs are useful for more than just structural reinforcement. Using MWCNT-infused poly [18-21] created optically clear nanocomposites demonstrating how CNTs may both strengthen and preserve optical clarity, providing guidance for the development of advanced transparent PA6 films. In their investigation of nano fibrous electro spun blends of PA and PVA functionalized with carbon nanoparticles,

Research [22] demonstrated the advantages of dual-phase surface functionalization by adding a polydopamine and nano silica interfacial layer to short carbon fiber-reinforced PA6 composites, resulting in notable enhancements in modulus, strength, and thermal conductivity. Because of their structural similarities, Research [23] found that reinforcing PA66 with MWCNT-coated milled glass fibers improved its crystallinity and heat resistance. These results can be applied to PA6. Further validated additive manufacturing techniques by assessing 3D-printed hybrid PA6 composites that contained carbon fibers and MWCNTs. Their findings demonstrated their superior mechanical, thermal and tribological behavior, which made them suitable for use in abrasive, sliding, or load-bearing conditions. Finally for environmental remediation, Research [24] synthesised electrospun PA6 nanofibers functionalised with SiO₂ and TiO₂. The final materials demonstrated enhanced mechanical durability and efficient dye adsorption expanding the use of PA6 nanocomposites to sustainability-focused applications.

This study assesses the effects of mixing SiO₂ and CNT nanofillers in a PA6 matrix to create lightweight composites for automobile door panel applications that have better stiffness and heat stability.

# Materials and Methods

## Materials

Injection grade Polyamide 6 is a popular engineering thermoplastic in industrial and automotive applications due to their good mechanical strength, heat resistance and processing ability used as the matrix material for this investigation. Multi walled carbon nanotubes with diameters stretching from 10 to 20 nm and lengths amongst 1 and 3 mm were used as the main nanofillers [25-28]. Because of their remarkable tensile strength, aspect ratio and electrical conductivity with all of which greatly aid in mechanical reinforcing through stress bridging mechanisms these CNTs were chosen. As secondary fillers, silicon dioxide nanoparticles with a high purity of 99.5% and a spherical shape with an typical diameter of 30 nm were employed in addition to CNTs. Because of its ceramic nature, high surface area and insulating properties, SiO₂ was added to increase thermal stability and decrease crack propagation [29-33].

## Composite Formulations

To investigate the combined effects of CNT and SiO₂ reinforcement on the thermomechanical performance of PA6, five different composite formulations were prepared. These are detailed as follows:

**TABLE 1.** Mechanical Composite Formulations Table

|  |  |
| --- | --- |
| **Sample** | **Description** |
| 1 | PA6 (Neat) |
| 2 | PA6 + 2 wt% CNT |
| 3 | PA6 + 2 wt% CNT + 1 wt% SiO₂ |
| 4 | PA6 + 2 wt% CNT + 3 wt% SiO₂ |
| 5 | PA6 + 5 wt% CNT + 1 wt% SiO₂ |

This progressive design allowed the study of individual and synergistic effects of the nanofillers, as well as optimization of their respective weight fractions.

## Processing Technique

Before blending all raw materials including PA6 pellets, CNTs and SiO₂ nanoparticles were dried in a zero pressure oven for 12 hours at 90°C to guarantee ideal dispersion and reduce moisture-induced deterioration during processing [34-39]. A twin screw extruder running at 240°C barrel temperature was used to compound the dry ingredients. The material was subjected to compression moulding into test specimens for five minutes at 230°C and 10 MPa pressure in a hydraulic press [40-43]. To mitigate internal stress, increase crystallinity and stabilise the mechanical properties of the moulded components, post-curing was performed for two hours at 80°C. This two-step production procedure ensured the dimensional precision and reproducibility of the specimens for subsequent mechanical and thermal characterisation.

# Results and Discussion

## Flexural Strength

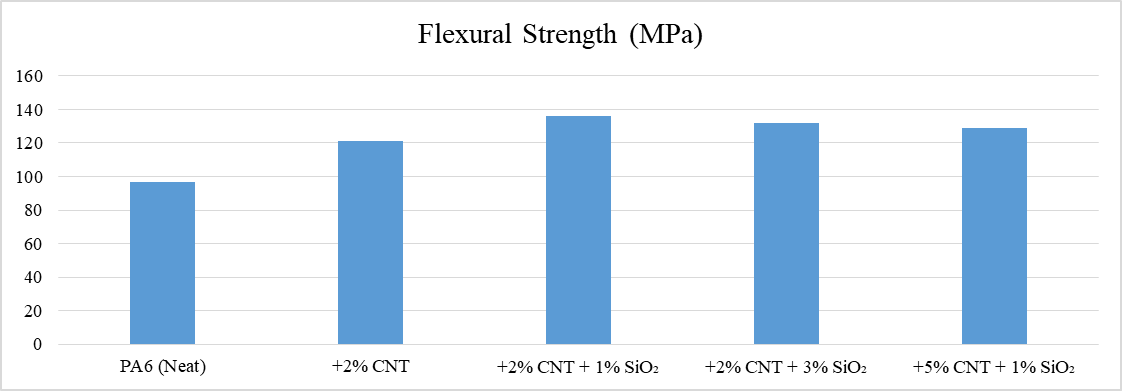
Flexural testing was accompanied to calculate the bending resistance and stiffness of the developed composites. The results are summarized below:

**TABLE 2.** Flexural Strength (MPa)

|  |  |
| --- | --- |
| **Sample** | **Flexural Strength** |
| PA6 (Neat) | 97 |
| PA6+2% CNT | 121 |
| PA6+2% CNT + 1% SiO₂ | 136 |
| PA6+2% CNT + 3% SiO₂ | 132 |
| PA6+5% CNT + 1% SiO₂ | 129 |

Flexural strength significantly improved with the addition of 2 weight % carbon nanotubes to the PA6 matrix showing an increase of about 25% above pure PA6. This notable improvement is mostly because to the stiffness, high aspect ratio and remarkable load-bearing capability of CNTs serve as nanoscale bridging elements that effectively transfer stress across the polymer strands. Carbon nanotubes improve resistance to deformation under flexural loads by limiting the mobility of polymer chains and effective stress transfer is improved [44-48] and fracture propagation pathways are impeded by the uniform distribution and strong interfacial adhesion of CNTs within the PA6 matrix.

As 1 weight % silicon dioxide nanoparticles and 2 weight % carbon nanotubes were added together the flexural strength increased to about 136 MPa is a significant improvement of about 40% over the unfilled PA6. The ability of SiO₂ nanoparticles to fill interstitial spaces both inside and across CNT networks is largely responsible for the improved mechanical performance; this increases filler packing density and decreases the creation of micro voids. As secondary reinforcing agents these nanoparticles improve energy dissipation under loading and prevent microcracks from forming and spreading.



**Figure 1.**Flexural Strength

However, the composites showed either slight increases or, in some cases, slight decreases in flexural strength above the optimal filler loading of 3 weight % SiO₂ or 5 weight % CNTs. The onset of particle agglomeration and decreased dispersion quality are the causes of this phenomena which is commonly observed in systems reinforced with nanoparticles. At elevated filler concentrations the augmented probability of filler filler interactions surpasses that of filler matrix interactions resulting in stress concentration points that compromise the integrity of the composite structure. Moreover the saturation of interfacial bonding sites restricts the development of robust interfacial connections hence reducing the total load transfer efficiency. These characteristics combined underscore the presence of a crucial filler threshold beyond which the mechanical advantages stabilize or diminish due to impaired microstructural uniformity [49-52].

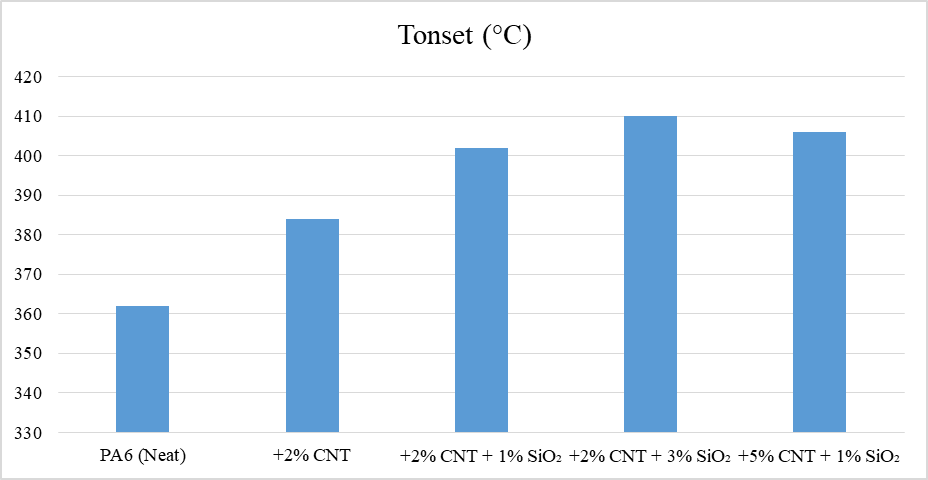
## Thermal Stability

Thermal stability was assessed using thermogravimetric analysis, focusing on the decomposition onset temperature (Tonset). The data are presented below:

**TABLE 3.** Thermal Stability

|  |  |
| --- | --- |
| **Sample** | **Thermal Stability** |
| PA6 (Neat) | 362 |
| PA6+2% CNT | 384 |
| PA6+2% CNT + 1% SiO₂ | 402 |
| PA6+2% CNT + 3% SiO₂ | 410 |
| PA6+5% CNT + 1% SiO₂ | 406 |

The decomposition onset temperature rose by 22°C when CNTs were added alone suggesting improved heat resistance as a result of the intrinsic stability of CNTs and limited chain mobility. When SiO₂ nanoparticles were added. Tonset increased even further up to 410°C with a 3 weight percent SiO₂ concentration. SiO₂ acts as a thermal diffusion barrier lowering localised heating and delaying decomposition leading to improved performance with higher CNT content causes a modest drop in Tonset which is probably caused by aggregates that serve as thermal defects or stress concentration sites. These findings support the use of hybrid filler systems to dramatically delay thermal degradation and expand the operational window of PA6 composites in high-temperature environments.



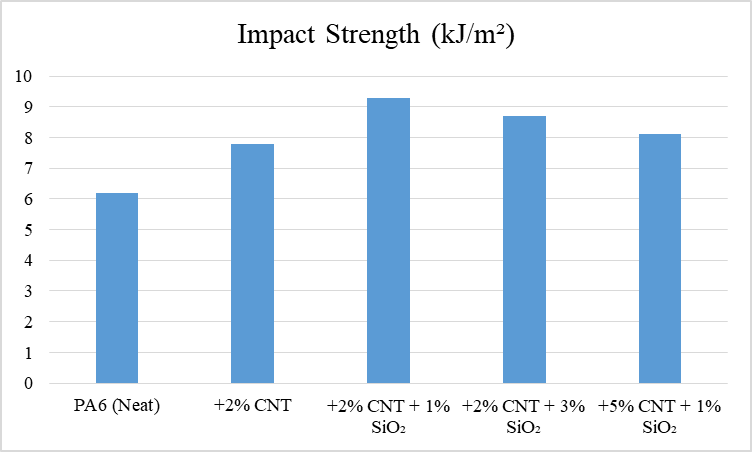
**Figure 2.**Thermal Stability

## Impact Resistance

Impact testing was carried out using the unnotched Charpy method to measure the composite’s ability to engage energy under rapid loading. The results are as follows:

**TABLE 4.** Energy Absorption

|  |  |
| --- | --- |
| **Sample** | **Impact Strength (kJ/m²)** |
| PA6 (Neat) | 6.2 |
| PA6+2% CNT | 7.8 |
| PA6+2% CNT + 1% SiO₂ | 9.3 |
| PA6+2% CNT + 3% SiO₂ | 8.7 |
| PA6+5% CNT + 1% SiO₂ | 8.1 |



**Figure 3.**Impact Resistance

The addition of 2 wt% CNT increased impact resistance by about 26% due to nanotubes capacity to stop crack development and disperse energy by bridging and pull out mechanisms and the hybrid composite containing 2 wt% CNT and 1 wt% SiO₂ had the strongest impact resistance with a 50% increase over plain PA6. This best combination most likely supports efficient load distribution and energy dissipation [. However excessive addition of either filler component resulted in a decrease in impact strength most likely due to matrix embrittlement and reduced filler matrix interaction limits the capacity to plastically bend and absorb impact energy of the composite [53-54].

# Applications in Automotive Door Panels and Structural Components

PA6+CNT+SiO₂ hybrid nanocomposites have optimal mechanical stiffness, heat resistance and impact toughness making them suitable for vehicle door panels, interior trims, and load-bearing inserts. In current automotive design predominantly for electric and fuel efficient automobiles increasing the requirement for lightweight yet durable materials that can endure high temperatures, mechanical shocks and long term weather exposure. The optimized formulation outperforms unreinforced PA6 by boosting flexural strength by over 40%, accelerating thermal decomposition onset by over 50°C and improving impact resistance by 50%. These qualities provide improved crash energy absorption dimensional stability under heat and resistance to repeated opening and closing of doors.

Nano fillers like CNTs and SiO₂ improves properties at low filler loadings by reducing the requirement for heavy mineral reinforcements like talc or glass fibre and helps to reduce overall weight and it is consistent in the car industry's sustainability and fuel efficiency standards. The ease of compression moulding also allows for mass production without sacrificing structural integrity or surface polish. Beyond automotive applications, these composites are ideal for electrical enclosures, thermal barriers, consumer electronics casings and even industrial housings that require improved mechanical performance under thermal stress. As a result the PA6 hybrid system is useful in a variety of industries that require lightweight, high-strength, and thermally stable materials.

# Conclusion

This study effectively shows the fabrication of high-performance PA6 based hybrid nanocomposites reinforced by multi walled carbon nanotubes and silicon dioxide nanoparticles. Adding 2 wt% CNT and 1 wt% SiO₂ to the PA6 matrix led in the best optimized formulation providing significant improvements in mechanical and thermal behaviour. The hybrid composite has a flexural strength of 136 MPa, a thermal degradation onset temperature of 402°C and an impact resistance of 9.3 kJ/m² and these improvements are principally owing to the synergistic reinforcing processes of CNTs acting as load transferring bridges and SiO₂ nanoparticles serving as thermal barriers and crack inhibitors.

While increasing filler content resulted in decreased or plateaued performance due to agglomeration effects, the optimized formulation delivers a balanced and efficient filler loading that maximizes structural performance while retaining process ability. PA6/CNT/SiO₂ nanocomposites are suitable for advanced technical applications such car door panels, interior safety components and thermal enclosures, as confirmed by our findings. Further the future research may focus on durability testing, fatigue resistance, recyclability and integration with surface modification approaches to improve interfacial adhesion and dependability. The reported gains represent a step ahead in the transition from traditional composites to nanotechnology enabled lightweight materials for next-generation industrial applications.

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