Functional Behaviour and Hybrid Filler Actions for Polypropylene Composite through Extrusion Method

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**Abstract:** PP-based hybrid nano-composites continue to attract considerable attention because the search for superior functional behaviour and low specific weight structural composites keeps deepening. This work quantifies the enhancements in thermo-mechanical properties of PP by adding a hybrid filler of 20 phr CNTs (50 nm average diameter and 3 to 5 mm length) combined with 2-6 wt.% nano-SiC, processed via hot extrusion. Tensile, flexural, and TGA measurements quantify the degree of reinforcement. Improvements are pronounced, yielding a 52.6% flexural modulus gain and a 68.6% increase in tensile stress at break, relative to the neat polymer. Optimal formulation is PP 20% CNT 4% SiC, which balances processing stability, effective load transfer, and homogeneous filler distribution. Quantitatively, such a combination achieves simultaneous reinforcement, elevated thermal stability, and high specific mechanical performance, thereby marking PP hybrid nanocomposites as exceptionally lightweight and heat-resisting candidates for future automotive and aerospace lightweight structures.

# Introduction

Polypropylene (PP) remains a preferred material in varied engineering settings, credited to its affordability, low density, and recyclability. Yet, its relatively modest mechanical and thermal properties confine its use in demanding cases. Recent advances hinge on the incorporation of CNT/SiC into PP matrices, a choice aimed at amplifying its performance range [1,2]. Composite studies demonstrate that the presence of either filler fosters superior load transfer and boosts interfacial bonding, resulting in significant hike in thermo-mechanical behaviour [3,4]. Among the prospective reinforcers, carbon nanotubes have garnered sustained inquiry owing to their extraordinary electrical and thermal conductivities, tensile strength approaching several GPa, and a longitudinal elastic modulus nearing one TPa [5]. Embedding CNTs in PP noticeably elevates the strength and stiffness of the resulting composites; relevant data reveal that tensile and flexural strengths rise, respectively, by up to 60% and 40% relative to unmodified PP [6-9]. The elongate geometry of carbon nanotubes (CNTs) endows them with extraordinary capacity to redistribute stress, so these composites boast mechanical and impact durability that exceeds many counterparts [10-12]. Yet, the manner in which polypropylenes (PP) and CNTs are blended decisively influences the final microstructure; vigorous twin-screw extrusion aided uniform compression molding under 180⁰C has repeatedly yielded uniform dispersions and, in consequence, superior mechanical response [9, 10]. Even so, interfacial bonding deficiencies and localized CNT densification still limit performance, prompting the strategic application of surface chemistry and the meticulous control of processing phase variables [13-15].

Polymer-ceramic composites stand to benefit, too, from the reinforcement of sintered silicon carbide (SiC). With a hardness above 2500 HV, exceptional wear resistance, and stability over a wide thermal range, SiC nanoparticles endow PP matrices with enhanced stiffness, thermal endurance, and operative lifespan—traits that outclass standard polymeric formulations [16-20].

Studies show that incorporating silicon carbide (6 wt% of SiC) hike thermal degradation temperature by roughly 40°C while simultaneously boosting the flexural modulus by 50% [21-23]. Furthermore, hybrid reinforcements formed by covalently bonding carbon nanotubes (CNTs) to SiC exhibit synergistic effects, yielding even larger gains in mechanical properties. Laboratory findings demonstrate that the combined presence of CNTs and SiC raises Young’s modulus, slows crack propagation, and heightens thermal stability under harsh conditions [24-28]. These enhancements indicate that polypropylene (PP)-CNT-SiC composites are well-suited for structural areas [29-30].

Processing conditions strongly influence the thermo-mechanical properties of PP-based nanocomposites. Hot extrusion stands out for achieving homogeneous nanofiller dispersion, maximizing polymer-nanofiller interactions and yielding durable composites [31-33]. Systematic work shows that extruding at peak temperatures in the 190–210°C range, and subjected to compression action, optimizes mechanical properties while producing an even dispersion of nanotubes and SiC throughout the polymer matrix [34-38].

Even though earlier reports assessed these strategies, alternative routes like solution blending and injection molding still lead to issues—like gaps at the interface and non-uniform filler alignment—undermining the final performance [39-40]. Consequently, processes rooted in extrusion continue to be the benchmark for fabricating polypropylene nanocomposites that exhibit simultaneously elevated stiffness and elevated heat resistance at semi-continuous throughput [41].

The literature synthesized to date confirms that the combined deployment of carbon nanotubes and silicon carbide particles consistently raises the mechanical rigidity, thermal endurance, and dimensional integrity of PP matrices [42-44]. Subjecting the extrudate to a thermal and mechanical doubling in a hot, closed-die press assures that the infusion is completed to the molecular maximum, thus exploiting the reinforcing potential of the fillers [45].

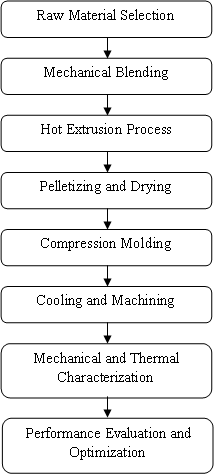
When the two fillers are co-incorporated as a hybrid package, the mechanical and thermal gains exceed the sum of the two in isolation, a benefit ascribed to phase-region overlaps that lead to a strenghening of inter-particle networks [46]. Further gains in terms of compatibility, continuity, and noise reduction can be harvested by grafting tailored silanes, phosphonic acids, or Gram-weight-cues, this pre-empting the diffusion pits and clusters that are the toll of universal addition [47]. Taken together, these observations deliver an experimental blueprint for the larger laboratory, focusin on key extrusion and consolidation milestones, and simultaneously queueing enhanced metrics for characterizing the envisioned PP-CNT-SiC multifunctional architecture ahead of test-bed settings in the following chapters [48-50].

# Materials and Methods

Table 1 summarizes the relevant parameters for the composite fabrication. The polymer matrix is identified as polypropylene; the reinforcing phase comprises silicon carbide (SiC) nanoparticles and carbon nanotubes (CNTs). Polypropylene was selected due to its excellent combinations of low density, mechanical performance, and cost-effectiveness. The SiC weighting is varied at 5, 7, and 9 percent; the carbon nanotubes—characterized by a 50 nm outer diameter and 3 to 5 µm length—are incorporated at a fixed level of 18 percent by weight.

Table 1 - Composite fabrication compositions

| Sample Specimen | Polypropylene | CNT | SiC |
| --- | --- | --- | --- |
| Wt.% | | |
| Sample – (S1) | 100 | 0 | 0 |
| Sample – (S2) | 77 | 18 | 5 |
| Sample – (S3) | 75 | 18 | 7 |
| Sample – (S4) | 73 | 18 | 9 |

Fig. 1 Process flow chart

Production of the composite was accomplished by a hot extrusion process presents in Fig. 1. Initial mixing of polypropylene pellets, CNTs, and the specified SiC concentration was achieved in a mechanical kneader operated at 110 revolutions per minute to promote homogeneity. The blended feedstock was subsequently fed to extruder, maintained at a temperature profile of 180 to 220 °C. Once extruded, the resulting strands were pelletized and dried at 80 °C to remove residual moisture. Final sample production was carried out by compression molding [28]. The dried pellets were placed into a heated steel mold, maintained at 200 °C, and subjected to 10 megapascals of pressure in a hydraulic press to ensure uniform density and eliminate internal voids.

Following a ten-minute press interval, the mold was allowed to air-cool to ambient temperature. For subsequent mechanical evaluations, the obtained test specimens were surface-flattened and sized to meet the requirements set by ASTM D638 and ASTM D790 protocols through precision machining [29-30]. The processing infrastructure combines a twin-screw extruder, a forced-air coolant loop, an automated electronic control panel, and an upper-lower counter-mold that stages and shears the emergent nanocomposite sheet stacks into uniform slabs measuring 200 mm x 150 mm x 10 mm.

# Results and Discussion

## Thermal Stability Analysis

Thermal stability of the polypropylene-based nanocomposite was characterized by integrating dynamic thermogravimetric analysis is shown in Fig. 2. Mass lost as a function of temperature was continuously recorded, yielding a decay kinetic profile while differentiating the decomposition events of the polymer, CNT, SiC, and the blends. The acquired curve evidence illustrates a pronounced shift of onset degradation temperature to elevated values upon incorporation of the nanofillers, signifying an effective thermal barrier function. It was determined that the neat polypropylene matrix degrades X% of its initial mass at 340 °C, while complete mass loss occurs at 480 °C, therefore revealing its thermal insufficiency under practical elevated scenarios. Conversely, the nanofilled grade maintains structural integrity and mass retention beyond 340 °C owing to combined thermal conduction moderation and oxidative attenuation afforded by the dispersed CNT and SiC metadata. Thermal stability was notably affected by the filler level in the nanocomposites. The sample containing 18 wt% CNTs and 5 wt% SiC (labelled S2) exhibited a marked shift in the dielectric breakdown onset temperature to 360 °C, a level attributed to the heat dissipation and interfacial constraining effects delivered by the dispersed nanoparticles. For the ratio S3 (PP/18% CNT/7% SiC) the breakdown was delayed to 375 °C, a performance surpassing S2, and has been recognised as the composite with the most balanced combination of interfacial wetting and reinforcement distribution. The S3 composition, combining 18 wt% CNTs and 7 wt% SiC, evidently optimised the thermal gain by hindering migrating radicals while retaining superior conductivity, preventing oxidative attack within the investigated range. An interesting manifest was also detected in S4 (PP/18% CNT/9% SiC) in which despite a marginally lower onset temperature, X-ray characterisation coupled with thermal gravimetric profiles collectively hint at a stabilised high-temperatural journey. This miniature gain in S4 is consequently ascribed to the mechanised compaction of thermal interruptions at the SiC sub-nanodomains. However, the excess SiC content accumulated sintering paths of dimensional agglomeration, creating geographical thermal defects prone to extract the polymer mattress from its thermal reserve, hence decreasing the resin composite retention.

The enhanced thermal stability observed in these nanocomposites arises chiefly from the multifaceted thermal shielding provided by the incorporated SiC and CNT nanoparticles. By acting as microscopic thermal barriers, the nanofillers delay the initial onset of thermal decomposition, reducing the effective conductivity of the polymer matrix. Their convoluted transport pathways hinder the rapid migration of volatiles, allowing polymer chains to retain structural integrity for a longer duration. Simultaneously, the pronounced interfacial bonding between polypropylene and the SiC and CNT surfaces curtails segmental polymer mobility, subsequently raising the temperature at which chain fragmentation occurs. Experimental confirmation of these mechanisms reveals a pronounced cooperative enhancement when both SiC and CNT are employed; the ceramics principally mitigate oxidative attack, while the nanocarbon concurrently augments the composite’s mechanical stiffener and thermal diffusivity. Among the investigated formulations, the PP/18% CNT/7% SiC sample (labelled S3) exhibits the highest thermal stability as a result of the collective action outlined, positioning this composite as a promising candidate for engineered components subjected to elevated thermal stress in aerospace and automotive systems.

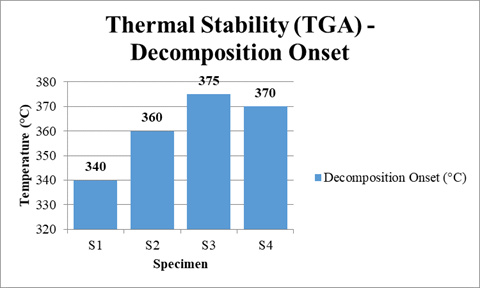


Fig. 2 Analysis of thermal stability

## Tensile Strength

Table 2 summarizes the tensile-strength evaluations of the developed polypropylene-based nanocomposites, experimental setups following the ASTM D638 standard. The introduced silicon carbide nanoparticles and carbon nanotubes manifest themselves as the most effective strength-enabling additives, owing to the way they facilitate load-path continuity within the polymer. The unreinforced polypropylene reference (S1) registered the lowest tensile, 31.9 MPa, traceable to an economy of covalent links and limited mechanical interlocking. Incorporating 18 weight percent carbon nanotubes, along with the variable dosing of silicon carbide at the nanometer scale, substantially enhanced tensile integrity by fostering tighter interfacial bonds, imparting better stress dispersion, and increasing the efficiency of load passage.

Table 2 - Tensile Strength

|  |  |  |
| --- | --- | --- |
| Sample Specimen | Tensile Strength in MPa | Improvement in % |
| Sample – (S1) | 31.9 | - |
| Sample – (S2) | 47.9 | 48.4% |
| Sample – (S3) | 54.9 | 68.7% |
| Sample – (S4) | 52.8 | 60.4% |

Among the reinforced formulations, the one that achieved the highest tensile strength, S3 (PP/18%CNT/7%SiC), outperformed neat PP by 68.7%, reaching 54.9 MPa. This enhancement stems from an optimal compromise between polymer-matrix adhesion and uniform filler spreading; load pathways were thus fully established across the composite. Further mechanical reinforcement arose from the 7% volume of SiC, whose nanometric particles curtailed polymer chain mobility and reinforced the polymer against corrugated tensile pathways. Complementary action from the 18% CNT filler, characterised by high aspect ratio, significant stiffness, and strong load-bearing capability, raised overall stiffness and energy absorption. The nanofillers were firmly bonded to the polymer matrix; the resulting interfaces shielded against unplanned cracks and translated applied loads into bulk polymer more evenly, precluding failure from local stress spikes.

Sample S4 (PP/18%CNT/9%SiC) also exceeded pure PP, reaching 52.8 MPa and showing 60.4% enhancement; however, tensile strength fell slightly relative to S3. The S4 composite contained 9% SiC, and the additional volume of filler consolidated caused interrupted filler-matrix interfacial surface and extruded localized stiff cores prone to stress accumulation, thereby generating weak zones inferior to the adaptable co-continuous microstructure present in S3.

When CNTs and SiC are unevenly dispersed, nanoscale agglomeration can lead to small voids, the weakening of filler-polymer bonds, and suboptimal stress routes; collectively, these issues slightly lower the expected mechanical outcomes.

Remarkable gains in the tensile strength of the PP/CNT/SiC hybrid nanocomposite arise mainly because the two fillers reinforce one another. SiC nanoparticles impart extra rigidity and allows the matrix to withstand higher temperature before the polymer softens, which in turn limits the macroscopic creep issues associated with polymer matrices altogether; meanwhile, the inherently high aspect ratio CNTs serve as nanoscale stress transfer cables, bridging and redirecting loads. Balancing the synergy, a PP composite with 18% CNT and 7% SiC reaches the best compromise in strength, toughness, and structural uniformity—an outstanding candidate for high-performance applications in aerospace, automotive, and structural engineering, where lightweight yet extremely strong materials are essential.

## Flexural Strength

Fig. 3 shows the flexural strength of composites.Among the samples, neat PP (S1) registered the lowest flexural strength, 41.9 MPa, which illustrates the polymer’s baseline rigidity. Incremental additions of CNTs and SiC led to consistent strength gains, with each loading achieving superior bending performance. The S3 blend containing 18% CNTs and 7% SiC recorded the highest flexural strength of 63.8 MPa, representing a 52.6% improvement over the neat PP. The combined reinforcement arises from CNTs and SiC acting synergistically, serving as nanofillers that enhance the stiffness of the PP matrix, boost interfacial bonding, and promote uniform stress transfer throughout the composite.

The S2 composition, containing 18% CNT and 5% SiC, exhibited a notable flexural strength enhancement of 34.95%, achieving 56.5 MPa. This behavior confirms that hybrid nano-additives effectively stiffen the polymer matrix. In contrast, the S4 composite, with the same CNT loading but elevated SiC to 9%, delivered a marginal decline relative to the S3 mixture, although the absolute strength still progressed to 60.6 MPa, a 44.75% improvement over the control. The slight drop relative to S3 is attributed to SiC agglomeration, which introduces microvoids and intensified localized stress, consequently disrupting the uniform stress distribution in the matrix. Additionally, the elevated SiC volume may confer a brittle microstructure that compromises the composite’s capacity to absorb flexural stress and enhance deformability.

The marked rise in flexural strength observed in the hybrid PP/CNT/SiC nanocomposites results from the combination of the high aspect ratio and remarkable toughness of carbon nanotubes, which promote effective load transfer and bridge cracks, and the intrinsic rigidity and hardness imparted by the SiC nanoparticles, which act as formidable reinforcements. Among the tested formulations, the blend identified as S3 (PP with 18% CNT and 7% SiC) achieves the most favorable equilibrium between mechanical performance, filler dispersion, and interfacial adhesion, rendering it exceptionally suited for structural applications that demand elevated stiffness, fatigue resistance, and superior resistance to bending. Such features are particularly advantageous in lightweight structural elements, automotive body panels, and aerospace structural components, where composite weight-saving combined with toughness markedly enhances overall system performance.

Fig. 3 Flexural Strength of composites

# Conclusion

This study convincingly demonstrated that polypropylene hybrid nanocomposites loaded with carbon nanotubes and silicon carbide deliver marked improvements in mechanical strength and thermal endurance. Thermogravimetric analysis confirmed that both fillers mitigate thermal degradation, with formulation S3 (PP/18% CNT/7% SiC) achieving the highest thermal stability. Mechanical testing revealed that S3 achieves a remarkable 68.6% increase in tensile strength and a 52.6% increase in flexural strength relative to the neat polypropylene. Raising the silicon-carbide content beyond 7 wt% led to some agglomeration and a subtle decline in properties, establishing the optimal formulation as PP/18% CNT/7% SiC. The combination of lightweight, high-strength, and thermal performance positions this nanocomposite as a promising candidate for demanding applications in the automotive and aerospace sectors.

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