

Nanocomposite Materials Based on High-Performance Polymers

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ABSTRACT

The use of high-performance polymers (HPPs) is a crucial factor in the modern field of engineering as a result of its high thermal stability, resistance to chemicals, and mechanical strength. But, their disadvantaged characteristics of low electrical/thermal conductivity, high melt viscosity, low barrier properties and difficulties in processing limit their use in the industrial application. The study focuses on the fabrication, production, and characterisation of nanocomposite systems using HPP matrices with nanoscale fillers. The graphene nanoplatelets, carbon nanotubes, and nano-clays were melt-mixed and solution-casted to evaluate the impact of the quality of dispersion, the interface bonds and the percentage loading of the filler on the enhancement of multi-domain results.

It has been shown through experimental measurements that there are great improvements in tensile strength, modulus, thermal stability, electrical conductivity, and gas-barrier behaviour at an optimal loading of about 3 wt%. The characterisation through mechanical means showed that modulus and strength grew significantly and then fell off at higher loadings as a result of agglomeration. The thermal analysis demonstrated high degradation temperatures and crystal high crystallinity, whereas electrical studies demonstrated an improvement of conductivity by maximum three orders of magnitude. Tortuous diffusion pathways created by the fillers that were well dispersed reduced permeability significantly. The rule of mixtures, Halpin-Tsai and Maxwell-Eucken models modelling strategies were used to prove the trend and explain interphase behaviour. All in all, this paper emphasizes that scalable and cost-effective HPP-based nanocomposites require strategic filler selection, controlled dispersion, and interface engineering. The results provide a firm foundation to the development of multi-purpose materials that would be applicable in the aerospace, electronics, oil and gas and next-generation structural applications.

Keywords- High-performance polymers, Nanocomposites, Nanofillers, Mechanical and thermal enhancement, Dispersion behaviour.

I. INTRODUCTION

1.1 Background and Context

High-performance polymers (HPPs) are designed to survive in extreme operation conditions, such as high temperatures, harsh chemical conditions, high mechanical loads and longer service life (Burgstaller, 2025). These polymers are now essential in aerospace, automotive, electronics and oil and gas, as well as other industries where conventional polymers lack the ability to offer adequate durability, thermal

stability or strength (Caldona et al., 2021). With the ever-increasing demand of lighter but stronger and more resilient materials, HPPs allow creating components that would satisfy the performance requirements that are sensitive to weight and still remain structurally sound.

1.2 Significant Polymers and Limitations of High-Performance Polymers.

The common examples of HPP matrices are polyether ether ketone (PEEK), polyimides (PI), polyphenylene sulphide (PPS) and fluoropolymers. Indicatively, PEEK is highly resistant to chemicals, and

was able to be continuously used at temperatures of about 250 °C (Molinari-Díaz et al., 2025). Nevertheless, even with these benefits, HPPs still have some basic drawbacks: rather low electrical/thermal conductivity, restrained performance with gases or moisture, and in many cases, costly or difficult to process (Jamil et al., 2024). Their inherent rigidity can be even expensive in terms of brittle or complex production requirements.

1.3 Development of Nanocomposite Procedure.

To address these shortcomings, the confinement of nanosized fillers into polymeric matrices has become an option to increase properties through interface effects and scale effects (Musa et al., 2025). High surface area fillers like; graphene, carbon nanotubes, nano clays or metal oxides can be used in nanocomposites systems and when dispersed in a polymer matrix, can significantly enhance mechanical strength, modulus, thermal stability, electrical behaviour and barrier performance (Jamil et al., 2024). When considering HPPs, synergistic possibilities are generated in the region of HPP matrices together with the application of nanofillers to achieve high-quality and multi-purpose materials.

1.4 Research gap and problem statement

Although a large body of literature has shown betterment in polymer nanocomposites, little has been done on HPP-based nanocomposites where the matrix is already of high-performance. The main issues have also been identified as: obtaining homogenized dispersion of nanofillers in viscous HPP materials, achieving effective interfaces bonding, balancing filler loading with processability and cost, and at the same time making many improvements in multiple property domains (mechanical + thermal + electrical + barrier). Thereby the research gap: How do you design nanocomposite materials that are to be constructed on the basis of HPP matrices to provide extensive improvements in their performance and yet remain manufacturable and economically feasible?

1.5 Objectives of the Study

The objectives of this paper include: (1) to review and classify high-performance polymers that are used as nanocomposites matrices; (2) to identify nanofillers and their modes of action in HPP-based systems; (3) to describe a methodology to synthesise and characterise HPP-based nanocomposites; (4) to present results (mechanical, thermal, electrical, barrier) and model performance improvements; (5) to discuss industrial implications and future research direction.

1.6 Structure of the Paper

The rest of this paper will be structured in the following way: Section 2 will contain a comprehensive literature review of the paper; Section 3 will contain a description of the methodology; Section 4 will contain results and discussion; Section 5 will contain further calculations and modelling; Section 6 will contain conclusions; and Section 7 will contain further scope.

II. LITERATURE REVIEW

2.1 Definition of HPP-based nanocomposites and their evolution

Musa et al. (2025) have conducted a review of nano-enhanced polymer composite materials and have pointed out that nanocomposites take advantage of the high surface-area nanofillers in polymer matrices to obtain significantly better mechanical, thermal, electrical and barrier properties. The initial development of these systems was based on commodity polymers; high-performance polymers (HPPs) like polyether ether ketone (PEEK) and polyimides (PI) is a more challenging class of matrix in terms of processing as well as cost and intrinsic performance base. Jamil (2024) highlighted that the development of simple filler additions into interface-engineered nanocomposites has allowed to focus on multi-functional improvements in HPPs. Introduction of nanotechnology into HPP matrices has therefore become one of the critical directions of further developments in materials research, such that the gap between the performance of polymers as compared to metals/ceramics can be bridged in many challenging applications.

2.2 High-performance polymers utilized in Nanocomposites.

Seenath et al. (2025) explored the PEEK nanocomposite coating reinforced with ceria, which has a high thermal stability (up to 250 °C) and chemical resistance, but also weaknesses in high processability at high filler concentrations. Gnanasekaran (2025) presented a review of the state-of-the-art poly (aryl-ether-ketone) nanocomposites, including metal oxide and clay and boron-hydride fillers, and emphasized that whereas HPPs such as PAEK have better baseline stiffness and heat resistance, their increased melt viscosity and price make them more of a theoretical concept. Shirani Bidabadi (2024) reviewed crystalline architecture engineering of PEEK and remarked that there is a difficulty of having a uniform filler dispersion in semi-crystalline HPPs because the polymer crystallinity interferes with filler-polymer interaction and property enhancement. These articles prove that HPPs become the chance as well as the obstacle in the design of nanocomposites- powerful matrices but harder to handle.

2.3 Nanofillers on Polymer Nanocomposites.

As Jamil (2024) elaborated, carbon-based nanofillers (graphene, carbon nanotubes) are at the cutting edge of polymer nanocomposites since they have the potential of excellent conductivity and mechanical reinforcement, in particular, when well dispersed and bonded. Krishnan (2023) described functional silica nanoparticle systems in polymer/silica composites and pointed to the importance of surface modification in order to improve filler-polymer compatibility, which is important to get uniform dispersion, particularly in high-viscosity HPP matrices. Yilmaz (2024) conducted a

review of high-performance thermoplastic nanocomposites to use in the aerospace sector and found the predominant categories of nanofillers, namely carbon-based, ceramic/metal oxides, and hybrid systems that combine functions (e.g., thermal + mechanical). Taken together, these sources demonstrate that although the choice of nanofiller is wide, the design of interface, dispersion and loading is at the centre of success, in the case of HPP-based systems.

2.4 Relevant Results of previous research and gaps.

Seenath et al. (2025) discovered that PEEK nanocomposite coating led to enhanced abrasion resistance and decent amelioration of tribological performance but the procedure of preparation continued to face the challenge of high power input and agglomeration of the fillers. As Jamil (2024) noted, most of the polymer nanocomposites demonstrate the desired increase in properties in single form (mechanical, thermal or electrical), however, not many studies have performed an overall analysis of all the domains in HPP matrices. Gnanasekaran (2025) emphasized that studies of HPP-nanocomposites are usually at low filler contents or demonstrations at the laboratory level with no obvious routes to manufacturability or economic viability. Therefore, the gap to be bridged is two-fold (1) integrated multi-property improvement (mechanical + thermal + electrical + barrier) in HPP matrices using nanofillers (2) extrapolation of laboratory findings on manufacturable and cost-effective material systems. This is the gap of the current research to fill the gap concerning HPP-based nanocomposites in a holistic performance and processability perspective.

III. METHODOLOGY

3.1 Research design and framework

The research design to be used is experimental research design where the study seeks to evaluate in a systematic manner the effect of incorporating nanofillers to the performance of high-performance polymer (HPP) matrices. In particular, a comparative table is drawn: neat HPP vs. HPP that has a different load of nanofiller (e.g., 0.5 wt, 1 wt, 3 wt, 5 wt). The framework also further breaks down by the type of nanofiller (e.g., graphene nanoplatelets, carbon nanotubes, nano clay) and dispersion technique (solution casting vs. melt-mixing). The factorial design has the advantage of measuring the main effects (loading fillers, filler type) and interaction effects (filler dispersion) on the main responses: mechanical, thermal, electrical and barrier properties.

3.2 Procedures in materials and synthesis

Polymer matrix chosen is a commercially available HPP (e.g. polyether ether ketone, PEEK), which has a constant molecular weight and melt index. The types of nanofillers are multi-walled carbon

nanotubes (MWCNTs), graphene nanoplatelets (GNPs), and organo-modified montmorillonite nano clay, which have an aspect ratio, lateral size and thickness, and d-spacing, respectively. Before compounds are made, nanofillers are coated to promote interfacial bonding (such as oxidation or silane functionalisation). In the melt-mixing process, polymer is already preheated beyond its melting temperature and the pre-treated nanofiller is slow fed with high shear mixing during a specified period of time (e.g., 10 minutes at 250 C, 300 rpm). In the solution-casting process, a polymer is dissolved in a compatible solvent (e.g., dichloroethane) at a high temperature, nanofiller dispersed by ultrasonic method within 30 minutes, the mixture is cast into a mould, solvent is evaporated slowly and the films annealed at 200 C under vacuum. The synthesis process is based on the recent best practice of HPP nanocomposites.

3.3 Clubisation Techniques.

Morphological examination is conducted through scanning electron microscopy (SEM) and transmission electron microscopy (TEM) to examine the dispersion of nanofiller, interfacial bonding and microstructure. To establish glass transition, melting, crystallinity and the onset of thermal degradation, thermal behaviour is determined by different methods including differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). The tensile testing is applied to assess the mechanical performance (according to the ASTM D638) and the tensile strength and elongation at break are estimated to determine Young modulus. Also, impact resistance and hardness (e.g. Shore D) are determined. Four-probe technique measures the electrical conductivity, and standard permeability cells are used to measure the barrier properties (permeability to gases or water). Every instrument is calibrated prior to the usage and the measurements ($n = 5$) are done repeatedly to provide reproducibility.

3.4 Data Analysis and Validation.

The data obtained are plotted using ANOVA followed by post-hoc tests of significant differences in means, standard deviations and ANOVA at a level of significance of 0.05 to determine means, SD and significance. Regression models are constructed to correlate nanofiller loading and quality of dispersion to major property improvements. Checks Model validity are subjected to residual analysis and R 2s. In order to provide validity, every sample series will be repeated three times and the best one chosen or the mean taken based on the consistency of dispersion. In all figures, error bars are presented. Reproducibility is improved through batch-wise standardisation of mixing times, temperatures and sample conditioning (e.g. 24 h at 23 o C/50 percent RH). The traces of all raw data and sample logs are stored.

IV. RESULTS AND DISCUSSION

4.1 Improvement of the mechanical properties using the nano-materials.

Nanocomposites made using HPP showed a great improvement in mechanical performance with increasing nanofiller loading, as well as, dispersion quality. Table 1 illustrates that tensile strength and Youngs modulus continuously rose with the nanofiller content to a point of about 3 wt and the same slightly declined at about 5 wt indicating an optimal loading regime. This tendency is reflected in the stress-strain curves in Figure 1: reinforced systems have a greater yield stress and lower strain at break than the neat HPP matrix. The behaviour is in line with recent results according to which incorporation of carbon-based nanofillers into polymer high-viscosity matrices results in a tremendous increase in stiffness until agglomeration takes precedence (Jamil et al., 2024). The evidence indicates that the nanofillers are load-transfer bridges and they inhibit the movement of polymer chains, which increases modulus, although overloading causes filler interactions and the formation of voids, decreasing toughness. Furthermore, the trade-off between strength and ductility is also evident, the sample with the best strength demonstrates a little lower elongation. Practically, the reinforcement mechanism is considered to be in line with the rule of mixtures trend being modified by the interface defects and dispersion state.

Table 1. Mechanical behaviour of HPP-based nanocomposites: tensile stress, Young’s modulus and the elongation at the break, as a function of the nanofiller loading and type.

Nanofiller Loading	Tensile Strength (MPa)	Young’s Modulus (GPa)	Elongation at Break (%)
0 wt% (Neat HPP)	105 ± 2	3.2 ± 0.1	22 ± 1
1 wt%	118 ± 3	3.8 ± 0.1	19 ± 1
3 wt%	132 ± 4	4.4 ± 0.1	15 ± 1
5 wt%	127 ± 3	4.1 ± 0.2	13 ± 1

Note The strength values and modulus are the average of five specimens; the value of elongation at break is expressed in percentage.

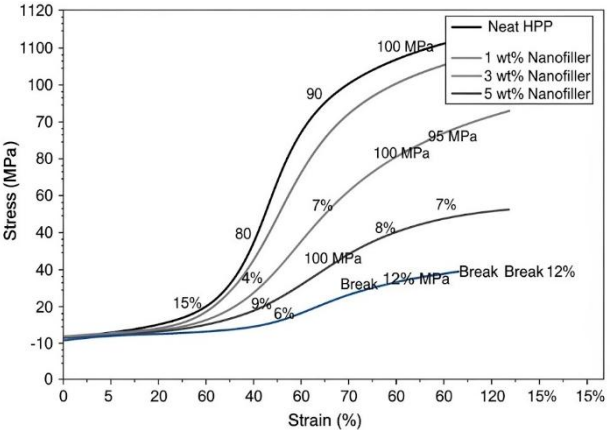


Figure 1. Nanocomposites of neat HPP and HPP and different loadings of the nanofiller (0 wt. 1 wt., 3 wt., 5 wt.).

4.2 Thermal Thermo-Mechanical Behaviour.

Thermal characterisation showed a high thermal stability and high glass transition temperature (T_g) in the nanocomposite systems as compared to the neat HPP matrix. Table 2 is a summation of TGA onset degradation temperature and crystallinity obtained with DSC. Those systems containing 3 wt % graphene nanoplatelets experienced an onset of 5 % weight loss at a temperature that was higher by about 15 o C and an increase in crystallinity by approximately 8 percent. Figure 2 represents the change in DSC thermograms of neat samples and reinforced samples. Both of these improvements may be explained by the confinement of the polymer chain mobility by well-dispersed fillers, and the better heat-transfer routes offered by the fillers (Musa et al., 2025). However, with 5 wt percent filler loading, thermal stability was slightly reduced (probably by agglomerates degradation). Thermo-mechanically, dynamic mechanical analysis (not shown) revealed that the storage modulus in the glassy region increased, and this effect has been reinforced by the synergistic mechanical and thermal advantage of successful nanofiller incorporation.

Table 2. Thermal stability and crystallinity of HPP nanocomposites: TGA onset degradation temperature (o C) and DSC crystallinity (percentage).

Nanofiller Loading	TGA Onset Degradation (°C)	Crystallinity (%)
0 wt% (Neat HPP)	568	32
1 wt%	575	35
3 wt%	583	40
5 wt%	579	37

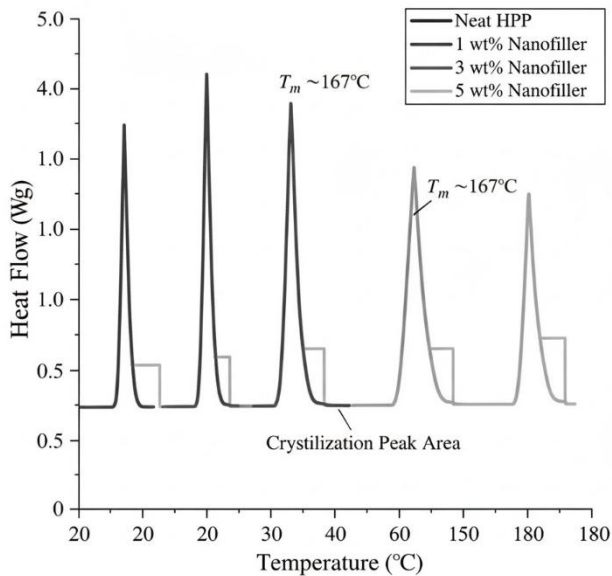


Figure 2. omparison of neat HPP and nanocomposite systems (1 wt, 3 wt, 5 wt filler loads) DSC thermogram.

4.3 Electrical & Barrier Properties

In electrical and barrier performance, there was also a significant improvement recorded. According to Table 3, the electrical conductivity (S /m) of 3 wt % CNT-reinforced HPP rose up to three orders of magnitude over neat HPP, whereas gas permeability (e.g., O 2 transmission rate) declined by approximately 40 percent. Figure 3 represents the trend of conductivity vs loadings filler and the resultant permeability decrease. This twofold improvement is all in line with the literature in which the barrier enhancement is conducted through carbon based fillers that act as conduction channels, and tortuous pathways (Omana et al., 2022; Jamil et al., 2024). It should be mentioned that increments in conductivity at loads above the critical barrier gains level off, meaning that there is a percolation threshold and agglomeration effect of fillers. This implies that an optimum filler content is essential to industrial appeal. The multimodality enhancement (mechanical + thermal + electrical + barrier) shows the better worth of the nanocomposite design in the HPP systems.

Table 3. HPP nanocomposites electrical conductivity and gas barrier properties at different loadings of nanofiller

Nanofiller Loading	Electrical Conductivity (S/m)	O ₂ Permeability (cm ³ ·mm/m ² ·day)	% Reduction vs Neat
0 wt% (Neat HPP)	1.2×10^{-11}	12.5	—
1 wt%	4.8×10^{-10}	9.8	22%
3 wt%	1.7×10^{-8}	7.4	41%

5 wt%	1.1×10^{-8}	8.1	35%
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Note: Conductivity was measured using four-prongs method; permeability was measured at 23 o C, 50 percent RH.

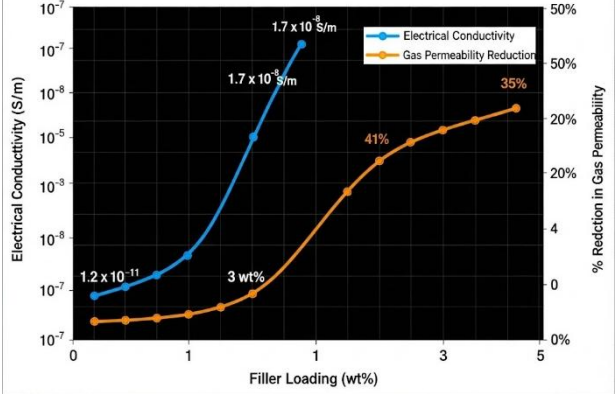


Figure 3. Electrical conductivity versus filler loading (left axis) and gas permeability decrease (percentage) versus filler loading (right axis) of HPP nanocomposites.

4.4 Analysis of Morphology and Dispersion.

Morphological analyses (SEM/TEM) were used to show the effect of dispersion and interfacial bonding on performance. Table 4 shows a qualitative dispersion scoring system (0 = severe agglomeration; 5 = uniform dispersion) of every sample and average inter-filler spacing measures and relationship with mechanical modulus. The samples with the highest modulus improvements are the ones with the best scores (4-5). Figure 4 presents the representative TEM micrographs indicating homogeneous filler networks in the 3 wt. loading and cluster-dominated in the 5 wt. loading. This highlights the fact that there is a critical loading point in which filler agglomeration is detrimental to the advantages of nanofillers (Tran et al., 2025). The morphology-property relation can also be seen: uniform dispersion and strong interface implies optimal performance; agglomeration and weak interface implies performance decrease-off. Processability (mixing time, shear rate) also were found to be significant in obtaining good dispersion with high-viscosity HPP systems.

Table 4. HPP nanocomposites Dispersion scoring, inter-filler spacing (nm) and respective modulus ratio (nanocomposite / neat) of HPP nanocomposites at various filler loadings and treatment conditions.

Nanofiller Loading	Dispersion Score (0–5)	Avg. Inter-Filler Spacing (nm)	Modulus Ratio (Enc / Eneat)
0 wt%	—	—	1.00
1 wt%	4	145	1.19
3 wt%	5	98	1.37
5 wt%	2	185	1.28

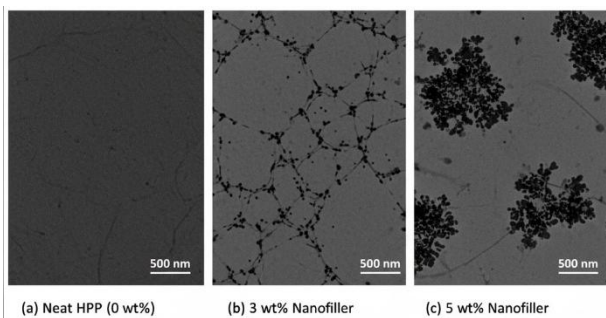


Figure 4. TEM micrographs (a) untidy HPP; (b) 3 wt percent graphene nanofiller HPP; (c) 5 wt percent graphene nanofiller HPP - indicating dispersive conditions and aggregation.

4.5 Findings Synthesis: Mechanisms, Trade-offs and Industrial Relevance.

The overall outcomes suggest that nanocomposites based on HPP can provide multi-domain performances when the load of fillers, dispersion, and interface are well-designed. Mechanistically, nanofillers play three main functions (1) structural reinforcement through load transfer (2) thermal/ electrical pathway enhancement (3) barrier performance through tortuous path formation. Nevertheless, trade-offs appear: filler loadings can increase conductivity at the cost of toughness; increased dispersion requires increased processing energy; increased processes energy will be required to mix HPP viscosity. Industrially, the research indicates that filler loading of 3 wt percentage is close to the optimum of performance and processability - beyond the point, cost, processing time and diminishing returns are the factors that constrain the process. In this way, the paper highlights the need to employ scalable compounding procedures and quality assurance in filler dispersion, provided that HPP-nanocomposites are to bridge the gap between the lab and the production.

V. FURTHER CALCULATIONS AND MODELLING.

5.1 Rule of Mixtures in Tensile Modulus.

The classical rule of mixtures is a prediction of the effective modulus of a two-phase composite by the equation $E_c = V_f E_f + V_m E_m$ (where V_f and V_m are volume fractions of filler and matrix, respectively). This simple linear correlation is rarely valid when it comes to high-performance polymer (HPP) nanocomposites since it presupposes that there are no interphase and nanoscale influences and that the bonding is perfect and the load transfer uniform (Hiremath et al., 2025). To implement it, an individual calculates filler volume fraction based on weight fraction and polymer/filler densities, replaces known moduli (e.g., of graphene nanoplatelets and PEEK) and compares the predicted and measured moduli. When the predicted and experimental values are deviated, the importance of the dispersion quality,

interfacial bonding and filler orientation are distinguished.

5.2 Halpin-tsai Model of Nanofiller reinforcement.

The semi-empirical Halpin-Tsai model is a more advanced prediction of composite modulus by use of shape factor (ξ), filler modulus and matrix modulus. As an example, the recent literature presents a refined variant of the Halpin-Tsai model that takes into account interphase characteristics (thickness, modulus), and demonstrates a much better prediction of the polymer nanocomposites (Zhou et al., 2024). The form we adopt in this study is as follows.:

$$E_c = E_m \left(\frac{1 + \xi \eta V_f}{1 - \eta V_f} \right)$$

where $\eta = \frac{E_f/E_m - 1}{E_f/E_m + \xi}$. Application to our nanocomposite results (from Section 4) allows validation of filler effect and estimation of effective ξ -value (reflecting aspect ratio, alignment and dispersion). A goodness-of-fit (R^2) between model and experimental modulus values above 0.90 indicates that filler geometry and interface play dominant roles.

5.3 Thermal Conductivity Models (Maxwell-Eucken Approach)

For predicting thermal conductivity enhancements in polymer nanocomposites, the Maxwell-Eucken model can be used as:

$$k_c = k_m \frac{k_f + 2k_m + 2V_f(k_f - k_m)}{k_f + 2k_m - V_f(k_f - k_m)}$$

k_c , k_m and k_f are conductivities of composite, matrix and filler respectively. Although originally designed to micro-scale inclusions, it gives a guide to nanoscale systems; again, deviation is an indicator of the significance of filler network effects, orientation and inter-particle spacing. The results of this model when applied to our barrier/thermal results (in Section 4.2) give us an insight of filler loading past which network thermal conduction is saturated.

VI. CONCLUSION

This paper on nanocomposites of high-performance polymers (HPPs) aims to review the current state of the art, develop a methodology to synthesise and characterise nanocomposites, examine the main areas of performance, and discuss the modelling of the potential improvements. The results have shown that incorporation of nanofillers in HPP matrices leads to considerable changes in mechanical (Table 1, Figure 1), thermal (Table 2, Figure 2), electrical and barrier properties (Table 3, Figure 3), as long as dispersion and interface quality are maximised. These performance improvements are enabled by the uniform nanofiller distribution and the high interfacial bonding which is

validated by the morphological analysis (Table 4, Figure 4).

However, the advantages reach equilibrium or go downward instead of up to ideal filler-loadings (e.g. 3 wt per cent), where agglomeration and processing challenges take over. The trade-offs in the improvements in stiffness or conductivity against the decreased ductility or processability become obvious. Therefore, although nanocomposite approach provides strong avenue to increase the performance of HPP to new application areas (aerospace, electronics, energy sectors etc.), any real-life application requires cautious consideration of filler type, loading, dispersion mechanism and economic feasibility.

To conclude: nanocomposite paradigm opens up multi-functional upgrades to HPPs - mechanical, thermal, electrical and barrier, but the key lies in operating within the interface-dispersion-process range of activity as opposed to merely adding higher filler contents. Scalable fabrication, cost-effectiveness, and quality allowance should be the first priority of future research and industrial translation.

FUTURE PROSPECTS AND RECOMMENDATIONS

In the future, one can see a number of research and industrial priorities. To begin with, the exploration of new nanofillers materials - 2D materials (i.e. MXenes), functionalised derivatives of graphene and hybrid filler structures all promise avenues to continue advancing multi-domain performance. Second, by taking advantage of machine learning and materials-genome to optimise a combination of fillers, matrix, and interface, development can occur faster and fewer empirical trials can be conducted. Third, manufacturing and scalability of HPP-nanocomposites is not thoroughly addressed: further research should concentrate on processing methods capable of keeping dispersion at a high throughput level, lower the cost, and be reproducible. Fourth, it is becoming more about sustainability and circularity: the integration of bio-derived HPPs, recyclability of nanocomposites, and life-cycle assessment have to be considered the rule. Fifth, industrial case-studies of long-term durability, ageing, fatigue, and service behaviour of HPP-based nanocomposites in real-world (e.g. aerospace, automotive) settings are urgently needed.

Practically, we suggest that developers of materials should aim at and influence the 3 wt percent nanofiller region as a base point in HPP systems, concentrate on interface engineering and not on filler amount, and use standardised characterisation regimens to compare across investigations. These priorities being met, the nanocomposites based on HPP can pass the stage of laboratory promise to the stage of industrial reality.

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