



Polypropylene-Based Hybrid Composites: Interplay of Elastomeric Toughening, Mineral Reinforcement and Structure–Property Relationships

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ABSTRACT

Polypropylene (PP) is widely used in engineering applications because of its low density, chemical resistance, processability, and favourable mechanical properties; however, its stiffness–toughness balance often limits performance in demanding applications. Hybrid modification through the incorporation of elastomeric toughening agents and mineral fillers provides an effective approach to tailoring this balance. This review examines PP-based hybrid composites containing elastomers, particularly polyolefin elastomer (POE) and propylene-based elastomers, together with mineral fillers such as talc, calcium carbonate, and mica. Emphasis is placed on the relationships among composition, phase morphology, filler dispersion, polymer–filler interactions, crystallization, processing, and mechanical and thermal performance. The effects of elastomer content and mineral-filler type and loading on stiffness, tensile strength, flexural behaviour, impact resistance, hardness, thermal stability, and dimensional stability are critically discussed. Particular attention is given to the competing and synergistic effects arising in ternary PP/elastomer/mineral systems. The review highlights the importance of controlling multiphase morphology and interfacial interactions to achieve an optimized stiffness–toughness balance and identifies key research directions for structure-based design of high-performance PP hybrid composites.

Keywords: Polypropylene; Hybrid composites; Elastomeric toughening; Polyolefin elastomer; Mineral fillers; Talc; Calcium carbonate; Mica; Structure–property relationships; Stiffness–toughness balance.

1. Introduction

Polypropylene (PP) is a semicrystalline thermoplastic widely used in automotive, electrical, packaging, and consumer applications because of its low density, chemical resistance, processability, stiffness, and cost effectiveness (Gahleitner & Paulik, 2014; Hossain et al., 2024). Its relatively high specific stiffness and thermal stability are advantageous for structural applications; however, neat PP exhibits an inherent stiffness–toughness trade-off and may show limited impact resistance, particularly under low-temperature or high-strain-rate conditions. Consequently,

polymer blending, elastomeric toughening, mineral reinforcement, and their combinations have been extensively investigated to tailor the performance of PP.

Elastomeric modification is an established approach for increasing the toughness and impact resistance of PP. Under deformation, dispersed elastomer domains can promote cavitation and subsequent matrix shear yielding, increasing the energy dissipated during fracture. The effectiveness of this toughening depends on elastomer content, domain size and distribution, interfacial adhesion, matrix morphology, and deformation conditions rather than on elastomer concentration alone. A major limitation is the accompanying reduction in modulus and stiffness as the elastomer fraction increases (Liang & Li, 2000; Wee et al., 2024).

Mineral fillers provide an effective means of increasing the stiffness and dimensional stability of PP and can also modify its crystallization behaviour. Among commonly used fillers, talc, calcium carbonate (CaCO_3), and mica differ substantially in particle geometry, aspect ratio, surface characteristics, dispersion behaviour, and reinforcing efficiency. Talc is particularly effective in increasing modulus and promoting heterogeneous nucleation, whereas CaCO_3 can provide a different balance between rigidity and impact performance. Mica, owing to its platelet morphology and relatively high aspect ratio, can provide significant reinforcement and dimensional stability when adequately dispersed (Leong et al., 2004; Altay et al., 2021). Thus, filler loading alone is insufficient to describe the resulting composite behaviour; filler morphology, dispersion, and polymer–filler interactions are also critical.

The influence of mineral fillers is not restricted to mechanical reinforcement. Their surfaces can act as heterogeneous nucleation sites and modify the crystallization kinetics and crystalline morphology of PP. Changes in crystallinity, crystal form, and lamellar structure can consequently affect modulus, strength, ductility, and impact behaviour. Therefore, the mechanical response of mineral-filled PP results from the combined effects of filler reinforcement, interfacial stress transfer, defect formation, and changes in the polymer crystalline structure (Leong et al., 2004).

Greater complexity arises when elastomeric and mineral phases are incorporated simultaneously. In PP/elastomer/mineral systems, the two dispersed phases may interact through changes in phase morphology, filler localization, interfacial adhesion, and crystallization. Filler particles may preferentially reside in the PP matrix, the elastomer-rich phase, or the interfacial region, depending on the relative surface energies and compatibility of the constituent phases. Such morphological differences can substantially influence stress transfer, crack propagation, modulus, and impact resistance (Premphet & Horanont, 2000; Karagöz et al., 2024; Hou et al., 2024).

Accordingly, the performance of PP-based hybrid composites is governed by the interaction of composition, morphology, interfaces, crystallization, and processing. Melt compounding determines the dispersion and distribution of the elastomer and mineral phases, while injection moulding can further influence particle orientation, phase morphology, and the crystalline structure developed during cooling. These factors determine the extent to which mineral reinforcement compensates for the stiffness loss associated with elastomeric toughening.

The principal materials-design problem is therefore the optimization of the stiffness–toughness balance. Increasing the elastomer fraction can improve impact resistance but reduce rigidity, whereas increasing mineral content can restore stiffness while potentially introducing stress concentrations and reducing ductility. The magnitude of these competing effects depends strongly on filler type, filler loading, elastomer characteristics, phase morphology, and interfacial interactions.

This review examines PP-based hybrid composites containing elastomeric modifiers and mineral fillers, with particular emphasis on polyolefin elastomer (POE) and propylene-based elastomers in combination with talc, CaCO_3 , and mica. The review focuses on the relationships among composition, phase morphology, filler dispersion, interfacial

interactions, crystallization, processing, and mechanical and thermal performance, with particular attention to the mechanisms controlling the balance between stiffness, strength, toughness, and dimensional stability.

2. Polypropylene as a Matrix Material

Polypropylene (PP) is a semicrystalline polyolefin whose structure and properties are governed by stereoregularity, molecular weight and molecular-weight distribution, crystallinity, and processing history. These parameters determine melt rheology, crystallization, deformation, and stress transfer and therefore influence the dispersion and morphology of elastomeric and mineral phases in hybrid composites (Gahleitner & Paulik, 2014; Hossain et al., 2024).

2.1 Molecular Structure and Stereoregularity

The methyl substituents along the PP backbone give rise to different stereoregular configurations, principally isotactic, syndiotactic, and atactic PP. Tacticity strongly affects chain packing and crystallizability. Isotactic PP is the predominant grade used in structural and engineering applications because its regular chain configuration permits substantial crystallization while maintaining thermoplastic processability.

Molecular weight and molecular-weight distribution also influence chain entanglement, melt viscosity, deformation behaviour, and processability. These parameters become particularly important during melt compounding because they affect the breakup and redistribution of elastomer domains and the dispersion of mineral particles. Molecular characteristics can therefore influence composite morphology indirectly through their effects on melt flow and processing (Gahleitner et al., 1995; Stern et al., 2007).

2.2 Crystalline Structure and Morphology

The semicrystalline morphology of PP consists of crystalline regions embedded within an amorphous phase. The crystalline fraction contributes substantially to stiffness, strength, and thermal resistance, whereas the amorphous phase provides molecular mobility and contributes to deformation. Crystallization is controlled by molecular structure, nucleation, cooling conditions, and thermal history.

Processing-induced flow can also modify PP crystallization. Shear during injection moulding may generate oriented molecular structures that influence nucleation, lamellar development, and the final mechanical response. Thus, the crystalline morphology present in a processed component may differ significantly from that obtained under quiescent cooling (Stern et al., 2007). Recent work further demonstrates that crystallization behaviour can provide information on the molecular microstructure of PP and that changes in crystalline form can strongly affect structure–property relationships (Krajenta & Pawlak, 2024).

In composite systems, mineral particles can act as heterogeneous nucleating sites and modify crystallization kinetics and crystalline morphology. The magnitude of this effect depends on filler chemistry, surface characteristics, particle size, dispersion, and concentration. Talc is particularly effective as a nucleating mineral for PP, although its influence on mechanical properties is coupled with reinforcement and interfacial effects (Leong et al., 2004).

2.3 Mechanical and Thermal Characteristics Relevant to Composite Development

The crystalline–amorphous structure of PP provides a useful combination of stiffness, strength, chemical resistance, and thermal performance, but its relatively limited resistance to impact-induced fracture can restrict applications requiring high toughness. This limitation provides the basis for modification by elastomeric and particulate phases.

Elastomer incorporation introduces a compliant dispersed phase capable of increasing energy absorption, but increasing elastomer concentration generally reduces modulus and rigidity. Mineral fillers have the opposite primary

effect, increasing modulus and dimensional stability through restriction of matrix deformation and load transfer. However, poorly dispersed particles or weak polymer–filler interfaces can act as defects and reduce ductility and impact resistance. Hybrid PP systems therefore require optimization of the relative proportions and morphology of the compliant and rigid phases.

The melting temperature of PP is grade dependent and is typically within approximately 160–170 °C for common isotactic grades. During melt processing, the polymer is heated above its melting range and subsequently crystallizes during cooling. Cooling rate, flow-induced orientation, molecular mobility, and the presence of nucleating fillers or dispersed elastomer phases can modify the resulting crystalline morphology. Processing conditions therefore contribute directly to the final structure and properties of PP-based composites rather than merely determining component shape.

2.4 Implications for PP-Based Hybrid Composites

For PP/elastomer/mineral systems, the matrix is therefore an active structural component rather than an inert continuous phase. Its molecular characteristics determine melt behaviour and crystallization, while the resulting crystalline–amorphous morphology controls deformation and contributes to stress transfer. Elastomeric and mineral phases subsequently modify this matrix structure through phase separation, nucleation, reinforcement, and interfacial interactions.

Consequently, the properties of PP-based hybrid composites depend on the coupled effects of molecular characteristics, crystallization, phase morphology, filler dispersion, interfacial adhesion, and processing history. These interactions provide the structural basis for the stiffness-toughness balance that is central to the design of PP/elastomer/mineral hybrid composites.

3. Strategies for Modification of Polypropylene

The limited ability of neat PP to simultaneously provide high rigidity and fracture resistance has led to several modification approaches, including copolymerization, polymer blending, elastomeric toughening, mineral reinforcement, and hybrid modification. These approaches differ in whether they alter the polymer architecture, introduce a second polymer phase, or incorporate rigid dispersed phases. For engineering applications, the objective is generally to obtain a controlled combination of stiffness, strength, toughness, thermal stability, and dimensional stability rather than maximize an individual property (Gahleitner & Paulik, 2014; Hossain et al., 2024).

3.1 Copolymerization and Molecular Modification

Copolymerization modifies the chemical architecture of PP through incorporation of comonomer units, thereby altering chain regularity, crystallinity, molecular mobility, and mechanical behaviour. Such molecular modification can provide intrinsic control over the balance between rigidity and ductility, but it requires control during polymer synthesis. For melt-processed composite applications, physical blending and particulate reinforcement offer greater formulation flexibility because commercially available PP grades can be modified without changing the primary polymer architecture.

3.2 Polymer Blending

Polymer blending provides a practical route for combining PP with polymers having complementary properties. The resulting behaviour is governed by composition, phase compatibility, interfacial adhesion, and dispersed-phase morphology. In immiscible blends, the minor component generally forms dispersed domains whose size, distribution, and interfacial characteristics influence stress transfer and deformation.

Blending PP with elastomeric phases is particularly important for improving impact resistance. Effective toughening requires a morphology capable of activating energy-dissipation mechanisms while maintaining sufficient continuity of the PP phase for load bearing. Recent reviews emphasize that elastomer particle size, interparticle distance, matrix yielding, strain rate, and temperature collectively influence the brittle–ductile response of rubber-toughened PP (Wee et al., 2024).

3.3 Elastomeric Modification

Elastomeric modification introduces a compliant dispersed phase into PP to increase impact resistance and fracture energy. POEs and propylene-based elastomers are particularly attractive because their polyolefin character permits melt processing with PP while providing substantially greater compliance. The resulting toughening is strongly dependent on elastomer concentration, domain morphology, interfacial adhesion, and the ability of the matrix to undergo plastic deformation.

At increasing elastomer concentration, improved impact resistance is generally accompanied by reductions in modulus and rigidity. Consequently, elastomer modification involves optimization of the dispersed-phase morphology rather than simply increasing elastomer content. Recent studies also demonstrate that elastomer molecular structure can influence phase dispersion and toughening efficiency. For example, Jiang et al. (2024) reported enhanced toughness of waste-appliance-derived PP using a syndiotactic-PP-based elastomer and showed that the resulting morphology differed from that obtained with conventional POE.

3.4 Mineral Reinforcement

Mineral reinforcement provides a complementary strategy for increasing modulus, rigidity, dimensional stability, and resistance to deformation. Talc, CaCO_3 , and mica are particularly relevant to PP because they differ in particle geometry, aspect ratio, surface characteristics, nucleating ability, and reinforcing efficiency. Their effects are controlled by filler loading, particle size, dispersion, and polymer–filler adhesion rather than filler content alone (Leong et al., 2004; Altay et al., 2021). Altay et al. (2021), for example, demonstrated that talc, mica, and carbonate-based mineral fillers produce different mechanical, thermal, and rheological responses in PP, confirming the importance of filler identity and morphology.

Increasing mineral content can enhance rigidity but may also increase particle–particle interactions and promote agglomeration. At excessive loading, poorly dispersed particles can act as stress-concentration sites and reduce ductility or impact resistance. Mineral reinforcement therefore requires an appropriate balance between filler concentration, dispersion, and interfacial stress transfer.

3.5 Hybrid Modification

Combining elastomeric and mineral phases provides a means of addressing the opposing effects of toughening and reinforcement. The elastomeric phase can increase energy absorption, whereas the mineral phase can compensate for the reduction in stiffness associated with elastomer incorporation. However, the two phases do not necessarily behave independently. Their relative localization, interfacial interactions, and influence on PP crystallization can produce morphologies that differ substantially from those of the corresponding binary systems.

This interaction is particularly important in PP/POE/talc systems. Hou et al. (2024) demonstrated that the processing sequence can influence the selective localization of talc between the PP matrix, POE phase, and interfacial region. Their results also showed that interactions between POE droplets and the talc network can contribute to the rheological reinforcement of the ternary system. Such findings demonstrate that hybrid-composite properties depend not only on the identity and concentration of the individual components but also on their spatial distribution.

Similarly, ternary PP/elastomer/filler systems can exhibit morphology-dependent mechanical behaviour because elastomer polarity and filler surface characteristics influence filler localization and interfacial structure. The hybrid approach should therefore be considered a coupled multiphase design strategy rather than a simple combination of two independent modification methods.

3.6 Selection of the Modification Strategy

The modification routes described above provide different means of controlling PP performance. Copolymerization primarily modifies polymer architecture; blending introduces a second polymer phase; elastomeric modification increases deformability and energy absorption; and mineral reinforcement primarily increases rigidity.

4. Elastomer-Modified Polypropylene

Elastomeric modification of polypropylene (PP) is primarily employed to overcome the relatively limited impact toughness of the rigid semicrystalline matrix. The underlying principle is the incorporation of a rubbery phase that can undergo substantial deformation and dissipate mechanical energy during loading. However, the effectiveness of elastomeric toughening depends strongly on the morphology of the dispersed phase and its interaction with the PP matrix. Consequently, elastomer content alone cannot be used to predict the final toughness of a PP/elastomer blend.

4.1 Role of Elastomers in Toughening Polypropylene

When an elastomer is dispersed within PP, the rubbery domains act as sites at which deformation can be initiated and redistributed. Under impact loading, the applied stress is transferred from the PP matrix to the elastomeric domains, where local deformation may occur. Depending on the morphology and interfacial characteristics, this can promote cavitation of the elastomer phase followed by plastic deformation of the surrounding PP matrix. Shear yielding, crack-tip blunting, crack deflection, and crack arrest can consequently contribute to increased energy absorption (Liang & Li, 2000; Liu & Qiu, 2013; Jiang et al., 2024).

This mechanism explains why a relatively small amount of a well-dispersed elastomer can sometimes produce a substantial improvement in impact resistance. The improvement is not simply proportional to the amount of elastomer added; rather, it depends on whether the elastomer domains have the appropriate size and distribution to activate matrix deformation mechanisms effectively.

At the same time, the introduction of a rubbery phase reduces the fraction of rigid PP available to carry load. Tensile and flexural modulus therefore generally decrease as elastomer concentration increases. The development of a useful PP/elastomer material consequently requires optimization of both the **quantity and morphology** of the elastomer phase.

4.2 POE as a Toughening Modifier

Polyolefin elastomers (POEs) are particularly attractive for PP modification because they combine elastomeric behaviour with a polyolefin-based chemical structure. Their relatively low glass-transition temperature and rubber-like response allow them to deform substantially under mechanical loading, while their nonpolar character facilitates processing with PP.

POE-modified PP systems have been widely investigated for applications in which impact resistance is important. The incorporation of POE can substantially increase impact strength, but the magnitude of improvement depends on elastomer concentration, molecular characteristics, phase morphology, and the quality of interaction between the POE and PP phases. Studies on toughened PP blends have demonstrated that POE addition can increase impact performance while simultaneously modifying tensile behaviour and crystallinity (Liu & Qiu, 2013; Wee et al., 2024).

An important consideration is that the optimum POE concentration is not necessarily the concentration producing the maximum impact strength. At increasing elastomer contents, the rubber phase may become increasingly interconnected or the morphology may undergo a transition from discrete domains toward a more complex multiphase structure. Such changes can produce significant reductions in stiffness and strength. The practical optimum must therefore be defined according to the required balance of impact resistance and load-bearing capability.

4.3 Propylene-Based Elastomers

Propylene-based elastomers provide another route for improving the toughness of PP while maintaining a strong chemical relationship with the matrix. Because the elastomeric phase contains propylene-derived structural units, its interaction with PP can differ from that of more chemically dissimilar elastomers.

The effectiveness of these materials depends on their molecular architecture and the distribution of comonomer units, which influence crystallinity, elasticity, phase compatibility, and melt behaviour. When incorporated into PP, propylene-based elastomers can produce a dispersed rubbery phase capable of improving impact resistance while maintaining useful processability.

From the perspective of hybrid-composite development, propylene-based elastomers are particularly interesting because their interaction with both PP and mineral fillers can influence the final three-phase morphology. Their effect therefore cannot be evaluated solely from binary PP/elastomer blends; the presence of talc, CaCO_3 , or mica can alter phase distribution and interfacial interactions.

4.4 Effect of Elastomer Content

Elastomer concentration is one of the most influential variables governing the properties of PP/elastomer blends. Increasing the elastomer fraction generally produces a progressive reduction in tensile and flexural modulus because the volume fraction of the compliant phase increases. At the same time, impact strength generally increases until an optimum morphological condition is reached.

The relationship is therefore often characterized by a property trade-off: Increasing elastomer content generally increases Impact strength, Elongation/ductility, and Energy absorption whereas Tensile modulus, Flexural modulus, and Matrix rigidity decreases. These trends should not, however, be interpreted as universal linear relationships. The magnitude and even the direction of a property change at a particular composition can depend on domain size, phase continuity, crystallinity, interfacial adhesion, and processing conditions. For this reason, reporting elastomer concentration without describing the resulting morphology provides an incomplete interpretation of toughening behaviour. Two blends containing the same nominal elastomer concentration may exhibit markedly different impact resistance because of differences in elastomer-domain size, distribution, and morphology (Deblieck et al., 2021; Han et al., 2023).

4.5 Elastomer-Phase Morphology

The morphology of the dispersed elastomer phase is a critical determinant of toughening efficiency. A finely and uniformly dispersed rubber phase generally provides a large number of deformation sites and can promote more homogeneous stress redistribution. In contrast, large elastomer domains or agglomerates can act as defects and provide preferential sites for crack initiation. The interfacial region between PP and elastomer is equally important. Efficient stress transfer requires sufficient interaction between the phases, but the interface must also permit the local deformation processes responsible for toughening. The optimum morphology is therefore not necessarily associated with maximum adhesion; instead, it represents a balance between interfacial load transfer and controlled deformation or debonding.

Processing conditions strongly influence this morphology. During melt compounding, the viscosity ratio between PP and elastomer, shear history, mixing intensity, temperature, and residence time affect the breakup and redistribution of the elastomer phase. Subsequent injection moulding can further modify domain orientation and distribution through the strong flow fields experienced during mould filling.

4.6 Crystallinity and Toughening

Elastomer incorporation can also influence the crystallization behaviour of PP by affecting nucleation, crystal growth, and overall crystallinity (Wu et al., 2007). The dispersed phase modifies the local environment available for PP chain organization and may alter nucleation and crystal growth. Changes in crystallinity and lamellar morphology can subsequently influence stiffness, strength, ductility, and fracture behaviour. This provides an important explanation for why two PP/elastomer blends with similar elastomer content may exhibit different mechanical properties. The elastomer affects not only the rubbery phase itself but also the crystalline structure of the surrounding PP matrix.

Conversely, the developing PP crystalline structure can constrain elastomer domains and influence their deformation under applied stress. The relationship is therefore bidirectional as elastomer morphology affects crystallization, while PP crystallization affects the mechanical constraint and deformation of the elastomer phase.

4.7 The Stiffness–Toughness Trade-Off

A central limitation of elastomeric modification is the competing contribution of the rubbery and crystalline phases. The elastomeric phase provides compliance and energy dissipation, whereas the crystalline PP phase contributes rigidity and load-bearing capability. Increasing the elastomer content generally enhances toughness but can reduce stiffness, thereby altering the overall balance between these properties. Consequently, effective toughening strategies must consider not only composition but also elastomer-phase morphology and the crystalline structure of the PP matrix. Studies of PP/elastomer systems indicate that improvements in strength and toughness can be achieved under favourable combinations of phase morphology and crystallinity (Liang & Li, 2000; Wee et al., 2024). These findings highlight that the stiffness–toughness balance is strongly influenced by the structural organization developed during processing rather than being determined solely by composition. This distinction is particularly important for hybrid composites. If mineral reinforcement is subsequently introduced into a PP/elastomer blend, the mineral phase can potentially compensate for the loss of stiffness caused by the elastomer. However, the filler may also modify elastomer-domain morphology, crystallization, and interfacial behaviour. The resulting performance must therefore be understood as the outcome of a coupled multiphase system.

4.8 Implications for Hybrid Composite Design

The literature on elastomer-modified PP establishes several important principles for the design of PP/elastomer/mineral composites. First, increasing elastomer content is an effective means of improving toughness but generally reduces rigidity. Second, elastomer-domain morphology is an important determinant of impact performance in addition to nominal elastomer composition. Third, the crystalline structure of PP and the processing history can influence the resulting toughening response (Liang & Li, 2000; Deblieck et al., 2021; Han et al., 2023; Wee et al., 2024).

These principles provide the basis for introducing mineral fillers as a complementary reinforcement phase. Mineral fillers can compensate, at least partly, for the stiffness loss associated with elastomer incorporation, while their effects on crystallization, phase morphology, interfacial interactions, and dimensional stability can further influence the overall performance of the hybrid system. The next section therefore examines mineral-filled polypropylene, with

particular emphasis on talc, calcium carbonate, and mica, their reinforcing mechanisms, morphology, effects of filler loading, nucleation behaviour, and the factors responsible for differences in stiffness–toughness response.

5. Mineral-Filled Polypropylene

Mineral reinforcement is widely used to increase the stiffness, modulus, dimensional stability, and resistance to deformation of polypropylene (PP). Unlike elastomeric modification, which introduces a compliant dispersed phase, mineral reinforcement introduces a rigid inorganic phase capable of carrying load and restricting matrix deformation. The extent of reinforcement depends on filler geometry, size, dispersion, surface characteristics, loading, and polymer–filler interfacial adhesion. Consequently, different minerals produce distinct structure–property relationships even at comparable concentrations.

Among the minerals used in PP, talc, calcium carbonate (CaCO_3), and mica are particularly relevant because of their different morphologies and reinforcing mechanisms. These differences become important when mineral-filled PP is subsequently combined with elastomeric phases.

5.1 Mechanism of Mineral Reinforcement

Mineral reinforcement results primarily from stress transfer from the PP matrix to the rigid filler through the polymer–filler interface. Filler geometry, dispersion, surface characteristics, and interfacial adhesion determine the efficiency of this transfer. Mineral particles can also restrict local polymer-chain mobility, thereby increasing resistance to deformation and raising tensile and flexural modulus.

Increasing filler concentration generally increases the rigid-phase fraction; however, reinforcement is not necessarily proportional to loading. At higher concentrations, particle–particle interactions and agglomeration become more significant. Filler clusters can act as stress-concentration sites and promote premature crack initiation, resulting in reduced ductility and impact resistance. Thus, effective reinforcement requires both an appropriate filler concentration and adequate dispersion.

5.2 Effect of Filler Characteristics

The reinforcing efficiency of a mineral is controlled by particle size, size distribution, shape, aspect ratio, specific surface area, surface treatment, dispersion, concentration, and polymer–filler adhesion. Systematic investigations of mineral-filled PP have demonstrated that these parameters can substantially alter tensile and impact behaviour (Jilkén et al., 1991; Leong et al., 2004).

Particle geometry is particularly important. Platelet-shaped fillers such as talc and mica provide a larger aspect ratio than relatively equiaxed CaCO_3 particles and can therefore produce greater restriction of matrix deformation and more efficient stress transfer. For anisotropic fillers, processing-induced orientation can additionally produce directional mechanical behaviour. Consequently, filler loading alone is an inadequate descriptor of composite reinforcement.

5.3 Talc-Filled Polypropylene

Talc is a layered magnesium silicate with a platelet morphology and is an important mineral reinforcement for PP. Its high stiffness, platelet geometry, and nucleating activity contribute to increases in tensile and flexural modulus. The extent of reinforcement depends strongly on particle size and dispersion; agglomerated talc can instead introduce defects and reduce mechanical efficiency.

Talc also has an important effect on PP crystallization. Its surface can provide heterogeneous nucleation sites, increasing the number of sites available for crystal formation during cooling. Talc generally exhibits stronger nucleating activity than CaCO_3 , although the resulting mechanical response depends on the combined effects of

crystallization, filler dispersion, interfacial adhesion, and fracture behaviour (Leong et al., 2004). Thus, the effect of talc involves both direct reinforcement by the mineral phase and indirect modification of PP crystalline morphology.

5.4 Calcium Carbonate-Filled Polypropylene

CaCO_3 is widely used in PP because of its availability, relatively low cost, and ability to increase stiffness and dimensional stability. Conventional CaCO_3 particles generally have a lower aspect ratio than platelet-shaped talc and mica; consequently, their reinforcing mechanism differs from that of anisotropic fillers. The mechanical response of CaCO_3 -filled PP depends strongly on particle size, surface treatment, dispersion, and interfacial interaction. Appropriately dispersed particles can increase modulus, whereas agglomeration can introduce defects and reduce toughness. Comparative studies have shown that CaCO_3 -filled PP can provide a more favourable toughness response than some highly reinforcing mineral systems, whereas talc generally produces greater stiffness enhancement (Leong et al., 2004). This difference illustrates that maximum rigidity and maximum impact resistance are not necessarily obtained with the same filler.

5.5 Mica-Filled Polypropylene

Mica possesses a pronounced platelet morphology and relatively high aspect ratio, making it an effective reinforcing phase for PP. Its geometry can increase stiffness and dimensional stability through enhanced stress transfer and restriction of matrix deformation. However, reinforcement efficiency depends strongly on platelet dispersion and orientation. During melt processing and injection moulding, flow can orient mica platelets preferentially along the processing direction. This orientation can increase mechanical anisotropy and make the measured properties dependent on specimen orientation. Excessive loading or inadequate dispersion can additionally promote platelet aggregation and reduce the effective reinforcing efficiency. Comparative studies have demonstrated that mica and talc can substantially modify the mechanical and rheological behaviour of PP, with the magnitude of the effect depending on filler characteristics and concentration (Altay et al., 2021).

5.6 Comparative Behaviour of Talc, CaCO_3 , and Mica

The three minerals provide different combinations of reinforcement and structural effects:

Filler	Characteristic morphology	Principal effects	Critical variables
Talc	Platelet/lamellar	High stiffness, modulus, nucleation	Particle size, dispersion, crystallization
CaCO_3	Relatively particulate	Stiffness with potentially favourable toughness	Particle size, surface treatment, agglomeration
Mica	High-aspect-ratio platelet	Stiffness and dimensional stability	Orientation, dispersion, anisotropy

These distinctions should not be regarded as absolute because filler grade, particle dimensions, surface treatment, concentration, PP grade, and processing conditions strongly influence the resulting properties. Nevertheless, comparative studies consistently demonstrate that mineral identity is a fundamental design variable rather than merely a substitution parameter (Azizi & Faghihi, 2009; Altay et al., 2021).

5.7 Mineral Fillers and PP Crystallization

Mineral fillers can modify PP crystallization by providing heterogeneous nucleation surfaces. Their presence may alter crystallization temperature, kinetics, crystal size, morphology, and overall crystallinity. These changes can influence stiffness and strength, while their effects on impact resistance are more complex.

Increased crystallinity generally favours rigidity but may restrict plastic deformation. Conversely, changes in crystal size and morphology can modify crack propagation and energy dissipation. The mechanical response therefore reflects the combined effects of crystallization, filler dispersion, interfacial adhesion, and fracture mechanisms. This effect is particularly significant for talc because of its pronounced nucleating activity.

5.8 Filler Loading and Reinforcement–Toughness Balance

Filler loading is a critical parameter in mineral-filled PP. At moderate concentrations, well-dispersed particles can substantially increase stiffness without severely disrupting matrix continuity. At higher concentrations, however, particle–particle interactions, agglomeration, and processing-induced defects become increasingly important.

The resulting behaviour represents a balance between increasing rigid-phase content, which favours stiffness, and increasing structural heterogeneity, which can promote stress concentration and loss of toughness. This balance becomes particularly important in PP/elastomer/mineral hybrids, where excessive mineral loading may restrict elastomer-domain deformation and consequently interfere with elastomeric toughening.

5.9 Processing, Dispersion, and Structure

Melt compounding and injection moulding strongly influence the final distribution and orientation of mineral particles. Adequate mixing is required to reduce agglomeration and obtain uniform filler dispersion, while excessive processing severity may promote polymer degradation. During injection moulding, flow can orient anisotropic fillers such as talc and mica, producing directional differences in mechanical properties. Simultaneous cooling determines the crystallization of the PP matrix and therefore contributes to the final composite morphology.

Accordingly, the properties of mineral-filled PP are controlled by the interaction among filler characteristics, dispersion, orientation, crystallization, interfacial stress transfer, and deformation. This interaction becomes more complex when an elastomeric phase is introduced, providing the basis for the structure–property behaviour of PP/elastomer/mineral hybrid composites.

6. PP/Elastomer/Mineral Hybrid Composites

The simultaneous incorporation of an elastomer and a mineral filler into polypropylene (PP) provides a route for balancing toughness and rigidity. The elastomeric phase primarily increases deformability and energy absorption, whereas the mineral phase increases stiffness, modulus, and dimensional stability. Unlike binary PP/elastomer or PP/mineral systems, however, ternary composites involve interactions among three phases, making the final properties strongly dependent on their spatial distribution, interfacial interactions, crystallization, and processing history.

6.1 Rationale for Hybridization

Elastomer incorporation generally improves impact resistance at the expense of modulus, whereas mineral reinforcement increases rigidity but may reduce ductility at higher loading. Hybridization aims to compensate for these opposing effects by combining a compliant energy-dissipating phase with a rigid reinforcing phase.

The effectiveness of this approach depends on the relative concentrations and, more importantly, the morphology of the constituent phases. Excessive elastomer content can produce a substantial reduction in stiffness, whereas excessive mineral loading may increase stress concentration and restrict matrix deformation. The optimum formulation is therefore determined by the extent to which the two modifiers provide complementary rather than competing deformation mechanisms.

6.2 Phase Morphology in Ternary Systems

Phase morphology is a primary determinant of the behaviour of PP/elastomer/mineral composites. In a typical PP/elastomer blend, the elastomer forms dispersed domains within the PP matrix. Addition of a mineral filler can alter

the size, distribution, and localization of these domains. The mineral may remain predominantly within the PP matrix, associate with the elastomer phase, or accumulate near the PP/elastomer interface. Such localization changes the stress-transfer environment and consequently the mechanical response. Premphet and Horanont (2000) demonstrated that elastomer polarity can strongly influence filler localization in PP/elastomer/CaCO₃ systems. Thus, filler performance cannot be considered independently of elastomer chemistry.

Recent work further demonstrates that phase localization in ternary systems can produce specific elastomer–filler structures. In PP/POE/talc composites, Hou et al. (2024) showed that the interaction between POE droplets and talc can influence the morphology and rheological behaviour of the ternary system. This provides direct evidence that the spatial arrangement of the phases is an important design variable.

6.3 Elastomer–Filler Interaction

The presence of an elastomer introduces an additional interface to the conventional PP–filler and PP–elastomer interfaces. If the mineral remains well dispersed in the PP matrix while the elastomer forms fine domains, the two phases can perform relatively distinct functions: the mineral reinforces the continuous matrix and the elastomer facilitates energy dissipation.

Preferential elastomer–filler interaction can modify this arrangement. Filler particles may become concentrated within or around elastomer domains, changing their deformation behaviour while simultaneously reducing the fraction of filler directly reinforcing the PP matrix. Whether such localization is beneficial depends on the required property balance. Therefore, a morphology that favours modulus enhancement is not necessarily the morphology that provides maximum impact resistance.

6.4 Mechanical Performance

The tensile and flexural properties of ternary PP/elastomer/mineral composites reflect the competing contributions of the compliant and rigid phases. Elastomer incorporation generally reduces modulus, whereas mineral reinforcement increases it. Appropriate filler incorporation can therefore partially compensate for the stiffness loss caused by elastomeric modification. Impact behaviour is more complex. The elastomer provides the principal energy-dissipation mechanism, while the mineral phase can modify crack propagation, local plastic deformation, and stress distribution. Well-dispersed particles may contribute to crack deflection or pinning, whereas agglomerates can act as stress-concentration sites. The resulting impact response therefore depends on elastomer-domain morphology, matrix yielding, filler dispersion, and both polymer–filler and polymer–elastomer adhesion.

Importantly, increasing filler concentration does not produce a universal trend in impact strength. Depending on morphology and interfacial structure, mineral particles may either complement elastomeric toughening or interfere with elastomer-domain deformation. This explains why optimum hybrid formulations cannot be established from filler and elastomer contents considered independently.

6.5 Influence of Mineral Filler Type

Talc, CaCO₃, and mica provide different reinforcement mechanisms in ternary systems because of their distinct morphology, aspect ratio, surface characteristics, and effects on PP crystallization.

Talc generally provides strong stiffness enhancement and nucleating activity. Its platelet morphology can also influence phase morphology and orientation during processing.

CaCO₃ provides effective particulate reinforcement and can offer a comparatively favourable stiffness–impact balance. Its surface characteristics and interaction with the elastomer are particularly important because they can influence filler localization.

Mica provides high-aspect-ratio platelet reinforcement and can substantially improve stiffness and dimensional stability. However, platelet orientation during injection moulding can produce anisotropic properties, while excessive loading or poor dispersion can adversely affect toughness.

Consequently, the three fillers should not be regarded as interchangeable. Their effects in ternary systems depend on the interaction between filler morphology, elastomer chemistry, phase localization, crystallization, and processing.

6.6 Synergistic and Antagonistic Effects

A central issue in hybrid-composite design is whether the combined modifiers produce a genuinely synergistic response. Synergy may be considered to occur when the hybrid formulation provides a combination of properties that is difficult to achieve through either modifier alone, particularly when increased impact resistance is obtained without a proportionate loss of stiffness.

Hybridization can also produce antagonistic effects. Mineral particles may restrict elastomer-domain deformation, while elastomer domains can disrupt mineral-particle networks or alter filler distribution. In addition, changes in PP crystallization produced by either phase may influence the deformation mechanisms associated with the other. Therefore, the presence of two modifiers does not inherently guarantee synergistic performance.

6.7 Hybridization and PP Crystallization

Mineral fillers and elastomeric phases can modify PP crystallization through different mechanisms. Mineral surfaces may provide heterogeneous nucleation sites, whereas elastomer domains can alter local chain mobility and crystallization conditions. The resulting changes in crystallization temperature, kinetics, crystalline morphology, and crystallinity can influence both rigidity and fracture behaviour.

The effect is therefore not simply related to the amount of crystalline material. Changes in crystal morphology can alter matrix deformability and crack propagation, while filler reinforcement provides an independent contribution to stiffness. The final mechanical response represents the combined effect of these structural changes.

6.8 Processing and Morphology

Processing is particularly important in ternary systems because phase morphology develops during melt mixing and subsequent moulding. Differences in viscosity and interfacial tension influence elastomer-domain breakup and coalescence, while mineral particles can modify melt rheology and phase distribution. During injection moulding, flow can orient anisotropic mineral particles and influence elastomer-domain morphology; subsequent cooling determines the crystalline structure of PP.

Hou et al. (2024) provide particularly relevant evidence that processing conditions can alter filler localization and the resulting morphology of PP/POE/talc ternary composites. Thus, formulations developed under one processing history cannot necessarily be expected to exhibit identical structure or properties under another.

6.9 Structural Requirements for Optimized Hybrid Composites

An effective PP/elastomer/mineral hybrid requires controlled phase morphology rather than simply an appropriate overall composition. Desirable characteristics include a continuous PP phase capable of carrying load, finely dispersed elastomer domains capable of promoting energy dissipation, effective mineral dispersion, adequate interfacial stress transfer, controlled PP crystallization, and limited agglomeration.

The central design challenge is therefore **morphological control**. The stiffness–toughness balance is determined not only by how much elastomer and mineral are incorporated, but also by where these phases are located, how they interact, and how processing establishes their final morphology. This provides the basis for the subsequent discussion of morphology, interfaces, crystallization, and processing–structure–property relationships.

7. Morphology, Interfacial Interactions, and Crystallization in Hybrid Composites

The performance of PP/elastomer/mineral hybrid composites is governed not only by composition but also by the multiphase structure generated during processing. Elastomer-domain morphology, filler dispersion and orientation, interfacial interactions, and PP crystallization collectively determine stress transfer, deformation, fracture, and thermal response. In ternary systems, modification of one component can consequently alter the morphology and behaviour of the other phases.

7.1 Elastomer-Domain Morphology

In most PP/elastomer blends, the elastomer forms dispersed domains within a continuous PP matrix. Domain size, shape, distribution, and interfacial adhesion strongly influence impact behaviour. Finely dispersed domains can promote more uniform matrix deformation and facilitate energy-dissipation mechanisms such as cavitation and matrix shear yielding. Excessively large domains or elastomer agglomerates, in contrast, can act as local stress concentrators and promote crack initiation.

Elastomer concentration, viscosity ratio, interfacial tension, mixing intensity, and processing history all influence domain morphology. Increasing elastomer concentration can increase domain–domain interactions and eventually alter phase continuity. Therefore, the effect of elastomer content on impact strength cannot be interpreted independently of the resulting morphology (Liang & Li, 2000; Wee et al., 2024). In hybrid systems, mineral particles introduce an additional morphological variable because they can modify elastomer-domain breakup, coalescence, and spatial distribution.

7.2 Filler Dispersion and Orientation

Filler dispersion determines the effective reinforcing efficiency of mineral particles. Uniform dispersion provides a relatively homogeneous distribution of rigid inclusions and maximizes the effective polymer–filler interface, whereas agglomeration creates local stiffness heterogeneities and stress-concentration regions. The tendency toward agglomeration generally increases with filler loading because of increasing particle–particle interactions. Particle geometry is also important. Talc and mica, with their platelet structures, can undergo preferential orientation during injection moulding. Flow-induced orientation can improve reinforcement along the principal flow direction but can also produce mechanical anisotropy. Filler morphology must therefore be considered together with processing history (Altay et al., 2021; Mittal et al., 2019).

7.3 Polymer–Filler Interface

The PP–mineral interface controls stress transfer between the relatively compliant polymer and rigid filler. Weak interfacial interaction can promote debonding and limit reinforcement, whereas stronger interaction generally improves load transfer. Surface treatment is consequently used for selected mineral fillers to modify compatibility and interfacial adhesion. However, interfacial adhesion does not have a universally positive relationship with toughness. The nature and strength of the interface can alter debonding, crack propagation, and plastic deformation mechanisms. Comparative studies of talc-, kaolin-, and CaCO_3 -filled PP demonstrate that differences in filler characteristics and matrix–filler interactions contribute substantially to the resulting mechanical properties (Leong et al., 2004). In ternary systems, the problem is more complex because mineral particles can interact with both PP and the elastomer. Their relative affinities can therefore determine filler localization and influence both reinforcement and toughening.

7.4 Elastomer–Filler Interaction and Filler Localization

Filler localization is a critical structural parameter in PP/elastomer/mineral composites. Particles located predominantly in the PP matrix directly reinforce the continuous load-bearing phase, whereas preferential localization within the elastomer can reduce their contribution to PP stiffness. At the same time, filler incorporation into elastomer domains can alter their deformation and energy-dissipation behaviour. Premphet and Horanont (2000) demonstrated that elastomer polarity influences filler localization and phase structure in PP/elastomer/CaCO₃ composites. Their results show that elastomer chemistry must be considered when interpreting ternary-composite behaviour rather than treating the mineral filler as an independent reinforcing component.

This consideration is particularly relevant to POE and propylene-based elastomers. Their predominantly nonpolar character can produce phase-localization behaviour different from that of more polar elastomeric modifiers. Consequently, identical mineral fillers may produce different structure–property responses depending on the elastomer used.

7.5 Crystallization of PP in Hybrid Systems

Crystallization provides an important connection between multiphase morphology and macroscopic properties. PP crystallizes during cooling after melt processing, and the resulting crystalline morphology contributes to stiffness, strength, dimensional stability, and deformation behaviour. Mineral fillers can act as heterogeneous nucleating agents and modify nucleation density and crystal development. Talc is particularly effective in promoting PP crystallization, although the magnitude of the effect depends on filler characteristics and dispersion (Leong et al., 2004). Elastomer domains can simultaneously modify local chain mobility and the environment in which PP crystals develop.

Consequently, the crystallization behaviour of a PP/elastomer/mineral composite may differ from that of either corresponding binary system. The final mechanical response reflects both the direct reinforcing effect of the mineral phase and the indirect consequences of changes in PP crystalline morphology.

7.6 Coupling Between Morphology and Crystallization

Morphology and crystallization are closely coupled during processing and cooling. The dispersed elastomer and mineral phases can modify the local environment for PP crystallization, while crystallization progressively changes the rigidity and deformation characteristics of the PP matrix. This coupling is particularly important during injection moulding. Strong flow and rapid cooling near mould walls can generate different crystallization and orientation conditions from those in the interior of the moulded component. As a result, filler orientation, elastomer-domain morphology, and PP crystalline structure can vary spatially even when the overall composition is uniform.

7.7 Processing as a Morphology-Controlling Variable

Melt compounding establishes the initial dispersion of elastomer and mineral phases. Temperature affects melt viscosity and molecular mobility, while shear influences elastomer-domain breakup and redistribution of filler particles. The viscosity ratio between PP and elastomer is also an important determinant of elastomer-domain size. Injection moulding subsequently imposes a strong flow field that can orient platelet-shaped fillers and influence dispersed-phase morphology. Cooling then determines PP crystallization and effectively fixes the structure generated during flow. Processing should therefore be regarded as a **structure-forming variable**, rather than simply a manufacturing step.

The importance of processing is particularly evident in PP/POE/talc systems. Hou et al. (2024) showed that processing conditions can influence filler localization and the interaction between POE droplets and talc, demonstrating that the same nominal composition can produce different ternary morphologies.

7.8 Structure–Property Relationships

The mechanical response of hybrid composites is ultimately determined by the interaction of composition with the structure generated during processing. Elastomer incorporation generally reduces modulus, but the magnitude of this reduction depends on domain size, distribution, adhesion, and PP crystallinity. Similarly, mineral reinforcement depends on particle geometry, dispersion, orientation, and interfacial stress transfer rather than filler concentration alone.

Impact behaviour is particularly sensitive to morphology. An elastomer does not necessarily provide effective toughening when its domains are excessively large or poorly distributed. Similarly, mineral addition does not inevitably cause embrittlement; its effect depends on dispersion, interface quality, and the resulting crack and deformation mechanisms. Thus, formulation–property correlations should be interpreted through the intermediate structural variables of phase morphology, filler dispersion and orientation, interfacial interactions, and PP crystallization.

7.9 Implications for Material Optimization

For PP/elastomer/mineral composites, optimization should therefore focus on morphological control rather than composition alone. An effective structure requires a continuous PP phase capable of carrying load, finely dispersed elastomer domains capable of promoting energy dissipation, and adequately dispersed mineral particles capable of efficient stress transfer. Controlled crystallization, limited agglomeration, and suitable interfacial interactions are also required. For the specific systems considered in this review-POE and propylene-based elastomers combined with talc, CaCO_3 , and mica-the critical questions concern filler localization, elastomer-domain morphology, filler-induced crystallization, platelet orientation, and the ability of mineral reinforcement to compensate for elastomer-induced stiffness loss without suppressing impact toughening. These variables provide the basis for understanding the observed differences in mechanical and thermal performance among hybrid formulations.

8. Comparative Role of Talc, Calcium Carbonate, and Mica in Hybrid PP Composites

The selection of mineral filler is a critical variable in PP/elastomer/mineral hybrid composites because talc, calcium carbonate (CaCO_3), and mica differ in morphology, aspect ratio, surface characteristics, nucleating ability, and reinforcing efficiency. These differences influence not only the direct reinforcement of the PP matrix but also filler dispersion, phase localization, crystallization, and interaction with the elastomeric phase. Filler selection should therefore be based on the required balance of stiffness, strength, toughness, dimensional stability, and processability rather than on filler loading alone.

8.1 Talc: Rigidity and Nucleation

Talc is a platelet-shaped magnesium silicate and is particularly effective when increased rigidity and dimensional stability are required. Its platelet morphology favours stress transfer and restricts matrix deformation when adequate dispersion and interfacial interaction are achieved. Comparative studies generally associate talc with greater stiffness and tensile or flexural reinforcement than less anisotropic mineral fillers (Leong et al., 2004). Talc also exhibits pronounced nucleating activity in PP. Its surface provides heterogeneous nucleation sites during cooling, thereby modifying the crystalline morphology of the matrix in addition to providing direct rigid-phase reinforcement. The resulting properties therefore reflect both filler reinforcement and changes in PP crystallization.

In elastomer-modified PP, this combination can be advantageous for recovering part of the modulus lost through elastomer incorporation. However, increasing talc concentration can also increase rigidity at the expense of ductility and, under some conditions, impact resistance. The overall response therefore depends on talc dispersion, elastomer morphology, interfacial interactions, and crystallization.

8.2 Calcium Carbonate: Reinforcement and Toughness Balance

CaCO_3 is widely employed in PP because of its availability, cost effectiveness, and ability to modify stiffness and dimensional stability. Unlike the platelet morphology of talc and mica, conventional CaCO_3 is generally particulate and has a lower aspect ratio, resulting in a different reinforcement mechanism. Comparative studies indicate that CaCO_3 can provide a different stiffness–impact balance from talc. Leong et al. (2004) reported stronger stiffness enhancement with talc, whereas CaCO_3 -containing systems showed comparatively favourable toughness-related behaviour. Similarly, Azizi and Faghihi (2009) demonstrated that filler type significantly influences the tensile and impact response of PP composites.

This distinction is particularly relevant when an elastomer is present. CaCO_3 may provide sufficient reinforcement while imposing less severe restrictions on impact performance than a highly reinforcing platelet filler. However, particle size, surface treatment, dispersion, and interfacial adhesion can substantially modify this behaviour.

8.3 Mica: High-Aspect-Ratio Reinforcement

Mica provides a distinctly anisotropic reinforcement because of its platelet morphology and relatively high aspect ratio. These characteristics favour stress transfer and restriction of matrix deformation, making mica suitable for applications requiring high stiffness and dimensional stability. Its high aspect ratio also makes mica sensitive to processing-induced orientation. During injection moulding, the platelets can preferentially orient along the flow direction, producing directional reinforcement and mechanical anisotropy. Consequently, mica performance depends not only on loading and dispersion but also on the flow history of the moulded material.

In hybrid systems, this orientation interacts with elastomer-domain morphology and may influence the tensile and flexural response of the composite. Comparative investigations of mineral-filled PP confirm that mica can substantially modify mechanical and rheological behaviour, with the magnitude of these effects depending on filler characteristics and concentration (Altay et al., 2021; Mittal et al., 2019).

8.4 Comparative Stiffness–Toughness Behaviour

The three minerals occupy different positions in the stiffness–toughness design space. **Talc** is particularly attractive when rigidity, modulus, dimensional stability, and PP nucleation are priorities. **CaCO_3** offers useful reinforcement with the potential for a more favourable impact response under appropriate formulation and dispersion conditions. **Mica** provides high-aspect-ratio reinforcement and dimensional stability but is more sensitive to orientation and processing history.

These distinctions should not be interpreted as universal rankings. Filler grade, particle dimensions, surface treatment, concentration, dispersion, PP grade, elastomer chemistry, and processing conditions can substantially alter the relative performance of the three minerals. The appropriate comparison is therefore between specific formulations prepared and tested under comparable conditions.

8.5 Effect of Filler Loading in the Presence of an Elastomer

Filler loading becomes more complex when the PP matrix already contains an elastomeric dispersed phase. Moderate mineral concentrations can compensate for the modulus reduction caused by elastomer incorporation. With

further addition, however, particle-particle interactions, agglomeration, and reduced matrix continuity may become increasingly important.

The optimum filler concentration must therefore satisfy three competing requirements: sufficient mineral content to recover rigidity, sufficient elastomer content to maintain effective toughening, and sufficient PP continuity to sustain load transfer and matrix deformation. Maximum filler loading is consequently unlikely to provide the optimum overall property balance.

8.6 Filler Type and Interfacial Behaviour

Mineral surface characteristics influence the interactions among PP, elastomer, and filler. Differences in surface affinity can alter whether particles remain predominantly within the PP matrix or become associated with elastomer domains. Such localization changes the effective fraction of mineral directly reinforcing the load-bearing PP phase.

Premphet and Horanont (2000) demonstrated that filler localization in PP/elastomer/ CaCO_3 systems is influenced by elastomer polarity. This provides an important general principle for hybrid composites: filler efficiency is determined by the chemical environment of the complete multiphase system, not by filler identity alone.

8.7 Rheological Implications

Mineral fillers modify PP melt rheology by increasing resistance to flow and changing the response to deformation. The magnitude of this effect depends on filler concentration and geometry; platelet-shaped fillers can produce different rheological behaviour from approximately equiaxed particles.

Altay et al. (2021) reported distinct rheological responses for different mineral-filled PP systems, with filler type influencing the extent of viscosity modification. In ternary composites, these rheological changes become coupled with the viscosity of the elastomer phase and can influence elastomer-domain breakup, filler dispersion, particle orientation, and mould filling. Rheology is therefore an important link between filler selection and the morphology developed during processing.

8.8 Selection of Mineral Filler for Hybrid Systems

Mineral selection should ultimately be linked to the desired structure–property balance. Talc is attractive when rigidity and nucleation are dominant requirements; CaCO_3 when a balance between reinforcement and impact performance is required; and mica when high-aspect-ratio reinforcement and dimensional stability are particularly important.

For hybrid PP/elastomer systems, however, these general tendencies must be evaluated together with filler localization and elastomer morphology. A filler that produces the highest modulus in a binary PP/mineral composite may not provide the best overall performance after elastomer incorporation. The presence of the elastomer changes the phase structure, interfacial environment, and deformation mechanisms and can therefore alter the relative effectiveness of the mineral fillers.

8.9 Implications for the Present Hybrid-Composite Concept

The comparative behaviour of talc, CaCO_3 , and mica provides the basis for evaluating their effectiveness in elastomer-modified PP. The relevant comparison is not simply which filler provides the highest modulus, but which filler most effectively compensates for elastomer-induced stiffness loss while retaining useful impact resistance and dimensional stability.

For the specific systems considered in this review-POE and propylene-based elastomers combined with talc, CaCO_3 , and mica-the comparison must therefore consider filler morphology and localization, elastomer-domain structure,

interfacial interactions, PP crystallization, platelet orientation, rheology, and processing history. These factors determine whether mineral reinforcement complements or interferes with elastomeric toughening and ultimately govern the overall mechanical and thermal performance of the hybrid composite.

9. Processing–Structure–Property Relationships in PP-Based Hybrid Composites

The final properties of polypropylene (PP)/elastomer/mineral hybrid composites depend not only on composition but also on the processing conditions used to develop the multiphase structure. Melt compounding establishes the initial distribution of the elastomer and mineral phases, whereas injection moulding can subsequently alter phase morphology, filler orientation, dispersion, and PP crystallization through flow and cooling. Processing should therefore be considered an integral part of structure development rather than merely a manufacturing step.

9.1 Melt Compounding and Phase Development

Melt compounding provides the shear and thermal environment required to incorporate the elastomer and mineral filler into molten PP. Adequate temperature and mixing are necessary to achieve polymer mobility and phase dispersion, whereas excessive temperature or residence time may promote molecular degradation.

The relative viscosity of PP and the elastomer strongly influences elastomer-domain breakup and coalescence. Applied shear determines whether the elastomer develops relatively fine dispersed domains or remains as larger structures. Mineral particles simultaneously modify melt rheology and can influence elastomer deformation and breakup. Thus, in a ternary system, mineral addition can alter elastomer morphology even when elastomer concentration is unchanged.

9.2 Mineral-Filler Dispersion

Efficient filler dispersion is essential for effective reinforcement. Adequate shear must overcome particle–particle attraction and agglomeration so that the mineral phase is distributed throughout the polymer matrix. Good dispersion increases the effective interfacial area and promotes more uniform stress transfer.

Poor dispersion produces aggregates that can act as stress concentrators and promote premature crack initiation. Increasing filler concentration can intensify particle-particle interactions and make uniform dispersion progressively more difficult. Consequently, reinforcement does not necessarily increase proportionally with filler loading, and an optimum concentration may exist beyond which agglomeration and loss of matrix continuity become detrimental.

9.3 Elastomer-Domain Morphology

Elastomer-domain size and distribution are strongly dependent on shear rate, mixing intensity, residence time, temperature, and component viscosity. Relatively fine and uniformly distributed elastomer domains are generally favourable for impact toughening because they provide multiple sites for localized deformation and energy dissipation.

However, excessive processing severity may alter polymer molecular structure or interfacial morphology. Mineral particles can further influence elastomer-domain development according to their interfacial affinity, either remaining predominantly in the PP phase or becoming associated with elastomer domains. Processing therefore affects the relationship between the toughening and reinforcing phases rather than controlling them independently.

9.4 Injection Moulding and Filler Orientation

Injection moulding introduces strong flow fields that can reorganize the morphology established during compounding. This effect is particularly important for platelet-shaped fillers such as talc and mica, which tend to orient preferentially along the flow direction. Such orientation can enhance reinforcement in the principal flow direction while simultaneously producing mechanical anisotropy.

Elastomer domains may also become elongated or redistributed during mould filling. Consequently, the mechanical properties of an injection-moulded hybrid composite reflect not only the intrinsic properties of its constituents but also the orientation state and morphology generated during processing.

9.5 Cooling and PP Crystallization

Cooling after injection moulding provides the thermal history under which PP crystallizes. Cooling rate influences molecular organization and crystal growth, while mineral surfaces can provide heterogeneous nucleation sites.

Talc is particularly important because of its strong nucleating activity, which can modify the crystallization behaviour and resulting crystalline morphology of PP (Leong et al., 2004). Thus, the influence of a mineral filler cannot be separated completely from the cooling history: identical compositions may develop different structures and properties under different thermal conditions.

9.6 Processing and Interfacial Development

Processing also affects the effective interfaces among PP, elastomer, and mineral filler. Adequate mixing promotes intimate contact between phases and more uniform interfacial regions, whereas insufficient mixing can leave poorly contacted or agglomerated regions.

Conversely, excessive processing temperature or residence time can reduce polymer molecular weight and alter melt viscosity, thereby affecting both filler dispersion and elastomer-domain formation. Processing optimization therefore requires a balance between sufficient mixing and avoidance of thermal or mechanical degradation.

9.7 Rheology as a Link Between Processing and Structure

Rheology provides an important connection between formulation, processing, and morphology. Mineral fillers modify the viscosity and flow response of PP, while elastomers change the viscosity ratio between the polymer phases. The combined rheological behaviour determines how effectively the phases can be dispersed during compounding and how they respond to flow during injection moulding.

Mineral-filled PP studies have demonstrated that filler type and concentration influence melt rheology, with the magnitude of the effect depending on filler morphology and characteristics (Altay et al., 2021). Platelet-shaped talc and mica can therefore produce different flow responses from more nearly equiaxed particles such as CaCO_3 , with consequences for filler orientation and multiphase morphology.

9.8 Processing–Structure–Property Relationships

The principal significance of processing lies in its ability to modify structure, which subsequently controls deformation and macroscopic properties. Formulation determines the constituents and their relative proportions, but processing determines how these constituents are distributed, oriented, and crystallized. In PP/elastomer/mineral systems, melt viscosity and interfacial characteristics influence phase breakup and dispersion during compounding. Subsequent injection flow can orient mineral platelets and elastomer domains, while cooling determines the resulting PP crystalline structure. The final morphology consequently governs stress transfer, localized deformation, crack initiation and propagation, and ultimately the measured mechanical and thermal properties.

This relationship is particularly important when comparing different formulations because an apparent composition effect may actually include a processing-induced morphology effect. Processing conditions must therefore be controlled when attempting to establish meaningful structure–property relationships.

9.9 Influence on Mechanical Properties

Tensile behaviour depends on PP matrix continuity, mineral reinforcement, interfacial stress transfer, and the extent to which elastomer incorporation disrupts load-bearing pathways. Flexural behaviour is particularly sensitive to mineral content and platelet orientation, making talc and mica attractive where high flexural rigidity is required.

Impact behaviour is governed by different mechanisms, including elastomer-domain morphology, localized matrix deformation, particle-induced stress concentrations, and interfacial failure. Consequently, a formulation that provides high tensile or flexural modulus may not necessarily provide the highest impact strength. Evaluation of hybrid composites should therefore consider tensile, flexural, and impact properties together rather than relying on a single mechanical parameter.

9.10 Thermal and Dimensional Stability

Mineral fillers can restrict thermal and mechanical deformation of the PP matrix, while changes in crystallinity can further influence dimensional stability. Platelet-shaped talc and mica are particularly relevant where resistance to dimensional deformation is important, whereas CaCO_3 can also contribute to dimensional stability depending on particle characteristics and dispersion. The elastomeric phase introduces greater compliance and thermal expansivity, creating a potential reduction in dimensional stability. Mineral reinforcement can partially counteract this effect, providing an additional rationale for hybridization beyond simple recovery of stiffness.

9.11 Optimization of Processing Conditions

Important processing variables include melt temperature, screw speed and shear intensity, residence time, component-addition sequence, mixing efficiency, injection temperature and speed, mould temperature, and cooling conditions. These variables can simultaneously affect elastomer-domain size, filler dispersion, platelet orientation, interfacial contact, and PP crystallization.

An important consequence is that formulation and processing are coupled design variables. A formulation that performs poorly under one processing condition may exhibit substantially different properties when processing produces a more favourable phase morphology. Therefore, optimization should target the final structure rather than processing convenience alone.

9.12 Toward Predictive Structure–Property Design

The ultimate objective of processing-structure-property analysis is to move beyond empirical selection of elastomer and filler contents toward structure-based composite design. Important considerations include elastomer-domain size and distribution, mineral localization, filler orientation, PP crystallinity, interfacial characteristics, and the processing conditions required to reproducibly obtain the desired morphology.

For the PP/POE/propylene-based elastomer/talc/ CaCO_3 /mica systems considered in this review, this approach is particularly important because the three mineral fillers possess different geometries and nucleating characteristics, while the elastomer phases introduce additional morphological and interfacial variables.

10. Critical Research Gaps and Future Perspectives

Despite extensive research on polypropylene blends and mineral-filled PP composites, PP/elastomer/mineral hybrid systems remain less systematically understood than their corresponding binary systems. Most studies focus either on elastomer-modified PP or on mineral-filled PP, whereas simultaneous incorporation of a rubbery phase and a rigid mineral phase introduce additional variables involving phase localization, interfacial interactions, crystallization, rheology, and processing. Consequently, the behaviour of ternary composites cannot always be predicted by simply combining the trends observed in the corresponding binary systems.

10.1 Need for Systematic Ternary Composition-Property Studies

A major limitation of the existing literature is the lack of systematic studies in which PP grade, elastomer type and concentration, mineral type and loading, and processing conditions are controlled within a common experimental framework. Differences in molecular weight, filler particle size and surface treatment, compounding history, and specimen preparation frequently make direct comparison between published results difficult. This limitation is particularly significant for comparisons among talc, CaCO_3 , and mica because their morphology, aspect ratio, surface characteristics, and nucleating activity differ substantially. Consequently, a higher modulus obtained with one filler cannot necessarily be attributed solely to greater intrinsic reinforcement; dispersion, orientation, crystallinity, and interfacial adhesion may also contribute (Altay et al., 2021; Leong et al., 2004).

Future studies should therefore use matrix-controlled experiments in which the same PP and elastomer systems are maintained while the mineral reinforcement is systematically varied. Such an approach would provide a more reliable basis for distinguishing filler-specific effects from formulation and processing effects.

10.2 Quantitative Characterization of Multiphase Morphology

Morphology is central to the performance of toughened and filled PP, yet it is frequently described using qualitative terms such as “uniform dispersion” or “good adhesion.” Such descriptions are insufficient for establishing predictive structure–property relationships. For ternary PP/elastomer/mineral systems, quantitative characterization should include elastomer-domain size and distribution, mineral-particle or platelet dimensions, degree of agglomeration, filler orientation, filler localization relative to elastomer domains, interparticle distance, and interfacial characteristics. These parameters should preferably be evaluated using image analysis in combination with SEM or TEM, DSC, WAXS, and rheological measurements.

Quantitative characterization is particularly important because identical nominal compositions can produce different morphologies when processing histories differ. Establishing measurable morphological descriptors would therefore improve comparison between formulations and provide stronger links between structure and mechanical performance.

10.3 Filler Localization and Interfacial Design

The spatial location of mineral particles in a ternary system remains an important but insufficiently resolved design variable. Depending on surface chemistry and processing conditions, a filler may preferentially reside in the PP phase, associate with the elastomer, or accumulate near the PP/elastomer interface. Premphet and Horanont (2000) demonstrated that elastomer polarity can influence phase structure and filler localization. This suggests that nominal filler loading alone is inadequate to describe reinforcement efficiency. Future studies should determine whether deliberate control of filler localization can improve stress transfer while retaining the deformation mechanisms responsible for elastomeric toughening.

Surface modification of CaCO_3 and other minerals provides one possible strategy for controlling these interactions. However, surface treatments should be evaluated not only through tensile properties but also through their effects on elastomer-domain morphology, impact fracture, crystallization, and rheology.

10.4 Separating Reinforcement and Crystallization Effects

Mineral fillers can modify PP properties through two distinct but interacting mechanisms: direct reinforcement of the polymer matrix and indirect modification of PP crystallization. Talc is particularly important in this respect because its nucleating activity can modify crystallization kinetics and crystalline morphology in addition to providing rigid-phase reinforcement. Therefore, an increase in modulus or strength cannot automatically be attributed solely to mechanical load transfer. More rigorous studies should evaluate filler dispersion together with

crystallinity, crystallization temperature, crystal structure, and deformation behaviour. DSC and WAXS can be particularly useful for distinguishing changes in crystallization from the direct mechanical contribution of the filler. The problem becomes more complex in hybrid systems because elastomer incorporation may itself influence PP crystallization. Filler and elastomer effects may therefore interact rather than operate independently. Future studies should treat composition, crystallization, phase morphology, and deformation mechanisms as coupled variables rather than considering crystallinity as an isolated parameter.

10.5 Processing-Morphology Correlations

The preceding discussion demonstrates that processing is a structure-forming variable, yet processing conditions are often reported only briefly or treated as secondary experimental details. Melt temperature, screw configuration, mixing intensity, residence time, injection speed, mould temperature, and cooling conditions can all influence filler dispersion, elastomer-domain breakup, orientation, and PP crystallization.

Consequently, two composites having identical nominal compositions may exhibit substantially different properties when processed under different conditions. Rheological characterization should therefore be integrated with morphological and mechanical measurements so that changes in melt behaviour can be related directly to the structure generated during compounding and injection moulding (Altay et al., 2021; Azizi & Faghihi, 2009).

10.6 Moving Beyond Single-Property Optimization

A recurring limitation in hybrid-composite development is the optimization of one property at the expense of another. Increasing mineral loading may increase modulus, whereas increasing elastomer content may improve impact resistance. Neither approach necessarily produces the most useful engineering material.

The more appropriate objective is multi-property optimization, considering tensile and flexural stiffness, impact resistance, hardness, thermal stability, dimensional stability, density, processability, and cost simultaneously. The optimum formulation should therefore be considered as a performance window rather than a single composition corresponding to the maximum value of one property.

10.7 Long-Term Performance and Environmental Durability

Most formulation studies emphasize short-term tensile, flexural, and impact measurements. Although these are essential for material screening, they do not fully represent long-term service behaviour. Greater attention should be given to creep, stress relaxation, fatigue, repeated impact, thermal aging, low-temperature impact behaviour, dimensional stability during thermal cycling, environmental exposure, and retention of mechanical properties after aging. The multiphase nature of PP/elastomer/mineral composites makes these issues particularly relevant because interfaces and phase morphology may evolve during prolonged service.

A formulation exhibiting an attractive initial stiffness-toughness balance may therefore not retain that balance after thermal or mechanical aging.

10.8 Sustainability, Recycling, and Circularity

Future development of PP hybrid composites should also incorporate sustainability and recyclability. Mineral reinforcement can reduce the polymer fraction while increasing stiffness and dimensional stability, potentially supporting lightweight component design. However, elastomeric modification introduces additional phase complexity that may affect property retention during repeated recycling. An important research direction is therefore the development of recyclable hybrid PP systems with controlled property degradation over multiple processing cycles. Recycled PP should be evaluated not simply as a lower-cost matrix but as a material whose molecular degradation, crystallization, and rheological behaviour interact with the elastomer and mineral phases. Future recycling studies

should consequently combine mechanical testing with characterization of processing history, morphology, crystallization, and changes across successive recycling cycles.

10.9 Toward Structure-Based Material Design

A major future direction is the transition from empirical formulation toward structure-based design. Instead of asking only how much elastomer or filler should be incorporated, future investigations should determine what morphology is required to achieve a specified combination of properties. An effective hybrid structure would ideally contain a continuous PP phase capable of carrying mechanical loads, finely dispersed elastomer domains capable of dissipating fracture energy, and well-dispersed mineral particles or platelets capable of reinforcing the matrix. The interfaces should provide sufficient stress transfer while still permitting the deformation mechanisms required for toughening.

Such an approach also creates opportunities for computational modelling and data-driven optimization. However, predictive models will only be meaningful when experimental datasets contain reliable quantitative information on composition, processing, morphology, crystallinity, and interfaces. Better experimental standardization is therefore a prerequisite for predictive materials design.

10.10 Future Research Priorities

Based on the relationships established throughout this review, the most important research priorities are:

1. Direct comparison of talc, CaCO_3 , and mica under identical PP/elastomer and processing conditions.
2. Quantitative characterization of multiphase morphology, rather than reliance on qualitative microscopy.
3. Control and measurement of filler localization in relation to elastomer chemistry and interfacial interactions.
4. Coupled crystallization–morphology studies to distinguish nucleation effects from direct reinforcement.
5. Integration of rheology, processing, and morphology for injection-moulded hybrid systems.
6. Simultaneous optimization of stiffness and toughness, rather than maximization of individual properties.
7. Long-term durability assessment, including creep, fatigue, thermal aging, and repeated impact.
8. Recycling and circularity studies for multiphase PP systems.
9. Structure-property modelling linking formulation and processing variables with engineering performance.
10. Standardized reporting of composition, filler characteristics, processing history, and morphology.

10.11 Overall Perspective

The principal research opportunity is not simply to identify another filler or elastomer capable of modifying PP, but to establish how the elastomer and mineral phases interact with each other and with the PP matrix across multiple structural length scales. The next stage of development should therefore move from composition-centred formulation toward morphology-, interface-, and processing-centred design.

For the systems emphasized in this review-PP modified with POE or propylene-based elastomers and reinforced with talc, CaCO_3 , or mica-the key challenge is to obtain a reproducible combination of rigidity, toughness, dimensional stability, and processability. Achieving this objective requires simultaneous control of phase morphology, filler localization and orientation, crystallization, interfacial interactions, and processing history. This represents the central direction for developing more predictable PP-based hybrid composites.

11. Conclusions

Polypropylene-based hybrid composites provide an effective approach for overcoming the limitations of neat PP while retaining its low density, processability, and broad engineering utility. The central challenge is not to

maximize stiffness or toughness independently, but to achieve a controlled balance between these properties through the appropriate combination of elastomeric and mineral phases.

Elastomeric modification with polyolefin-compatible materials such as POE and propylene-based elastomers can substantially improve impact resistance and energy absorption, but generally reduces modulus and rigidity. The magnitude of this trade-off depends not only on elastomer concentration but also on elastomer-domain size and distribution, interfacial characteristics, and PP crystallinity. Elastomer content alone is therefore insufficient to predict toughening efficiency.

Mineral fillers provide the complementary function of increasing stiffness, modulus, hardness, and dimensional stability. Talc, CaCO_3 , and mica are not interchangeable reinforcements because their different morphologies, aspect ratios, surface characteristics, and nucleating behaviour produce different structure–property responses. Talc is particularly effective for rigidity and PP nucleation, CaCO_3 can provide a useful balance between reinforcement and toughness, and mica offers high-aspect-ratio reinforcement with strong sensitivity to platelet orientation.

The combination of an elastomer and mineral filler creates a more complex design problem than either binary PP/elastomer or PP/mineral systems. Filler localization, elastomer-domain morphology, interfacial interactions, filler orientation, and crystallization determine whether the two modifiers act synergistically or antagonistically. Consequently, the performance of a ternary hybrid cannot be reliably predicted by simply adding the effects observed in its individual binary components.

A central conclusion of this review is that composition, morphology, interfaces, crystallization, and processing must be considered as an interconnected system. Melt compounding controls initial phase dispersion and elastomer-domain development, injection moulding can introduce filler and phase orientation, and cooling determines the resulting PP crystalline structure. These structural features ultimately control stress transfer, localized deformation, fracture behaviour, and macroscopic properties. Thus, identical nominal formulations can exhibit different performance when their processing histories differ.

The most promising strategy is therefore morphology-controlled rather than composition-only optimization. An effective hybrid structure should combine a continuous PP matrix, finely dispersed elastomer domains capable of dissipating deformation energy, and well-dispersed mineral particles capable of efficiently reinforcing the matrix. The interfaces must provide adequate stress transfer while preserving the deformation mechanisms required for toughening.

For engineering applications, the optimum formulation should not be defined by a single maximum property. Instead, stiffness, strength, impact resistance, hardness, thermal and dimensional stability, processability, density, durability, and recyclability should be considered together. This multi-property perspective is particularly important for injection-moulded components, where processing-induced morphology can strongly influence final performance.

Overall, PP/elastomer/mineral hybrid composites represent a promising platform for obtaining tailored stiffness–toughness combinations. Further progress will require systematic ternary comparisons of **POE and propylene-based elastomers with talc, CaCO_3 , and mica**, quantitative characterization of phase morphology and filler localization, coupled analysis of crystallization and morphology, and stronger correlations between processing conditions and final structure. Such developments can move PP hybrid-composite design from empirical formulation toward more predictable, structure-based engineering of application-specific performance.

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