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Development of concrete-polymer composites from recycled materials

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Abstract

This study investigates the potential of recycled concrete (rBet) as a sustainable filler for both neat polypropylene (PP) and recycled polypropylene (rPP), contributing to the transition toward a circular economy through increased utilization of waste-derived materials. RBet obtained from laboratory concrete waste was processed by grinding and sieving into a fine powder with an average particle size of 12.5 µm. Composites containing 15, 30, and 45 wt% rBet were produced with and without maleic anhydride grafted polypropylene (MAPP) as a coupling agent (1-3 wt%). The materials were compounded using a twin-screw extruder and injection molded into test specimens.

Thermal behavior was characterized by differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), while mechanical performance was assessed through tensile and impact testing. The results showed that addition of rBet significantly increased stiffness (Young's modulus) but reduced tensile strength and elongation at break, indicating a transition toward brittle behavior at higher loadings. Impact toughness remained relatively stable across rBet contents, with most values generally ranging around 120-130 kJ/m² and showing no systematic decrease. DSC analysis revealed that PP exhibited higher crystallinity than recycled polypropylene, while rBet had a limited influence when normalized to polymer content. The inorganic rBet fraction increased thermal stability, evidenced by higher residual mass in TGA.

Overall, the findings demonstrate that rBet can serve as an effective filler in both neat and recycled polypropylene, with tunable properties depending on filler content and coupling agent concentration. The combined thermal and mechanical analyses provide valuable insight into structure-property relationships governing these sustainable composite systems.

1 INTRODUCTION

1.1 Background and problem description

The global demand for sustainable materials has intensified in response to growing environmental challenges and the need for a more circular economy. The construction and demolition sector represents one of the largest waste streams worldwide, with concrete being the most dominant material. At the same time, concrete production is highly resource and energy intensive, requiring large quantities of natural raw materials and generating significant carbon dioxide emissions. Managing and recycling concrete waste is therefore a key challenge for reducing both resource extraction and climate impact (Luo et al., 2024).

Concrete poses significant challenges in recycling, mainly due to its complex composition and the chemical transformations that occur during the curing process. Once hardened, the cement paste becomes fully hydrated and chemically stable, meaning it cannot be reactivated during recycling. When concrete is demolished and crushed, recycled coarse aggregates and fine concrete powder are produced. These fractions often contain residual cement paste, which exhibits high porosity, increased water absorption, and reduced mechanical performance when reused in new concrete applications (Poon et al., 2023; Luo et al., 2024).

During crushing, fragments of the old cement paste remain attached to the recycled aggregates. When these aggregates are mixed with fresh cement paste, new interfacial transition zones are formed between the old and new paste. These zones are generally more porous, less dense, and exhibit weaker bonding compared to the surrounding concrete matrix (Poon et al., 2023; Luo et al., 2024).

The interfacial transition zone is considered a critical weak region in recycled concrete (rBet), as cracks often initiate and propagate within these zones. This results in degraded mechanical performance, including reduced compressive strength, lower stiffness, and increased brittleness compared to concrete made from neat materials. In addition, the high porosity of these regions promotes increased water absorption, which can further compromise durability and freeze thaw resistance (Poon et al., 2023).

To mitigate these limitations, additional cement is often added during the production of concrete containing recycled materials. Although this approach can improve mechanical performance, it also increases both economic cost and environmental impact, as cement production is highly energy intensive and accounts for a significant share of CO_2 emissions within the construction sector (Luo et al., 2024). Consequently, rBet rarely becomes a truly sustainable option for high-performance applications, despite its recycled origin.

Due to these constraints, rBet is primarily used in low-demand applications such as backfill, road subbases, and foundation layers. This type of utilization is commonly referred to as downcycling, as the material is not returned to its original functional level (Poon et al., 2023; Luo et al., 2024).

Polypropylene (PP) is one of the most widely used plastics globally, due to its cost efficiency and balanced properties. At the same time, reliance on virgin resources is problematic from an environmental perspective. Today, inorganic fillers such as calcium carbonate are used in polypropylene composites to improve stiffness and dimensional stability, although this often comes at the expense of toughness. The study by Pietrzak et al., shows that syndiotactic PP can be improved both mechanically and economically by adding chalk ($CaCO_3$). The filler is much cheaper compared to the polymer itself, which lowers material costs while increasing impact resistance up to 4-5 times. The result is a cost-effective and more sustainable composite material. These fillers must be mined from nature, which entails further resource extraction and environmental impact (Pietrzak et al., 2016). The recycling of plastics, including PP, is mainly performed through mechanical or chemical recycling. Mechanical recycling is the most widely used industrial method and involves collecting, sorting, washing, and grinding plastic waste into flakes or pellets that can be reprocessed into new products. For PP, this typically includes density-based float sink separation in water, since PP has a lower density than many other plastics and therefore floats.

However, a major challenge is that plastic waste streams rarely consist of pure, single polymers. Mixtures of materials such as PP, PE, PET, and PVC are common, and because these plastics have different melting points and thermal stabilities, they are often incompatible during reprocessing. This incompatibility can lead to degradation, incomplete melting, and poor mechanical properties in the recycled material. For example, PVC releases chlorine gas before PET melts, contaminating the recycled mixture and potentially damaging processing equipment (Hopewell et al., 2009).

To address these issues, recent research has focused on improving the quality and functionality of recycled plastics. One approach involves optimizing sorting and pretreatment technologies to better separate polymer types and remove contaminants, while another explores the development of compatibilizers additives that enhance the interfacial adhesion between different polymers in mixed waste streams. These innovations can lead to stronger, more uniform recycled materials that retain performance closer to neat plastics (Ragaert et al.,2017; Hopewell et al., 2009).

Challenges in recycling PP include thermo-mechanical degradation during processing and the fact that mixtures with other plastics are often impossible to separate completely, resulting in immiscible materials with poorer properties. However, compatibilizers or stabilizers can be used to improve blend ability and the properties of recycled polypropylene (rPP), for example by adding maleic anhydride grafted polypropylene (MAPP). Plastics also contain numerous additives such as pigments, fillers, plasticizers and stabilizers. These additives influence the recycling process, particularly because many stabilizers are depleted after the materials first life cycle. Consequently, recycled plastics tend to be more susceptible to heat and oxidation. To counteract these issues, new stabilizers and modifiers must often be introduced, further increasing production costs (Ragaert et al.,2017).

Here lies an opportunity to bring together waste management and materials science. Concrete waste with its heterogeneous composition of hydrated cement phases and minerals can be ground and used as an alternative, low-cost filler in polymer composites. Since plastics are often compounded with inorganic fillers like chalk, and concrete already contains similar calcium compounds, ground concrete could potentially replace conventional fillers while also creating added value from a waste material stream (Rattanapan et al., 2020). In this way, both the amount of waste ending up in low value applications and the need for neat minerals can be reduced, while contributing to circularity and climate benefits through carbon dioxide capture.

Previous studies have indicated that fillers such as chalk improve stiffness and heat stability in PP but negatively affect toughness (Webb et al., 2024). RBet material has not yet been systematically investigated in this context, especially regarding mechanical properties, filler polymer matrix interactions, or durability performance. This research gap highlights a clear opportunity to evaluate rBet as a filler in neat PPand and rPP. Doing so could create fully recycled, circular composites that merge waste management with the development of new functional materials.

1.2 Research question

Can recycled concrete (rBet) be used as a functional filler in PP-based composites, and how does it affect their mechanical and thermal properties compared to neat and rPP?

1.3 Purpose and limitations

The purpose of this thesis is to evaluate whether ground rBet can function as a sustainable filler in both neat PP and rPP composites. The study investigates how filler content (15-45 wt%) and the addition of maleic anhydride grafted polypropylene (MAPP) influences mechanical performance and thermal behavior. The work is conducted at laboratory scale and focuses on structure-property relationships derived from tensile testing, impact testing, differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA).

2 LITERATURE REVIEW

2.1 Polypropylene, recycled systems and interfacial interactions

According to Ragaert et al., (2017), PP is widely used in engineering and packaging applications due to its favorable balance of properties and processability. The addition of inorganic fillers such as calcium carbonate ($CaCO_3$) is commonly employed to enhance stiffness and reduce material costs (Leong et al., 2004).

Rigid mineral particles act as load-bearing elements within the polymer matrix, typically increasing Young's modulus while reducing elongation at break. At higher filler contents, tensile strength and impact resistance may decrease due to stress concentration and particle debonding. The final mechanical performance therefore strongly depends on filler content, particle size, dispersion, and interfacial adhesion (Supaphol et al., 2004; Leong et al., 2004; Thenepalli et al., 2015).

In context the rPP plays an important role in circular material strategies but differs structurally from neat PP. During service life and reprocessing, thermal and oxidative degradation can occur, leading to chain scission and reduced molecular weight (Jansson et al., 2003; Ragaert et al., 2017).

According to the study by Jansson et al., (2003), degradation mechanisms in rPP can significantly affect mechanical performance and increase property variability. Compared to neat PP, rPP often exhibits reduced strength and ductility, while stiffness may in some cases increase due to changes in crystallinity. Furthermore, the addition of mineral fillers requires a careful balance between stiffness enhancement and increased brittleness.

PP is hydrophobic, while mineral fillers are typically hydrophilic. This difference in polarity can lead to weak interfacial bonding and particle debonding under mechanical loading.

To improve adhesion, coupling agents such as MAPP are commonly used. MAPP enhances interfacial interaction and improves stress transfer between matrix and filler. Improved interface quality can reduce brittleness and mitigate strength loss at higher filler contents (Leong et al., 2004; Thenepalli et al., 2015).

In recycled systems, compatibilization is particularly important since degraded matrices may be more sensitive to interfacial defects (Titone et al., 2025).

High filler contents increase melt viscosity and can negatively affect flow behavior, which is important for extrusion and injection molding stability. Processability issues become more pronounced if dispersion is poor and agglomerates form, as this can create unstable melt flow and increase variability in final properties (Chafidz et al., 2016). In this context, studies of re-granulated PP blends and reinforced PP mixtures also highlight that prior processing history and compound heterogeneity can influence flow and mechanical response, which is relevant for recycled feedstocks (Stachowiak et al., 2024).

Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) are widely used to evaluate crystallinity, melting and crystallization behavior, and thermal stability in PP-based composites (Supaphol et al., 2004; Jakubowska et al., 2022; Psyanchin et al., 2021). Mineral fillers influence nucleation and crystallization kinetics and may alter the degree of crystallinity, while rPP often exhibits modified thermal behavior due to oxidative degradation and chain scission (Jansson et al., 2003; Jakubowska et al., 2022).

Cementitious and recycled mineral fillers have also been shown to affect thermomechanical and degradation behavior in polyolefin systems, highlighting the importance of thermal analysis when such materials are used as functional fillers (Gnatowski et al., 2022).

2.2 Recycled concrete as mineral filler and research motivation

RBet originates from construction and demolition waste. When crushed and further ground, it generates a fine powder consisting of hydrated cement phases, carbonates, and silicate-rich mineral fractions. While coarse fractions are reused in construction, fine rBet is often underutilized.

From a materials perspective, rBet shares certain characteristics with $CaCO_3$, including high stiffness and thermal stability. However, unlike pure $CaCO_3$, it contains additional silicate and aluminate phases and typically exhibits irregular particle morphology and broader size distribution (Rattanapan et al., 2020; Poon et al., 2023; Luo et al., 2024).

Studies investigating waste cement or concrete as fillers in PP show increased stiffness but reduced tensile strength, behavior typical of rigid inorganic fillers. In some cases, waste cement has demonstrated comparable or even improved impact performance relative to $CaCO_3$, provided adequate dispersion and interfacial control are achieved (Rattanapan et al., 2020). Nevertheless, research on recycled ground concrete specifically in thermoplastic matrices remains limited.

While $CaCO_3$-filled PP systems are well established, the substitution of conventional mineral fillers by recycled cementitious materials introduces a newer pathway that connects polymer compounding with construction and demolition waste management. This is aligned with broader circular economy frameworks where both plastics and construction materials are targeted for waste reduction, improved recycling rates, and reduced climate impacts (Alhazmi et al., 2021; Poon et al., 2023; de Andrade Salgado & de Andrade Silva, 2022; Rintala et al., 2021).

Research on concrete waste recycling and accelerated carbonation shows that recycled cement paste and aggregates can be produced and, depending on the processing route, may incorporate CO_2 through carbonation. This can lead to secondary mineral streams with surface chemistry and reactivity that differ from those of conventional mineral fillers (Poon et al., 2023; Luo et al., 2024).

At the same time, research of the environmental and economic viability of concrete waste recycling highlight that supply chain structure and economic factors strongly influence which recycled mineral fractions become available at scale, representing an important practical constraint for their use in polymer composite applications (Los Santos-Ortega et al., 2024; Wang et al., 2025).

Rattanapan et al.,(2020) shows the potential of waste cement as a filler in PP composites. Waste cement from the ready mixed concrete industry was compared with commercial cement and $CaCO_3$ at loadings of 0-50 phr, showing that Young's modulus, flexural modulus, impact strength, and hardness increased with filler content, while tensile and flexural strength decreased responses typical of rigid inorganic fillers. Notably, waste cement showed a stronger positive influence on stiffness and impact strength than both commercial cement and $CaCO_3$, and SEM images suggested relatively homogeneous dispersion of waste cement in the PP matrix (Rattanapan et al., 2020).

This directly supports the relevance of investigating rBet as an alternative to conventional $CaCO_3$ in neat PP and rPP composites, particularly when performance must be balanced with sustainability objectives.

Related studies in polymer concrete and polymer cement composite technologies also support the broader concept that cementitious fractions and polymer matrices can be combined to create functional composites. Work on merging cement concrete, concrete polymer composites, and inorganic polymer technologies frames these approaches as sustainability driven routes, while case studies demonstrate the reuse of thermoset composite waste streams as aggregates or fillers in concrete and polymer composites (Gemert & Cizer, 2015; Ribeiro et al., 2015).

Additional research on polymer modified concrete and polymer, cement systems highlight that while stiffness and compressive resistance can improve, brittleness and durability challenges often increase, making interface engineering and microstructure control critical principles that are transferable when cementitious powders are used as fillers in thermoplastic matrices (Assaad & El Mir, 2020; Abdelsattar et al., 2023; Saleh et al., 2025).

The addition of inorganic fillers such as calcium carbonate ($CaCO_3$) to PP has long been used to increase stiffness, tailor tensile and impact performance, and reduce material costs, while also opening possibilities for material substitution and circularity using secondary mineral resources (Hopewell et al., 2009; Ragaert et al., 2017; Titone et al., 2025; Webb et al., 2024).

Studies on both isotactic and syndiotactic PP is that rigid mineral particles act as load bearing elements within the polymer matrix, leading to higher Young`s modulus but reduced elongation at break (Supaphol et al., 2004; Galeski et al., 1992; Pietrzak et al., 2016).

In parallel, statistical and comparative studies emphasize that while modulus can be increased by fillers and additives, tensile strength and ductility remain dependent on interfacial quality and filler matrix interactions (Yousef, 2022; Leong et al., 2004; Peng et al., 202).

Across $CaCO_3$ filled PP composites, increasing filler content typically results in increased stiffness but reduced ductility and at higher loadings reduced impact resistance due to stress concentration, particle debonding, and microcrack initiation around mineral particles or agglomerates (Thenepalli et al., 2015; Peng et al., 2021; Al-Samhan et al., 2021; Pietrzak et al., 2016).

In addition to filler loading, particle characteristics and purity can affect both processing and final properties. Supaphol et al., (2004) demonstrated that $CaCO_3$ and its purity influence crystallization and melting behavior as well as mechanical properties and processability in syndiotactic PP, linking thermal transitions to property evolution under loading.

Comparative studies on PP filled with different mineral fillers, such as talc, kaolin, and $CaCO_3$, indicate that filler mineralogy and surface characteristics influence interfacial behavior and lead to differences in mechanical property balance (Leong et al., 2004).

More recent work also supports that $CaCO_3$ filled PP can be positioned as a more sustainable alternative to neat PP when environmental performance is considered alongside mechanical performance (Webb et al., 2024).

3 MATERIALS AND METHODS

3.1 Materials

Two polymer matrices were used in this study: neat PP and post-consumer rPP. The neat PP was a commercial homopolymer grade Moplen HP648T, LyondellBasell supplied as pellets. The rPP was a PCR grade supplied by Ocean works and delivered as mixed PP pellets.

The mineral filler consisted of rBet originating from laboratory concrete waste. The material was mechanically milled and sieved to obtain a fine powder with a nominal particle size of approximately 12.5 µm.

MAPP was used as a compatibilizer to improve interfacial adhesion between the hydrophobic polymer matrix and the inorganic filler. MAPP was added at 1, 2, and 3 wt% relative to the polymer fraction.

Prior to compounding, the rBet was dried in an oven at 100°C for 24 hours to remove residual moisture. After drying, the material was stored in airtight containers to prevent moisture uptake before processing.

All composites in this study were prepared as 10 g batches, with the mass of each constituent expressed in grams and corresponding directly to its weight percentage. Two polymer matrices were used, namely neat PP and rPP, and identical formulations were applied to enable direct comparison between the two materials. For both the PP-based and rPP-based composites, three rBet filler loadings were investigated: 15, 30, and 45 wt%. At each filler level, the amount of MAPP varied between 0 and 3 wt% relative to the polymer content.

At 0 wt% rBet, the formulations consisted entirely of polymer, with a total mass of 10 g and no MAPP added. When rBet was introduced, the polymer mass was reduced accordingly to maintain the total batch mass at 10 g; for example, to 8.5 g at 15 wt% rBet, 7.0 g at 30 wt% rBet, and 5.5 g at 45 wt% rBet.

When MAPP was added, the polymer content was further reduced so that the total mass remained constant at 10 g. For example, at 15 wt% rBet and 1 wt% MAPP, the composition consisted of 8.415 g polymer, 0.085 g MAPP, and 1.5 g rBet.

This principle was applied to all formulations, meaning that increasing MAPP content corresponded to a proportional decrease in the polymer fraction, while the rBet content remained constant within each filler level.

Before melting processing, the components were weighed according to the specified formulations and manually premixed until a visually homogeneous mixture was obtained. The premixed materials were compounded using a DSM Xplore Micro 15 cc twin-screw extruder at 220 °C for 3 minutes using a screw speed of 70 rpm. During compounding, the polymer matrix melted and mixed with the filler and compatibilizer. The molten composite exited the extruder through the die as a continuous strand.

Immediately after compounding, the hot melt was transferred directly to an Xplore 10 cc injection molding machine maintained at 220 °C. Standard tensile test specimens were injection molded according to ISO geometry. After molding, the samples were cooled in the mold to 60 °C before ejection.

In total, 192 specimens were produced. For each formulation, n = 8 specimens were prepared for mechanical testing.

3.2 Mechanical and thermal characterization

Tensile testing was performed using a universal testing machine (Tinius Olsen, model H10KT) equipped with a clip-on extensometer, in accordance with ISO 527-4. The initial gauge length was 25 mm. The crosshead speed was 10 mm/min, while the extensometer speed for modulus determination was 2 mm/min. The gripping pressure was set to 2 bar. Young's modulus, tensile strength, and elongation at break were determined from the recorded stress–strain curves. For each formulation, n = 8 specimens were tested.

Charpy impact testing was conducted according to ISO 179 using a Cometech 639D impact tester equipped with a 5 J pendulum. Samples were tested edgewise. The absorbed impact energy was recorded and used to calculate impact strength. For each formulation, n = 8 specimens were tested.

The thermal behavior of the composites was evaluated using DSC and TGA. DSC analysis was performed using a DSC 1000 (TA Instruments) under a nitrogen atmosphere. Samples were subjected to three consecutive heating and cooling cycles between -30 °C and 300 °C at a heating rate of 10 °C/min. Crystallinity values were calculated from the melting enthalpy obtained during the second heating cycle in order to eliminate the influence of previous thermal history.

$$X_c(\%) = \frac{\Delta H_m}{\Delta H_m^0 \cdot w_p} \times 100$$

where ΔHm is the measured melting enthalpy, $\Delta Hm^0 = 207$ J/g is the melting enthalpy of 100% crystalline PP, and wp is the weight fraction of polymer in the composite.

Thermogravimetric analysis was performed using a TGA Q500 (TA Instruments) under a nitrogen atmosphere. Approximately 12 ± 3 mg of sample was placed in a platinum crucible and heated from room temperature to 900 °C at a heating rate of 10 °C/min. The mass loss was continuously recorded as a function of temperature. The onset degradation temperature, maximum degradation temperature, and residual mass were determined from the thermograms.

4 RESULTS

4.1 Impact testing

Impact testing measures the ability of a material to absorb energy before fracture. All impact tests in this study were performed using a pendulum hammer with an impact energy of 5 J, which was selected to ensure complete fracture of all specimens while still being sensitive enough to distinguish differences between the materials.

The impact performance of the neat reference materials is presented in Table 1, where neat PP exhibits an impact strength of 118 kJ/m² while rPP shows a slightly lower value of 108 kJ/m². This difference is expected and can be attributed to the thermal and mechanical degradation that occurs during recycling, although rPP still retains relatively high toughness.

The influence of rBet at 15, 30, and 45 wt.% is shown in Figure 1. At 15 wt.% rBet, both neat PP and rPP-based composites display higher impact strength compared to their unfilled counterparts, indicating that the addition of rBet does not reduce impact toughness at low filler contents. At 30 wt.% rBet, the impact strength remains high and does not show a systematic decrease, while PP-based composites continue to exhibit slightly higher values than rPP. At 45 wt.% rBet, the impact strength remains comparable to or slightly lower than at lower filler contents, but no drastic reduction in toughness is observed. This indicates that rBet does not act as a strong crack initiator in these composites.

Across all filler levels, PP-based materials generally show impact strengths that are approximately 5-10 kJ/m² higher than the rPP-based materials, as observed across all formulations in Figure 1. Nevertheless, rPP-based composites still perform well and, in several cases, reach values comparable to neat PP, demonstrating that rBet is compatible with rPP from a toughness perspective

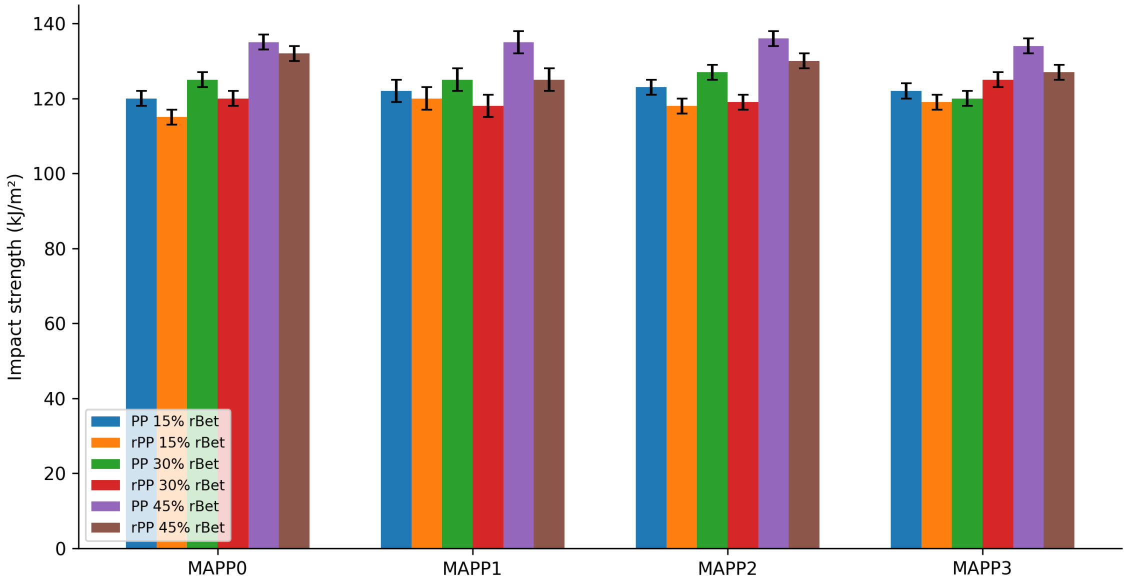
MAPP was evaluated by comparing formulations with identical rBet contents but varying compatibilizer levels Figure 1. For rPP-based materials at 15 and 30 wt.% rBet, a moderate increase in impact strength was observed with the addition of the compatibilizer, which may indicate improved interfacial interaction between the polymer matrix and the rBet particles. However, since no morphological analysis was performed, the underlying mechanisms cannot be confirmed. Overall, the effect of the compatibilizer appears secondary compared to the influence of filler content and polymer type.

Overall, the impact test results demonstrate that rBet functions as a mechanically compatible filler in both PP and rPP matrices. Rather than causing a deterioration in toughness, rBet maintains or slightly improves impact performance across the entire investigated filler range of 15-45 wt.%. This behavior distinguishes rBet from conventional mineral fillers and highlights its potential as a sustainable alternative for applications where resistance to impact and dynamic loading is required.

Table 1. Impact strength of neat polypropylene (PP) and recycled polypropylene (rPP) without recycled concrete (rBet) and maleic anhydride grafted polypropylene (MAPP).

PP/rPP (%)	rBet (wt.%)	MAPP (wt.%)	Impact strength (kJ/m²)
PP100	0	0	118.3 ± 5.4
rPP100	0	0	108.1 ± 8.2

Table 1 presents the impact strength of neat PP and rPP, providing a reference for the unfilled materials. In contrast, Figure 1 illustrates the corresponding results for composites containing different rBet contents and MAPP levels, enabling the influence of filler addition and compatibilization to be evaluated.



Figur 1. Impact strength of neat polypropylene (PP) and recycled polypropylene (rPP) composites containing 15, 30, and 45 wt.% recycled concrete (rBet) as a function of maleic anhydride grafted polypropylene MAPP content. Overall, the addition of recycled concrete maintains or slightly improves impact strength compared to the unfilled materials, even at high filler contents. PP generally shows slightly higher impact values than rPP, although the difference is relatively small. No clear systematic effect of MAPP is observed, but minor improvements in rPP systems suggest enhanced interfacial interaction. The results indicate that recycled concrete does not significantly reduce toughness, even at 45 wt.% loading.

4.2 Tensile testing

The tensile testing results clearly demonstrate the combined influence of polymer type, rBet and MAPP on the mechanical performance of the investigated materials. Figures 2-4 provide a comprehensive comparison of tensile strength, elongation at break, and Young's modulus for PP and rPP-based systems across increasing rBet contents.

Neat PP material consistently shows higher tensile strength and stiffness compared to rBet, while rBet exhibits substantially higher elongation at break Table 2. This behavior reflects the more controlled molecular structure of neat PP and the increased ductility of rPP, which is likely due to degradation during recycling, leading to lower molecular weight and enhanced chain mobility, allowing the material to deform more before fracture. These differences establish a clear baseline for understanding the effect of filler addition.

At 15 wt.% rBet, both neat PP and rPP show lower tensile strength compared to the unfilled materials. This indicates that the addition of rBet particles disturbs the load-bearing polymer matrix. Despite this reduction, neat PP-based composites consistently show higher tensile strength than rPP-based composites at all MAPP.

The addition of MAPP leads to a small increase in tensile strength for neat polypropylene, particularly at 3 wt.% compatibilizer, which may indicate improved interaction between the polymer matrix and the filler. However, the magnitude of this effect is limited and largely within the experimental scatter, as reflected by the standard deviations. For rPP-based composites, tensile strength remains relatively unchanged with increasing compatibilizer content, indicating a more limited compatibilization effect.

Elongation at break decreases compared to the unfilled materials but remains consistently higher for rPP than for neat PP. This shows that rPP retains higher ductility even when rBet is added. At the same time, Young's modulus increases clearly compared to the unfilled systems, with neat PP-based composites showing higher stiffness than rPP-based ones. This reflects both the higher stiffness of neat PP itself and more effective stress transfer in these composites.

Increasing the filler content to 30 wt.% rPP, leads to a further reduction in tensile strength and elongation at break for both polymer matrices. The decrease in elongation is particularly pronounced for neat PP-based materials, which show a transition toward more brittle behavior as the filler fraction increases. rPP-based materials continue to display higher elongation at break, although with increased scatter, especially at lower MAPP contents.

Young's modulus increases substantially with filler content, confirming the strong stiffening effect of rBet. At this level PP-based materials again show higher modulus values than rPP-based ones, while the effect of MAPP on stiffness remains secondary compared to the dominant influence of filler loading.

At the highest filler content of 45 wt.% rBet Figure 2, the mechanical behavior is the influence of filler content becomes more dominant. The tensile strength of PP and rPP-based composites reaches similar values, showing that the high amount of inorganic material largely controls the failure behavior.

Elongation at break reaches its lowest values for all compositions, especially for neat PP-based composites, indicating a strong loss of ductility and a more brittle fracture behavior. RPP-based composites still show slightly higher elongation at break than neat PP-based ones, although the difference is smaller than at lower filler contents.

Young's modulus reaches its highest value at 45 wt.% rBet, confirming the strong stiffening effect of the filler. However, the increased scatter in the results, particularly for rPP-based composites, may indicate a less uniform material structure and more variation in the results at high filler contents.

The tensile results show a clear tradeoff between stiffness and ductility with increasing rBet content. While rBet effectively increases stiffness in both PP and rPP composites, it also leads to lower tensile strength and elongation at break. Neat PP consistently shows higher strength and stiffness, whereas rPP maintains higher ductility across all filler levels.

The addition of MAPP has a small but noticeable positive effect at low to moderate filler contents, particularly for neat PP, by improving polymer and filler interaction. At high filler contents, the mechanical response is mainly controlled by the inorganic phase, and the influence of both polymer type and compatibilizer becomes less important. These results highlight the need to balance filler content and interfacial design when developing PP composites with rPP and adjusted mechanical properties.

Table 2. Mechanical properties of neat polypropylene (PP) and recycled polypropylene (rPP) based materials, tensile strength, elongation at break and Young's modulus.

PP/rPP (%)	rBet (wt.%)	MAPP (wt.%)	Tensile strength (MPa)	Elongation at break (%)	Young's modulus (MPa)
PP100	0	0	31.8 ± 1.11	13.3 ± 4.13	1980 ± 159
rPP100	0	0	21.3 ± 7.10	36.8 ± 36.2	1360 ± 388

Table 2 serves as a reference for the mechanical properties of neat PP and rPP. In comparison, Figure 2 presents the corresponding results for filled systems, illustrating the effect of rBet content and MAPP addition on tensile strength, elongation at break, and Young's modulus

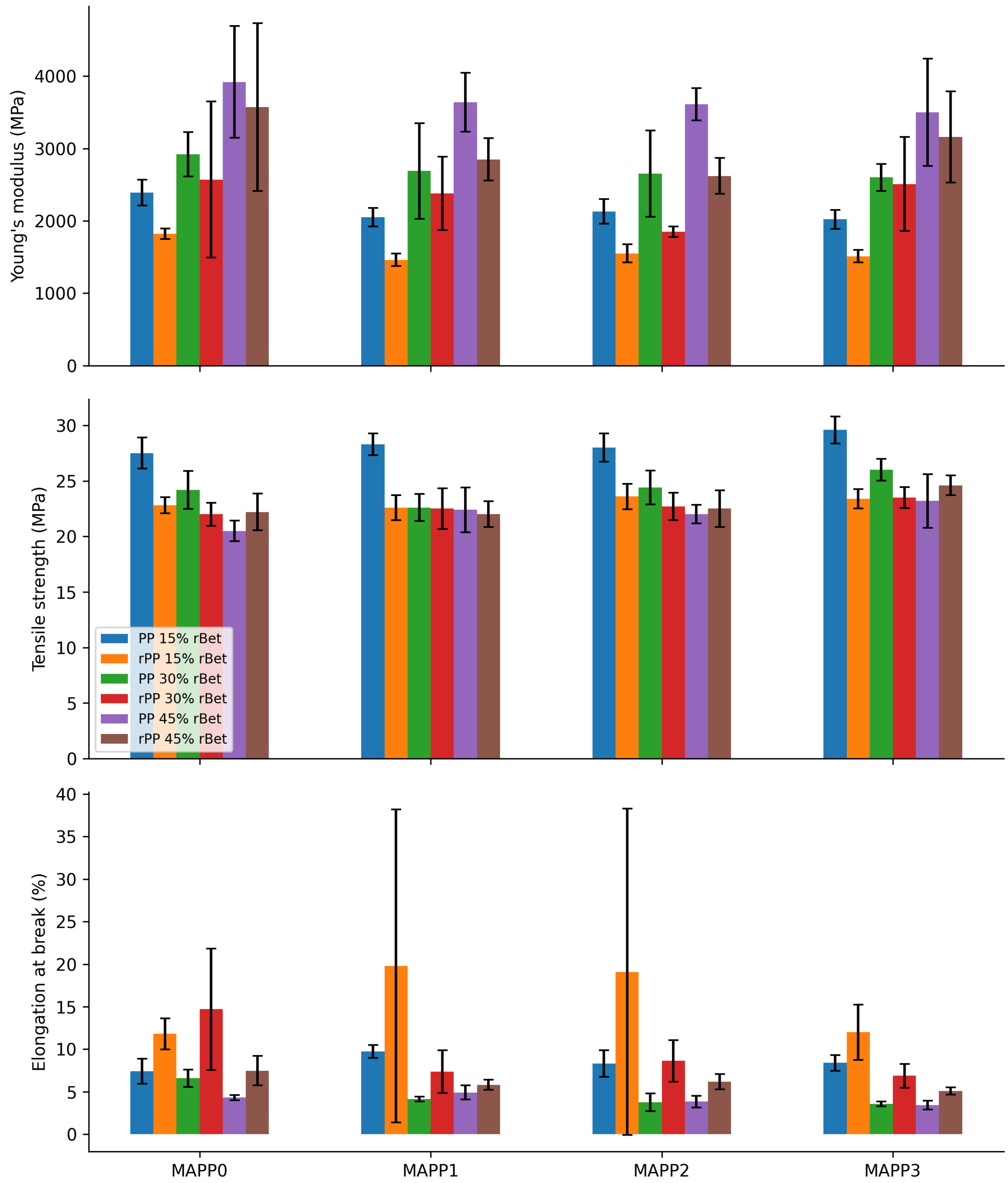


Figure 2. Tensile properties of neat polypropylene (PP) and recycled polypropylene (rPP) composites containing 15, 30, and 45 wt.% recycled concrete (rBet) as a function of maleic anhydride grafted polypropylene (MAPP) content. The figure shows that Young's modulus increases with increasing rBet content for both PP and rPP, reflecting the stiffening effect of the mineral filler. At the same time, elongation at break decreases with increasing filler content, indicating reduced ductility and more brittle behavior. Tensile strength remains relatively stable across different formulations, with only minor variations as a function of MAPP content. Overall, PP exhibits higher stiffness and strength, while rPP shows higher elongation at break.

4.3 Thermogravimetric analysis (TGA)

The thermal stability of PP-based materials produced from neat PP and rPP, both filled with rBet, was studied using thermogravimetric analysis. The analysis included both unfilled polymers and composites containing 15-45 wt.% rBet, as well as different amounts of MAPP 1-3 wt.% of the polymer. The aim was to examine whether polymer recycling, the use of rBet as a mineral filler, and interfacial modification influence the thermal degradation behavior of the materials.

All investigated materials show one clear and dominant degradation step within a relatively narrow temperature range Table 3 and Figure 3. This behavior is similar for neat and rPP, regardless of filler content or compatibilizer concentration. The absence of multiple degradation steps indicates that the addition of rBet does not introduce any new thermally active components that change the degradation mechanism within the studied temperature range. The thermal degradation can therefore mainly be attributed to the PP matrix, while the rBet remains thermally stable under these conditions.

The unfilled polymers display, as expected, very low residual mass after complete thermal decomposition. Upon addition of rBet, the char yield increases systematically with increasing filler content, with composites containing 45 wt.% rBet showing the highest residues, while materials with 15 wt.% rBet exhibit substantially lower values. Differences in residual mass between neat PP and rPP-based materials at the same filler content are generally small, indicating that the residue is mainly governed by the inorganic fraction of the composite rather than the origin of the polymer matrix. This observation is consistent with previous studies on concrete and cement-based materials, where the inorganic mineral phases are known to be thermally stable at elevated temperatures (Poon et al., 2023; Luo et al., 2024).

The degradation temperatures, expressed as T_{95}, T_{50} and the temperature at the DTG maximum, show only small differences between the investigated materials and remain within the experimental scatter. No clear trend is observed with increasing rBet content or with changes in the amount of MAPP, as the DTG peak temperature remains largely unchanged.

Neat PP and rPP show very similar degradation behavior. This indicates that mechanical recycling of PP does not lead to a noticeable reduction in thermal stability within the studied temperature range. This observation agrees with previous studies, which report that rPP, even though its molecular weight may be reduced, generally retains its characteristic thermal degradation behavior (Ragaert et al., 2017; Jansson et al., 2003; Titone et al., 2025).

At the same time, the results show that adding rBet does not introduce any new degradation steps. This indicates that rBet does not act as a catalyst for the thermal degradation of the polymer. Instead, the degradation behavior is mainly controlled by the PP matrix. This observation agrees well with what has been reported for PP composites filled with calcium carbonate ($CaCO_3$), where the filler is generally considered thermally inert and does not change the degradation mechanism (Pietrzak et al., 2016; Supaphol et al., 2004; Psyanchin et al., 2021).

In these systems, the main effect of adding $CaCO_3$ is an increase in the residual mass after degradation, while the degradation temperatures remain largely unaffected (Thenepalli et al., 2015; Webb et al., 2024).

The influence of MAPP on thermal stability is limited in all systems investigated. This suggests that the main role of MAPP is to improve the interaction between the polymer matrix and the filler, rather than to affect the thermal degradation behavior. Similar behavior has been reported for PP composites filled with $CaCO_3$, where MAPP noticeably improves mechanical properties but has only a minor effect on the thermal stability observed in TGA measurements (Leong et al., 2004; Al-Samhan et al., 2021; Yousef, 2022)

Table 3. Characteristic degradation temperatures and residual mass from thermogravimetric analysis (TGA) for neat polypropylene (PP) and recycled polypropylene (rPP), including T_{95}, T_{50}, DTG peak temperature, and residue after thermal degradation

PP/rPP (%)	T95 (°C)	T50 (°C)	DTG Peak (°C)	Residue (%)
PP	383.09	455.43	462.87	1.08
rPP	399.36	464.75	470.07	4.66

Table 3 presents the thermal degradation behavior of neat PP and rPP without additives, providing a reference for the unfilled materials. In contrast, Figure 3 illustrates the corresponding TGA results for composites containing 15, 30, and 45 wt.% rBet at different MAPP levels, allowing the effect of filler addition and compatibilization on thermal stability to be assessed.

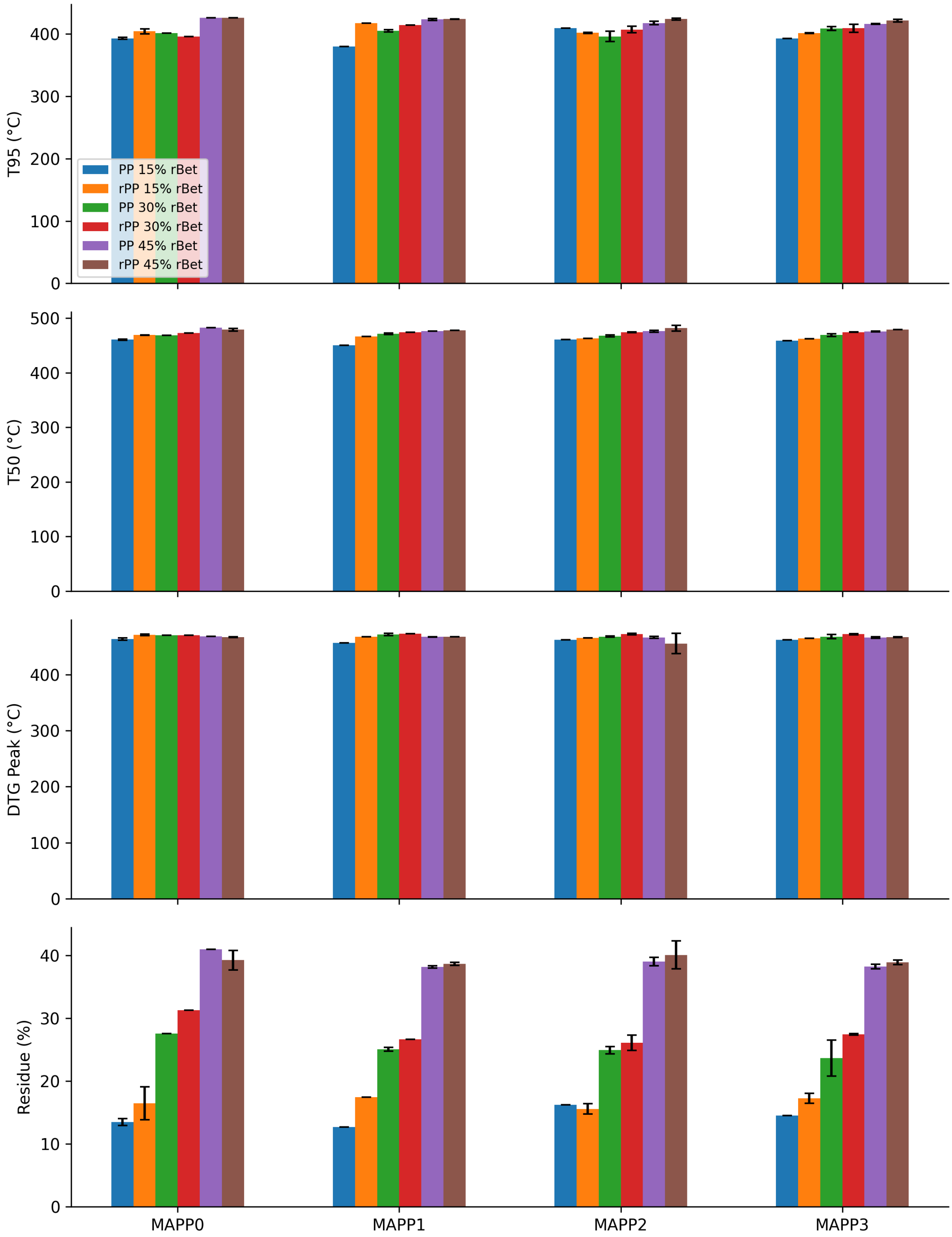


Figure 3. Thermogravimetric analysis (TGA) results for neat polypropylene (PP) and recycled polypropylene (rPP) composites containing 15, 30, and 45 wt.% recycled concrete (rBet) with varying MAPP content. The figure shows T_{95}, T_{50}, DTG peak temperature, and residual mass. Residual mass increases with increasing rBet content due to the presence of thermally stable inorganic material. In contrast, only small changes are observed in degradation temperatures, indicating limited influence of rBet and MAPP on thermal stability. Recycled polypropylene shows slightly higher variability, likely due to its heterogeneous nature.

4.4 Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) was used to analyze the crystallinity of neat PP and rPP-based composites containing rBet. The degree of crystallinity was calculated from DSC melting enthalpies and normalized with respect to the polymer content in each composite. The degree of crystallinity (Xc) is an important structural parameter for semi-crystalline polymers such as PP, as it strongly influences mechanical properties including Young`s modulus, tensile strength, and elongation at break. In general, higher crystallinity is associated with increased stiffness and strength, while lower crystallinity is often linked to increased ductility.

A summary of the crystallinity values for all investigated materials is presented in the table and figures. Comparisons between neat PP and rPP-based materials at corresponding rBet and MAPP contents are shown in more detail in Table 4 and Figure 4.

For the unfilled reference materials, neat PP shows higher crystallinity than rPP. This difference may be related to variations in material composition and structural uniformity between virgin and recycled materials. Post-consumer rPP is typically more heterogeneous and may contain residual additives, contaminants, or traces of other polymers, which can disturb regular chain packing and crystal growth.

The slightly lower crystallinity observed for rPP is consistent with the mechanical results, where rPP generally exhibits lower stiffness but higher elongation at break compared to neat polypropylene.

When rBet is added in the range of 15-45 wt.%, no clear or systematic changes in crystallinity are observed when the results are normalized with respect to the polymer content. For both neat PP and rPP-based materials, the crystallinity values remain within a relatively narrow range across the investigated rBet contents. This indicates that rBet does not significantly modify the crystallinity of PP within the investigated composition range.

At higher filler contents, a larger scatter in the crystallinity values is observed, particularly for rPP -based composites. This may be related to reduced polymer chain mobility at high inorganic contents, as well as an increased sensitivity to processing variations.

The influence of MAPP on crystallinity can be evaluated by comparing materials with the same rBet content, but different amounts of MAPP. Overall, the effect of the compatibilizer on crystallinity is small and less important than the influence of the polymer type itself. In some cases, particularly at 15 and 30 wt.% rBet, materials containing MAPP show slightly higher crystallinity compared to the corresponding materials without compatibilizer. However, these differences are often within the experimental scatter and should therefore be interpreted with caution.

When examining the crystallinity results, some deviations can be observed, mainly for rPP-based materials at higher rBet contents and when MAPP is present. In a few cases, rPP compositions show unusually low crystallinity values compared to both the corresponding neat PP materials and other rPP samples with the same rBet and compatibilizer contents. These values do not follow a clear or consistent trend and therefore cannot be directly linked to the material composition.

It was also observed that some DSC specimens were damaged or failed during sample preparation or during the measurement itself and could therefore not be included in the final

analysis. The exact reason for this could not be determined, but possible explanations include local material inhomogeneity, limited polymer continuity at high filler contents, or mechanical instability of the specimens during heating. As a result, the crystallinity values reported in this study are based only on specimens that produced stable and reproducible DSC signals.
The increased scatter in crystallinity values for rPP-based materials can thus be partially explained by the combination of the degraded nature of the material, the high inorganic filler content, and the experimental limitations mentioned above. This is supported by the observation that neat PP shows less variation in crystallinity compared to rPP. Despite these deviations, the overall conclusion remains that the polymer type has the strongest influence on crystallinity, while rBet content and MAPP addition only give secondary effects within the experimental scatter.

Table 4. Crystallinity (Xc) of unfilled neat polypropylene (PP) and recycled polypropylene (rPP), determined from DSC measurements.

PP/rPP (%)	rBet (wt.%)	MAPP (wt.%)	Xc (%)
PP100	0	0	43.09 ± 1.41
rPP100	0	0	25.14 ± 1.00

Table 4 presents the crystallinity of neat PP and rPP, serving as a reference for the unfilled materials. In contrast, Figure 6 illustrates the corresponding crystallinity (Xc) for composites containing different rBet contents and MAPP levels, enabling the influence of filler addition and compatibilization to be evaluated.

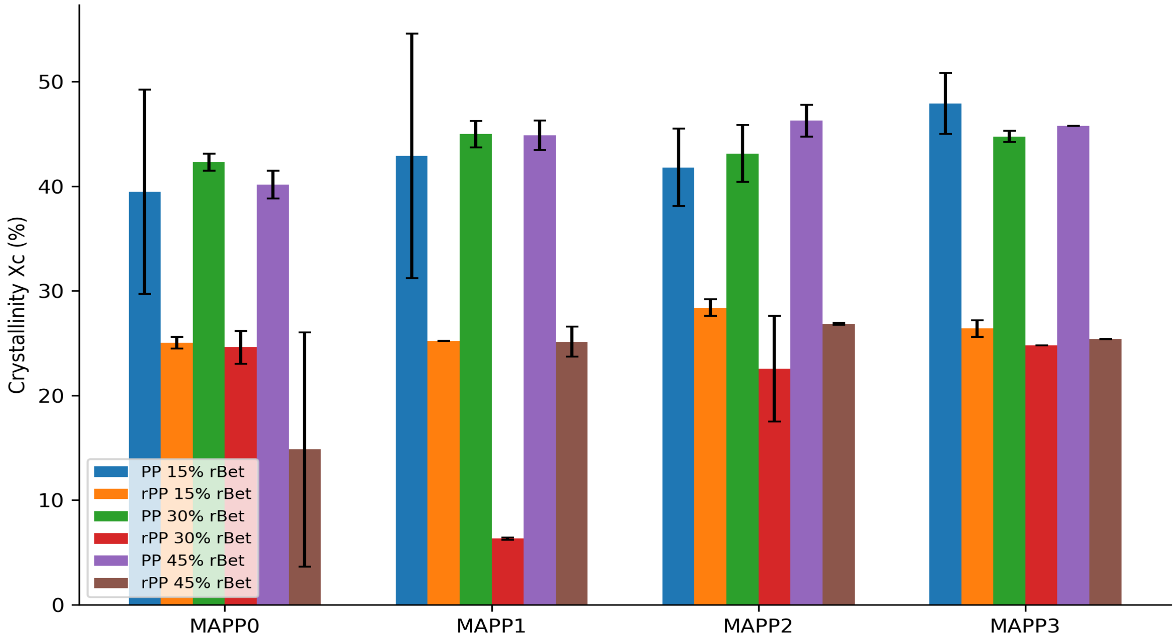


Figure 4. Degree of crystallinity (Xc) for neat polypropylene (PP) and recycled polypropylene (rPP) composites containing 15, 30, and 45 wt.% recycled concrete (rBet) as a function of MAPP content. PP shows consistently higher crystallinity than rPP, while rPP exhibits greater variability, particularly at lower filler contents

5 DISCUSSION

5.1 Mechanical performance, filler effects and interfacial interactions

The aim of this study was to investigate how neat PP and rPP are influenced by the addition of rBet as a mineral filler, and to evaluate the role of MAPP as a compatibilizer. Mechanical testing tensile and impact and thermal analyses DSC and TGA were used to relate material structure and interfacial behavior to the observed performance.

The results can be interpreted in relation to previous research on mechanical recycling of polymers, mineral-filled PP systems, and interfacial engineering in heterogeneous materials. Studies by Jansson et al., (2003), Titone et al., (2025), Yousef (2022), and Rattanapan et al., (2020) provide a relevant framework for understanding the differences between PP and rPP matrices and the mechanical behavior of rBet-filled composites.

The mechanical performance of the investigated composites is governed by both the inherent characteristics of the polymer matrix and the quality of stress transfer at the polymer-filler interface. A clear distinction is observed between neat PP and rPP. As shown in Table 2 and Figure 2, neat PP exhibits higher tensile strength and Young's modulus compared to rPP at corresponding filler contents. In contrast, rPP consistently shows higher elongation at break Table 2 and Figure 2, while impact strength remains comparable but slightly lower than that of neat PP, Table 1 and Figure 1.

These differences may be associated with molecular and structural changes introduced during mechanical recycling. Jansson et al., (2003) reports that repeated extrusion and thermo-oxidative ageing can lead to chain scission and a broader molecular weight distribution in PP, which may influence deformation behavior and fracture mechanisms. In addition, post-consumer rPP may contain residual additives or minor contaminants that contribute to variability in mechanical response.

Despite the reduced stiffness and strength, the relatively high elongation at break and the maintained impact performance of rPP observed in this study suggest that ductile deformation mechanisms remain active. This interpretation is consistent with literature on mechanically recycled polyolefins, which demonstrates that functional mechanical performance can be retained when degradation is moderate and interfacial design is properly managed (Ragaert et al., 2017; Titone et al., 2025).

The incorporation of rBet leads to a clear increase in stiffness in both PP and rPP systems, as shown in Table 2 and Figure 2. Young's modulus increases progressively with filler content from 15 to 45 wt.%, indicating that the rigid mineral phase increasingly governs the mechanical response. Similar stiffening trends are widely reported for $CaCO_3$-filled PP systems (Supaphol et al., 2004; Leong et al., 2004; Peng et al., 2021; Al-Samhan et al., 2021). At the same time, elongation at break decreases with increasing filler content Figures 4-6, reflecting the classical stiffness-ductility trade-off observed in mineral filled thermoplastics. Tensile strength does not increase with filler addition and shows slight reductions at higher filler loadings, which is consistent with stress concentration effects at the particle-matrix interface.

In contrast to many $CaCO_3$ filled systems where impact strength decreases at high filler contents the rBet filled composites in this study show relatively stable impact values across the investigated filler range Figure 1. Although no systematic improvement in impact strength is observed, the absence of a pronounced reduction suggests that rBet does not significantly embrittle the system within the studied concentration range.

This behavior is comparable to observations by Rattanapan et al., (2020), who reported that cement-based waste fillers can provide impact performance comparable to conventional limestone fillers. However, since no fracture surface analysis was performed in the present study, detailed conclusions regarding fracture mechanisms remain speculative.

The interface between the hydrophobic PP matrix and the hydrophilic mineral filler is expected to influence mechanical performance in PP-based composites. Without compatibilization, limited interfacial adhesion may contribute to particle debonding and earlier crack initiation under load.

In the present study, the addition of MAPP showed only a limited and non-systematic influence on mechanical properties. For example, at 30 wt.% rBet, a slight increase in impact strength was observed for rPP at 3 wt.% MAPP compared to the non-compatibilized system. However, at 45 wt.% rBet, impact strength remained essentially unchanged for neat PP and showed no consistent improvement for rPP with increasing MAPP content Figure 1.

Similar modest variations were observed for elongation at break. At 45 wt.% rBet, neat PP showed a small increase at 1wt.% MAPP but a decrease at higher MAPP levels, while rPP did not show a systematic improvement Figure 2. These results indicate that the effect of MAPP is minor compared to the dominant influence of filler loading and polymer matrix type.

Titone et al., (2025) emphasize that interfacial engineering is particularly important in recycled systems, where structural irregularities may amplify interfacial weaknesses. Likewise, studies on $CaCO_3$-filled PP report that MAPP can enhance adhesion and reduce particle pull-out (Leong et al., 2004; Yousef, 2022). The relatively limited improvements observed in this study suggest that the effectiveness of compatibilization depends strongly on formulation and filler level.

The minimal influence of MAPP on thermal properties further confirms that its primary function is related to interfacial compatibility rather than changes in degradation behavior or in the polymer matrix itself.

5.2 Thermal behavior, crystallinity and structure-property relationships

The thermal behavior of the composites investigated was evaluated using DSC and TGA to relate structural characteristics to the observed mechanical performance.

The DSC results Table 4 and Figure 4 do not show a fully consistent difference in crystallinity between neat PP and rPP, nor a systematic change with increasing rBet content. Although thermo-oxidative degradation during mechanical recycling may lead to chain scission and altered molecular structure (Jansson et al., 2003), the crystallization behavior of rPP does not necessarily follow a simple trend. As reported by Ragaert et al., (2017), post-consumer rPP is often chemically heterogeneous and may contain residual additives, minor contaminants, or traces of other polymers, which can contribute to variability in thermal response.

In the present study, the absence of a systematic change in crystallinity with increasing filler content indicates that rBet does not significantly modify the crystalline phase of the polymer matrix within the investigated concentration range. The observed variations between PP and rPP samples are therefore more plausibly associated with matrix heterogeneity rather than with a defined crystallization effect induced by the filler.

TGA analysis Figure 3 shows a single dominant degradation step for all investigated materials, indicating that the incorporation of rBet does not introduce additional degradation stages within the examined temperature range. Furthermore, the residual mass increases progressively with filler content, consistent with the presence of a thermally stable inorganic fraction in the composites. Similar thermal behavior has been reported for $CaCO_3$-filed PP systems, where mineral fillers remain stable within the degradation range of the polymer matrix (Thenepalli et al., 2015; Webb et al., 2024). The high thermal stability of cement-based mineral materials is also well documented in the concrete literature (Poon et al., 2023; Luo et al., 2024).

Overall, the thermal results indicate that the primary effect of rBet is related to its role as an inert mineral filler rather than to a modification of the intrinsic thermal transitions of the PP matrix. This supports the interpretation that the mechanical differences observed between formulations are mainly governed by filler reinforcement and interfacial effects rather than by significant changes in the crystalline structure.

5.3 Circular Economy and Industrial Implications

The combination of rPP and rBet represents a convergence of two major waste streams: plastics and construction materials. From a circular economy perspective, this approach aligns with strategies aimed at reducing virgin material consumption and increasing the valorization of secondary resources (Alhazmi et al., 2021; Poon et al., 2023; Rintala et al., 2021).

The results demonstrate that rBet can replace conventional $CaCO_3$-fillers without drastic loss of mechanical performance, particularly when compatibilization is applied. While high filler contents increase brittleness, appropriate interfacial design enables a balanced property profile suitable for semi-structural applications.

In the context of circular materials engineering, the objective is not necessarily to replicate the performance of virgin polymers but to develop optimized materials tailored for specific applications. The present findings therefore support the technical feasibility of rPP/rBet composites as sustainable alternatives in mineral-filled thermoplastic systems.

6 CONCLUSION AND FUTURE WORK

6.1 Conclusion

The aim of this work was to investigate whether ground rBet can be used as a functional and sustainable filler in both neat PP and rPP. The study also examined how filler content and the addition of the coupling agent MAPP influence the mechanical and thermal properties of the materials. The work has a clear circular perspective by combining two major waste streams plastic waste and construction and demolition waste into a single material system.

The results show that rBet can be used as a filler in both neat PP and rBet-based composites without changing the thermal degradation behavior of the polymers. TGA showed that all materials have a distinct main degradation step within a relatively narrow temperature range, independent of polymer type, rBet content, or the addition of MAPP.

This indicates that rBet is thermally stable within the studied temperature interval and that degradation is mainly controlled by the PP matrix. The increasing residual mass at higher rBet contents confirms that the concrete powder contributes an inorganic residue, comparable to that observed in traditional PP composites filled with $CaCO_3$.

DSC analysis showed that polymer type has a stronger influence on crystallinity than either rBet or MAPP. Neat PP consistently showed higher crystallinity than rPP, which agrees with trends reported in the literature for mechanically rPP. According to previous studies, rPP may undergo molecular and structural changes during prior processing cycles. However, no molecular characterization was performed in the present study, and the observed differences in crystallinity are therefore discussed with caution and without direct molecular evidence. The addition of rBet affected crystallinity only to a limited extent when the results were normalized with respect to polymer content. This indicates that rBet primarily acts as a structural filler within the investigated composition range rather than significantly modifying the crystallization behavior of the polymer matrix. MAPP also had only a limited influence on crystallinity, supporting the conclusion that its primary function is related to interfacial adhesion between the polymer matrix and the filler rather than to changes in crystalline structure.

The mechanical results show a clear and consistent trend in which increasing rBet content leads to higher stiffness but reduced ductility. The Young`s modulus increased markedly with increasing rBet content for both neat PP and rPP-based materials, demonstrating that rBet effectively acts as a stiffness enhancing filler. At the same time, elongation at break decreased and, at high filler contents, tensile strength also decreased, particularly for neat PP-based materials. This behavior is typical of mineral filled PP composites and is in good agreement with previous studies on $CaCO_3$ filled PP systems.

A clear difference was observed between neat PP and rPP-based materials. RPP generally showed lower strength and stiffness but significantly higher elongation at break, while impact toughness was similar to or slightly lower than that of neat PP at comparable rBet contents. This indicates that, despite its partially degraded molecular structure, rPP has a greater ability for plastic deformation and energy absorption. The results therefore suggest that rPP is not necessarily an inferior material, but rather a material with different properties that can be advantageous in applications where toughness is more important than maximum strength.

MAPP proved to have an important but limited role in the material system. At low and medium rPP contents, its addition contributed to improved elongation at break and, in some cases, improved impact toughness, indicating enhanced adhesion between the polymer matrix and the filler. At high rBet content 45 wt%, however, the relative importance of MAPP decreased, suggesting that the dominance of the filler outweighs improvements in interfacial adhesion.

From a circular and sustainability-oriented perspective, these results are particularly relevant. The study shows that rBet can serve as a technically viable alternative to $CaCO_3$ in PP composites while integrating two waste streams into a single material. This enables more value-added recycling rather than downcycling. The combination of rPP and rBet therefore appears especially attractive in a circular context, as it allows for a high share of secondary raw materials without completely compromising functional material properties.

In summary, this work shows that rBet is a technically relevant and sustainable filler in both neat PP and rPP. By adjusting polymer type, filler content, and coupling agent addition, the material properties can be tailored for different applications with varying requirements for stiffness, toughness, and thermal stability.

6.2 Future work

Even though this work shows that rBet works well as a filler in both neat PP and rPP, there are several areas that need further investigation to fully assess the material's potential from both an industrial and sustainability perspective. Continued studies are important to more clearly connect material properties, environmental benefits, and practical use.

A natural next step is to conduct a life cycle analysis (LCA) of the developed composites. Such an analysis should cover the entire chain, from collection and processing of construction and demolition waste to manufacturing, use, and final handling of the material. By comparing rPP and rBet composites with traditional PP and $CaCO_3$ composites, the actual environmental benefit can be clarified, for example regarding climate impact, energy use, and resource consumption. An LCA also makes it possible to assess how factors like transport distances and energy needs for grinding affect the total environmental performance, which is particularly relevant since rBet comes from construction and demolition waste where local conditions play a big role.

In addition to environmental aspects, it's also important to evaluate the material's economic conditions. A cost analysis where rBet is compared with established fillers like ($CaCO_3$) should include both raw material and process costs as well as potential savings linked to reduced need for neat polymer. Since $CaCO_3$ is a well-known and cost-effective filler, rBet needs to either be price competitive or offer clear added value, for example through reduced environmental impact or improved circularity. Together, life cycle analysis and cost analysis can provide a solid basis for assessing the possibilities for industrial use.

To increase understanding of the materials structure and behavior, future studies could also include microscopic analyses, such as scanning electron microscopy (SEM). With SEM, the distribution of rBet particles in the polymer matrix can be studied, as well as how well the filler is bonded to the polymer, both with and without addition of maleic anhydride grafted PP. By linking these observations to the measured mechanical and thermal properties, the relationships between structure and material performance can be clarified further.

To sum up, this work forms a solid foundation for continued research on polymer composites based on recycled construction and plastic waste. By combining technical results with environmental and cost analyses, future studies can further examine the role of rBet-based composites as a more sustainable alternative to traditionally mineral-filled polymer materials, thereby contributing to more resource-efficient and circular material use.

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8 APPENDICES

Table A1.All composites’ formulations were prepared as 10 g batches and the component contents are therefore presented in grams. Polypropylene (PP) based composites.

Formulation	PP (g)	MAPP (g)	rBet (g)
0% rBet (no MAPP)	10.000	0.000	0.000
15% rBet(no MAPP)	8.500	0.000	1.500
15% rBet+1% MAPP	8.415	0.085	1.500
15% rBet+2% MAPP	8.330	0.170	1.500
15% rBet+3 % MAPP	8.245	0.255	1.500
30% rBet (no MAPP)	7.000	0.000	3.000
30% rBet+1% MAPP	6.930	0.070	3.000
30% rBet+2% MAPP	6.860	0.140	3.000
30% rBet+3% MAPP	6.790	0.210	3.000
45% rBet (no MAPP)	5.500	0.000	4.500
45% rBet+ 1% MAPP	5.445	0.055	4.500
45% rBet+2% MAPP	5.390	0.110	4.500
45% rBet+3% MAPP	5.335	0.165	4.500

Table A2. All composites’ formulations were prepared as 10 g batches and the component contents are therefore presented in grams. Recycled polypropylene (rPP) based composites.

Formulation	rPP (g)	MAPP (g)	rBet (g)
0% rBet (no MAPP)	10.000	0.000	0.000
15% rBet(no MAPP)	8.500	0.000	1.500
15% rBet+1% MAPP	8.415	0.085	1.500
15% rBet+2% MAPP	8.330	0.170	1.500
15% rBet+3 % MAPP	8.245	0.255	1.500
30% rBet (no MAPP)	7.000	0.000	3.000
30% rBet+1% MAPP	6.930	0.070	3.000
30% rBet+2% MAPP	6.860	0.140	3.000
30% rBet+3% MAPP	6.790	0.210	3.000
45% rBet (no MAPP)	5.500	0.000	4.500
45% rBet+ 1% MAPP	5.445	0.055	4.500
45% rBet+2% MAPP	5.390	0.110	4.500
45% rBet+3% MAPP	5.335	0.165	4.500

Table A3. Thermogravimetric analysis (TGA) results for neat polypropylene (PP) and recycled polypropylene (rPP) based composites with 45 wt% recycled concrete (rBet) and varying maleic hydride grafted polypropylene (MAPP) contents, including characteristic degradation temperatures (T_{95}, T_{50}, and DTG peak) as well as residual mass. The results enable a comparison of how polymer type and interfacial modification influence thermal degradation at a constant filler content.

PP/rPP (%)	rBet (%)	MAPP (%)	T95 (°C)	T50 (°C)	DTG Peak (°C)	Residue (%)
PP55	45	0	425.68	482.38	468.24	40.97
rPP55	45	0	425.76 ± 0.03	478.94 ± 2.35	466.65 ± 0.65	39.24 ± 1.54
PP54	45	1	422.85 ± 1.80	476.53 ± 0.01	467.06 ± 0.47	38.17 ± 0.18
rPP54	45	1	423.61 ± 0.33	478.07 ± 0.02	467.00 ± 0.02	38.64 ± 0.24
PP53	45	2	417.31 ± 2.69	476.23 ± 1.77	466.23 ± 1.70	39.02 ± 0.67
rPP53	45	2	423.62 ± 1.49	481.71 ± 5.10	455.31 ± 18.04	40.08 ± 2.23
PP52	45	3	415.93 ± 0.62	475.78 ± 0.83	466.02 ± 1.19	38.21 ± 0.36
rPP52	45	3	421.23 ± 2.22	479.17 ± 0.30	466.48 ± 0.53	38.89 ± 0.35

Table A4. Thermogravimetric analysis (TGA) results for neat polypropylene (PP) and recycled polypropylene (rPP) based composites with 30 wt% recycled concrete (rBet) and varying maleic hydride grafted polypropylene (MAPP) contents, including characteristic degradation temperatures (T_{95}, T_{50}, and DTG peak) as well as residual mass. The results enable a comparison of how polymer type and interfacial modification influence thermal degradation at a constant filler content.

PP/rPP (%)	rBet (%)	MAPP (%)	T95 (°C)	T50 (°C)	DTG Peak (°C)	Residue (%)
PP70	30	0	400.79 ± 0.00	469.01 ± 0.00	470.00 ± 0.06	27.58 ± 0.00
rPP70	30	0	395.73	472.85	469.71	31.27
PP69	30	1	404.68 ± 2.01	471.56 ± 1.62	471.54 ± 2.11	25.05 ± 0.33
rPP69	30	1	413.65	474.58	472.49	26.63
PP68	30	2	395.72 ± 8.23	467.81 ± 1.68	467.52 ± 1.16	24.93 ± 0.58
rPP68	30	2	406.67 ± 5.30	474.30 ± 0.95	472.21 ± 1.51	26.10 ± 1.22
PP67	30	3	408.56 ± 2.91	469.25 ± 2.50	467.43 ± 3.62	23.66 ± 2.86
rPP67	30	3	408.79 ± 6.68	474.44 ± 0.48	471.75 ± 0.90	27.41 ± 0.13

Table A5. Thermogravimetric analysis (TGA) results for neat polypropylene (PP) and recycled polypropylene (rPP) based composites with 15 wt% recycled concrete (rBet) and varying maleic hydride grafted polypropylene (MAPP) contents, including characteristic degradation temperatures (T_{95}, T_{50}, and DTG peak) as well as residual mass. The results enable a comparison of how polymer type and interfacial modification influence thermal degradation at a constant filler content.

PP/rPP (%)	rBet (%)	MAPP (%)	T95 (°C)	T50 (°C)	DTG Peak (°C)	Residue (%)
PP85	15	0	392.76 ± 1.75	460.75 ± 1.18	463.18 ± 2.08	13.47 ± 0.53
rPP85	15	0	403.94 ± 4.08	469.03 ± 0.16	470.88 ± 1.29	16.45 ± 2.60
PP84	15	1	379.77	450.71	456.12	12.68
rPP84	15	1	417.11	466.66	467.34	17.42
PP83	15	2	409.09	460.72	461.95	16.20
rPP83	15	2	401.41	462.75	465.47	15.57
PP82	15	3	392.46	458.59	462.00	14.49
rPP82	15	3	401.16	462.50	464.77	17.25

Table A6. Degree of crystallinity (Xc) for neat polypropylene (PP) and recycled polypropylene (rPP) based composites containing 15 wt% recycled concrete (rBet) at varying maleic anhydride grafted polypropylene contents.

PP/rPP (wt.%)	rBet (wt.%)	MAPP (wt.%)	Xc (%)
PP85	15	0	39.47 ± 9.75
rPP85	15	0	25.05 ± 0.57
PP84	15	1	42.90 ± 11.70
rPP84	15	1	25.20
PP83	15	2	41.80 ± 3.70
rPP83	15	2	28.40 ± 0.80
PP82	15	3	47.90 ± 2.90
rPP82	15	3	26.40 ± 0.80

Table A7. Degree of crystallinity (Xc) for neat polypropylene (PP) and recycled polypropylene (rPP) based composites containing 30 wt% recycled concrete (rBet) at varying maleic anhydride grafted polypropylene contents.

PP/rPP (wt.%)	rBet (wt.%)	MAPP (wt.%)	Xc (%)
PP70	30	0	42.29 ± 0.81
rPP70	30	0	24.60 ± 1.57
PP99	30	1	44.98 ± 1.25
rPP99	30	1	6.32 ± 0.11
PP98	30	2	43.12 ± 2.72
rPP98	30	2	22.56 ± 5.07
PP97	30	3	44.75 ± 0.54
rPP97	30	3	24.79

Table A8. Degree of crystallinity (Xc) for neat polypropylene (PP) and recycled polypropylene (rPP) based composites containing 30 wt% recycled concrete (rBet) at varying maleic anhydride grafted polypropylene contents.

PP/rPP (wt.%)	rBet (wt.%)	MAPP (wt.%)	Xc (%)
PP55	45	0	40.15 ± 1.34
rPP55	45	0	14.84 ± 11.20
PP49	45	1	44.87 ± 1.41
rPP49	45	1	25.15 ± 1.45
PP48	45	2	46.28 ± 1.52
rPP48	45	2	26.85 ± 0.08
PP47	45	3	45.76
rPP47	45	3	25.38

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