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Mechanical Performance of Reprocessed Engineering Thermoplastics

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Abstract

Mechanical reprocessing provides one of the most direct pathways for retaining engineering thermoplastics within productive material cycles because manufacturing scrap and suitable post-use polymers can be sorted, ground, remelted, and formed into new components. The feasibility of repeated reprocessing, however, cannot be evaluated through recycled content alone. Successive thermal and mechanical histories can modify molecular weight, molecular-weight distribution, melt viscosity, crystallization behavior, rubber-phase integrity, reinforcement length, additive effectiveness, and ultimately the balance among strength, stiffness, impact resistance, ductility, fatigue behavior, and dimensional stability. Research involving polyamide 6, polycarbonate, and acrylonitrile–butadiene–styrene demonstrates that tensile modulus or tensile strength can remain comparatively stable through several controlled reprocessing cycles even when impact strength, elongation at break, or melt rheology deteriorate substantially. This conceptual–methodological study develops a property-retention framework for evaluating mechanically reprocessed engineering thermoplastics according to molecular degradation, processing history, moisture and contamination control, mechanical-property sensitivity, and application requirements.

The methodology distinguishes property retention from apparent short-term stiffness increases and proposes a testing hierarchy integrating tensile, flexural, impact, rheological, thermal, and molecular indicators. A simulated scenario demonstrates that repeated processing may produce relatively modest reductions in tensile strength while causing substantially greater losses in impact resistance and elongation at break. Because no original polymer-processing experiment or primary mechanical dataset was supplied, all quantitative results are explicitly simulated and should not be interpreted as observations from a specific commercial polymer grade. The study concludes that high-value mechanical recycling of engineering thermoplastics requires controlled feedstock identity, appropriate drying, minimized thermal history, monitoring of melt-flow or viscosity shifts, and application-specific property thresholds rather than an arbitrary maximum number of recycling cycles.

Keywords: engineering thermoplastics, mechanical recycling, polymer reprocessing, mechanical properties, polyamide, polycarbonate, ABS, circular materials, polymer degradation

1. Introduction

Engineering thermoplastics occupy an important position between commodity polymers and high-performance specialty materials because they combine processability with comparatively high strength,

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toughness, temperature resistance, dimensional stability, and chemical resistance. Materials such as acrylonitrile–butadiene–styrene (ABS), polyamide 6 (PA6), polyamide 66, polycarbonate (PC), thermoplastic polyesters, and reinforced engineering polymers are widely employed in transportation, electrical and electronic products, machinery, appliances, housings, consumer products, and technical components. Unlike thermoset matrices, thermoplastics can in principle be remelted and reshaped, making mechanical reprocessing particularly attractive for manufacturing scrap and sufficiently controlled post-use material streams. Reviews of polymer recycling nevertheless emphasize that repeated melting is accompanied by thermo-mechanical degradation and that inconsistent feedstock quality remains one of the central limitations to retaining polymers at high material value.

Mechanical reprocessing generally involves collection or recovery, identification, sorting, size reduction, cleaning where necessary, drying, melt compounding or direct remelting, pelletization, and subsequent extrusion or molding. This pathway is technically simpler than depolymerization when the polymer stream is sufficiently clean, but every additional melt history exposes macromolecular chains and additives to temperature, oxygen, moisture, shear, residence time, and pressure. Vilaplana and Karlsson's quality-oriented treatment of recycled polymers emphasizes that material degradation and upgrading must be considered together when judging the suitability of recyclate for new applications. Ragaert, Delva, and Van Geem similarly identify degradation, polymer mixing, contamination, and quality variation as fundamental challenges in mechanical recycling.

The mechanical consequences of reprocessing are not uniform across properties. Su, Lin, and Lin found that repeated PA6 processing reduced molecular weight and melt viscosity while some tensile and flexural characteristics increased, even as Izod impact performance declined. Pérez and colleagues reported a comparable property-specific response for polycarbonate: tensile strength and elastic modulus remained relatively stable through several reprocessing operations whereas impact strength deteriorated much more strongly. Rahimi, Esfahanian, and Moradi likewise observed comparatively small changes in tensile behavior of repeatedly processed ABS while impact resistance experienced a substantially larger decline. These studies demonstrate that a single tensile-strength value is insufficient for determining whether an engineering thermoplastic remains functionally suitable after recycling.

Polymer-specific degradation mechanisms further complicate interpretation. Moisture-sensitive polymers such as polyamides and polyesters may undergo hydrolytic chain scission if feedstock is inadequately dried before melt processing. Su and colleagues documented reduced PA6 molecular weight and viscosity under repeated processing, while earlier recycling work cited in their study showed that wet PA6 can experience particularly severe molecular-weight loss unless moisture is controlled. Badía and colleagues found that repeated thermo-mechanical processing of PET promotes chain scission, greater fluidity, and pronounced loss of deformation capability. ABS presents a different problem because its toughening behavior depends strongly on the polybutadiene-containing phase, which can undergo oxidative or structural degradation. Consequently, recycling limits must be established for each polymer system rather than transferred indiscriminately from one material family to another.

The present study develops a conceptual–methodological framework for evaluating the Mechanical Performance of Reprocessed Engineering Thermoplastics. Its central proposition is that engineering recyclability should be defined through retention of application-critical properties rather than simply through the number of times a polymer can be remelted. The study therefore links processing history with molecular degradation, rheological change, mechanical-property retention, and material qualification. Unreinforced ABS, PA6, and PC are used as representative engineering thermoplastics, while reinforced PA6 is discussed separately because fiber shortening introduces an additional degradation mechanism. No original experimental specimens were produced for this paper; accordingly, quantitative analysis is explicitly simulation based and serves to formulate testable engineering propositions for future laboratory validation.

2. Objectives of the Study

2.1 To Develop a Property-Retention Framework for Reprocessed Engineering Thermoplastics

The first objective is to establish a systematic framework through which reprocessed engineering thermoplastics can be evaluated according to their retained engineering function. The framework separates tensile strength, stiffness, impact resistance, elongation at break, rheological behavior, thermal characteristics, dimensional stability, and molecular condition rather than combining them into a single generalized statement that a polymer is either "recyclable" or "degraded."

This distinction is necessary because repeated processing can produce apparently contradictory results. A polymer may retain or slightly increase modulus as molecular weight falls, while simultaneously becoming less resistant to impact or fracture. Such a material could remain suitable for a rigid housing yet become unsuitable for a snap-fit, safety component, or dynamically loaded application. Recyclability should therefore be expressed relative to the mechanical requirements of the intended second or subsequent product.

2.2 To Identify Processing Variables Responsible for Property Deterioration

The second objective is to identify the processing conditions that accelerate or moderate deterioration. Melt temperature, residence time, oxygen exposure, shear history, moisture, contamination, grinding history, stabilization package, and the number of melt-forming cycles are treated as interacting variables rather than isolated factors.

Particular attention is given to drying because some engineering thermoplastics are strongly moisture sensitive. A recycled PA6 or polyester feedstock processed under inappropriate moisture conditions may undergo degradation that is not representative of the intrinsic recyclability of a properly conditioned polymer. Process-control studies must therefore distinguish avoidable handling damage from unavoidable changes associated with repeated thermomechanical exposure.

2.3 To Establish an Application-Oriented Strategy for Circular Reuse

The third objective is to develop an application-oriented approach in which recycled engineering polymers are directed toward new products according to verified property retention. A reprocessed thermoplastic should not automatically be downgraded merely because it is recycled, but neither should its virgin specification be assumed to remain valid without testing.

This approach allows closed-loop and controlled open-loop recycling to coexist. Where critical properties remain within specification, recyclate may return to demanding applications. Where impact resistance or elongation has fallen below the original requirement, the same material may still provide substantial value in a less fracture-sensitive component. The objective is to retain the highest technically defensible material value while preserving product safety and reliability.

3. Review of Literature

3.1 Thermo-Mechanical Degradation and Molecular Structure

Mechanical recycling subjects thermoplastics to repeated combinations of melting, shear, pressure, oxygen exposure, cooling, grinding, and remelting. These operations can cause chain scission, branching, crosslinking, oxidation, hydrolysis, volatilization of low-molecular-weight species, additive depletion, or changes in crystalline morphology depending on polymer chemistry and processing conditions. Schyns and Shaver emphasize that reprocessing-induced changes in polymer chain structure and properties are among the most important obstacles to effective mechanical recycling, while Ragaert and colleagues identify thermomechanical degradation and mixed material streams as major industrial constraints.

Molecular-weight reduction is particularly important because it influences melt viscosity, entanglement density, deformation behavior, and fracture resistance. Su, Lin, and Lin documented decreased PA6 molecular weight and increasing molecular-weight distribution with repeated processing, accompanied by reduced melt viscosity and altered crystallization behavior. Badía and colleagues observed chain scission in mechanically reprocessed PET and linked the resulting degradation with increased fluidity and severe reduction in deformation capability. These findings indicate why rheological measurement can serve as an efficient quality-control signal: a significant shift in melt-flow behavior may indicate underlying molecular change before all mechanical properties have fallen outside specification.

ABS illustrates why polymer architecture matters. Its toughness arises partly from a dispersed rubber phase within a styrene–acrylonitrile matrix. Repeated thermo-oxidative exposure can therefore affect the rubber phase and the relationship between the phases, producing a different mechanical response from that of a homogeneous thermoplastic. Studies of repeatedly reprocessed ABS have found that impact and elongation characteristics can deteriorate more strongly than tensile modulus or strength. The result demonstrates that a polymer's most degradation-sensitive structural feature may determine practical recycling limits more strongly than its nominal tensile strength.

3.2 Property Retention in ABS, PA6, and Polycarbonate

ABS has been extensively investigated because of its use in electronics, appliances, automotive components, and housings. Scaffaro, Botta, and Di Benedetto evaluated virgin/post-consumer ABS blends across repeated reprocessing and found progressive deterioration in physical and mechanical characteristics, with important changes occurring early in the recycling sequence. Rahimi, Esfahanian, and Moradi reported that repeated ABS processing produced relatively small changes in tensile behavior, a modest increase in flexural properties, lower viscosity, and a much larger decline in impact resistance. These findings indicate that impact testing should be treated as a primary qualification tool whenever recycled ABS will experience drops, collisions, snap-fit deformation, or other high-rate loading.

PA6 displays a different pattern because chain scission, crystallization behavior, and moisture sensitivity interact. Su and colleagues observed reduced molecular weight and viscosity with repeated reprocessing while tensile yield stress, flexural strength, and modulus did not necessarily deteriorate in parallel; impact strength, however, decreased. This response illustrates a crucial interpretation problem. Increased stiffness or yield stress does not automatically imply improved overall mechanical quality. Greater crystallinity or reduced molecular mobility can increase stiffness while reduced chain length and entanglement diminish toughness and ductility.

3.3 Reinforcement, Contamination, and Quality Variability

Reprocessed engineering thermoplastics are often reinforced with short glass fibers, mineral fillers, impact modifiers, flame retardants, pigments, or other functional additives. Reinforced systems require additional attention because reprocessing can degrade both the polymer matrix and the reinforcement architecture. Kuram and colleagues found that repeated processing of glass-fiber-reinforced PA6 shortened fibers and produced progressive reductions in mechanical properties. The number of recycling operations was among the most influential factors affecting the resulting performance.

This mechanism differs fundamentally from degradation in unfilled PA6. Even if the polymer matrix retains much of its strength, shorter glass fibers reduce aspect ratio and reinforcement efficiency. The recycled composite can therefore experience mechanical decline without a correspondingly dramatic chemical change in the polymer. Reinforced-material recycling must consequently include fiber-length distribution, orientation, and matrix–fiber interface considerations in addition to conventional polymer characterization.

4. Research Methodology

4.1 Conceptual–Experimental Study Design

The present study employs a conceptual–methodological design intended to structure a future experimental investigation rather than claim a completed polymer-reprocessing trial. Representative engineering thermoplastics are grouped into three primary unreinforced categories—ABS, PA6, and PC—with reinforced PA6 included as a supplementary case because reinforcement degradation requires additional measurements.

A laboratory implementation would begin with virgin, single-grade material having documented manufacturer specifications. Each polymer would be dried where required, injection molded into standardized specimens, mechanically tested, granulated, dried again, and remolded under controlled conditions. The regrind generated from each cycle would constitute the feedstock for the subsequent cycle. Processing temperature, residence time, screw speed, injection pressure, mold temperature, drying history, and environmental exposure would be recorded for every cycle.

4.2 Mechanical, Rheological, and Molecular Characterization

Mechanical characterization should not rely on one test. Tensile testing would provide modulus, yield strength or tensile strength, and elongation at break; flexural testing would assess bending stiffness and strength; and impact testing would quantify sensitivity to rapid fracture. Where the intended application is dynamically loaded, fatigue or fracture testing should also be considered.

Rheological characterization should include melt-flow index, melt-volume flow rate, or more detailed shear-viscosity measurements. For research-grade investigations, gel permeation chromatography can quantify molecular-weight evolution. Differential scanning calorimetry may identify changes in crystallization and melting behavior, while Fourier-transform infrared spectroscopy can assist in identifying oxidation or chemical change. This multi-method approach reflects published reprocessing studies in which mechanical trends have been interpreted through corresponding rheological, molecular, and thermal measurements.

4.3 Property-Retention and Qualification Framework

Mechanical property retention can be normalized to the virgin material through:

$$R_{P,n}=\frac{P_n}{P_0}\times100$$

where ($R_{P,n}$) is the property-retention percentage after reprocessing cycle (n), (P_n) is the measured property after cycle (n), and (P_0) is the corresponding virgin-material property.

A degradation sensitivity coefficient can additionally be represented as:

$$D_P=\frac{P_0-P_n}{nP_0}$$

where higher positive values indicate greater average loss of the property per processing cycle. The coefficient is conceptual and should not be assumed linear across extended recycling histories.

Table 1: Proposed Qualification Framework for Reprocessed Engineering Thermoplastics

Qualification Domain	Recommended Measurement	Main Degradation Signal	Engineering Interpretation
Tensile behavior	Modulus, yield/tensile strength, elongation at break	Loss of ductility or load capacity	Indicates suitability for static structural loading
Impact behavior	Izod or Charpy impact strength	Rapid decline despite stable tensile strength	Sensitive indicator of embrittlement
Rheology	MFI/MFR, viscosity curve	Increasing flow or major viscosity shift	Possible molecular-weight reduction
Thermal behavior	DSC and thermal stability testing	Shift in crystallization or thermal transitions	Indicates morphology and degradation changes
Molecular condition	GPC and FTIR where available	Chain scission, broadening, oxidation	Provides mechanistic explanation
Reinforced grades	Fiber length and fracture morphology	Progressive fiber shortening	Indicates loss of reinforcement efficiency

Source: Author's methodological synthesis based on published thermoplastic reprocessing studies.

4.4 Simulation Strategy and Limitations

Because no primary experimental dataset was supplied, the analytical section uses a hypothetical generic engineering thermoplastic. Virgin performance is normalized to 100%, and the simulated material is followed over five reprocessing cycles. Tensile strength, flexural strength, impact resistance, and elongation at break are assigned different degradation trajectories based on qualitative patterns repeatedly observed in the literature.

The simulated values do not correspond to a specific grade of ABS, PA6, PC, PET, or another commercial polymer. They are used exclusively to illustrate why different properties can reach unacceptable levels at different times. Actual recycling limits must be established experimentally for the polymer grade, additives, environmental history, processing equipment, and final application concerned.

5. Analysis

5.1 Mechanical Property Retention Is Non-Uniform

The conceptual analysis indicates that mechanical deterioration should be expected to occur unevenly across different properties. Tensile strength may remain comparatively stable because moderate chain scission does not immediately eliminate the load-bearing ability measured under a slow uniaxial test. Flexural strength can even remain constant or increase slightly if crystallinity, molecular orientation, or stiffness changes after processing.

Impact resistance and elongation at break are substantially more sensitive to embrittlement. The published PA6, PC, and ABS studies reviewed earlier repeatedly demonstrate this pattern: tensile strength or modulus can remain comparatively stable while impact or deformation capacity decreases. Consequently, an assessment based exclusively on tensile strength could incorrectly classify a material as fully equivalent to virgin polymer.

5.2 Simulated Mechanical Retention Across Five Reprocessing Cycles

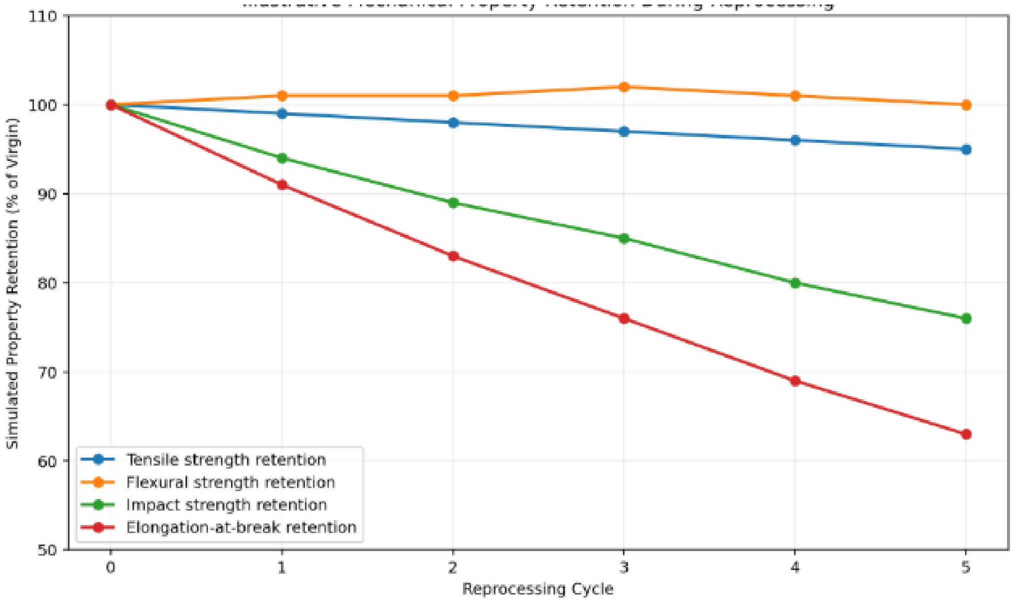
Table 2: Simulated Mechanical Property Retention of a Reprocessed Engineering Thermoplastic

Reprocessing Cycle	Tensile Strength Retention (%)	Flexural Strength Retention (%)	Impact Strength Retention (%)	Elongation-at-Break Retention (%)
Virgin / Cycle 0	100	100	100	100
Cycle 1	99	101	94	91
Cycle 2	98	101	89	83
Cycle 3	97	102	85	76
Cycle 4	96	101	80	69
Cycle 5	95	100	76	63

Note: Values are simulated for conceptual analysis and are not measurements from a specific engineering thermoplastic.

The simulated material retains 95% of its original tensile strength after five cycles, which could appear highly favorable if tensile testing were the only qualification criterion. Flexural strength remains essentially unchanged. In contrast, impact retention decreases to 76%, while elongation at break falls to 63%. The same material can therefore simultaneously appear mechanically stable under static strength testing and substantially embrittled under deformation-sensitive loading.

Graph 1: Illustrative Mechanical Property Retention During Reprocessing



Key Finding: The simulated curves show that the application-limiting property may be impact resistance or ductility rather than tensile strength. This pattern is consistent with published findings for ABS, PA6, and PC, although the magnitude of deterioration is polymer- and processing-specific.

5.3 Process Control Can Extend Useful Reprocessing Windows

The analysis further suggests that the useful recycling window is not defined exclusively by polymer chemistry. Processing conditions determine how rapidly molecular degradation accumulates. Pérez and colleagues specifically identified thermomechanical environment, molecular weight, moisture, and additives as important factors governing reprocessed PC behavior. Su and colleagues' PA6 work likewise demonstrates the importance of molecular-weight evolution and rheological change under repeated processing.

A controlled reprocessing sequence should therefore minimize unnecessary residence time and excessive melt temperature while preventing moisture-driven hydrolysis. Regrind should be protected from contamination, mixed grades should be avoided unless compatibility has been demonstrated, and processing history should be recorded whenever material is intended for high-value reuse.

Where degradation has begun but the polymer remains recoverable, controlled blending with virgin material, stabilizers, compatibilizers, or chain extenders can potentially restore specific aspects of processing and performance. Schyns and Shaver identify antioxidants, chain extenders, fillers, plasticizers, and blending strategies among approaches used to improve mechanically recycled polymers, although they also caution that additives introduce additional compositional complexity. The intervention should therefore be based on a diagnosed degradation mechanism rather than routine additive addition.

6. Discussion

6.1 Tensile Strength Alone Can Misrepresent Recycling Quality

A major implication of this study is that tensile strength is an incomplete indicator of engineering recyclability. A recycled thermoplastic that retains more than 90% of its virgin tensile strength may still have undergone significant molecular or morphological changes. Impact resistance, elongation, fatigue life, fracture toughness, creep, and stress-cracking performance can respond differently to the same degradation mechanism.

The PA6 evidence is particularly illustrative. Su and colleagues observed molecular-weight and viscosity reductions while yield stress, flexural strength, and modulus increased rather than decreased monotonically. At the same time, impact strength deteriorated. Polycarbonate displays a related pattern in which repeated reprocessing produced little early change in tensile strength or elastic modulus but a pronounced decline in impact resistance. Such evidence shows why polymer-recycling studies should not interpret a stable tensile curve as proof that the material remains mechanically unchanged.

Industrial qualification should instead establish an application-specific property hierarchy. For a rigid electrical enclosure, dimensional stability, stiffness, flame performance, and impact resistance may dominate. For a gear or bearing component, wear, fatigue, creep, and temperature behavior may be more important. For snap-fits, elongation and local fracture resistance can determine service life. Recycled material should be approved against the properties relevant to the component rather than against a generic percentage-retention rule.

6.2 Moisture, Thermal History, and Material Identity Must Be Controlled Before Recycling Limits Are Declared

A second implication is that poor processing practice can be mistaken for inherent recyclability limitation. Moisture-sensitive polymers provide the clearest example. PA6 and thermoplastic polyesters can undergo hydrolytic degradation when melt processed with excessive moisture. Su and colleagues note that thermomechanical stress reduces PA6 molecular weight and discuss earlier evidence showing particularly severe deterioration of wet material. Badía and colleagues similarly connect repeated PET processing with chain scission and loss of deformation capability.

Therefore, statements such as “this polymer can be recycled three times” or “five cycles are safe” should be treated cautiously unless processing conditions are specified. The same nominal polymer can show different recycling behavior when residence time, screw geometry, oxygen exposure, moisture, temperature, stabilizer package, or contamination level changes.

Traceability is equally important. Clean in-plant scrap often has known composition and a limited service history. Post-consumer engineering plastic may have undergone years of heat, ultraviolet exposure, chemicals, cyclic loading, and environmental ageing before entering recycling. Scaffaro and colleagues showed that increasing post-consumer ABS content can interact with reprocessing history to worsen physical properties. A circular material-control system should therefore track not only polymer type but also source, grade, additive package, prior use, and recycling history where high-performance reuse is intended.

6.3 Reprocessing Should Preserve the Highest Defensible Engineering Value

A third implication concerns the distinction between recycling and downcycling. Mechanical recycling is most valuable when the recovered polymer retains sufficient performance for demanding applications rather than being automatically diverted into products with minimal technical requirements. Ragaert and colleagues emphasize that effective recycling should be considered within the realities of polymer quality, compatibility, and industrial process constraints.

A useful strategy is to establish property-based material classes. A reprocessed grade retaining high strength, toughness, rheological stability, and dimensional performance may be suitable for near-closed-loop reuse. A second grade with reduced impact strength but stable stiffness may remain appropriate for protected housings, covers, fixtures, or non-impact-loaded components. Material showing severe molecular degradation may require blending, reactive modification, alternative processing, or movement to a less demanding application.

Reinforced engineering thermoplastics require particularly careful value preservation. Kuram and colleagues demonstrated that reprocessing of glass-fiber-reinforced PA6 shortens reinforcement and progressively lowers mechanical performance. In such systems, adding virgin polymer alone cannot restore lost fiber aspect ratio. Closed-loop strategy may require controlled addition of longer reinforcement, blending with virgin reinforced feedstock, or redesigning the subsequent application around the properties of the shortened-fiber recyclate.

7. Conclusion

Mechanical reprocessing provides a technically important pathway for retaining engineering thermoplastics within circular material systems, but repeated melt processing does not affect every engineering property equally. Molecular-weight reduction, viscosity change, oxidation, hydrolysis, morphology modification, additive depletion, and reinforcement shortening can occur simultaneously or sequentially depending on polymer chemistry and processing history. Consequently, recyclability should be defined through retained function rather than simply through the ability of the material to melt and be molded again.

The conceptual framework developed in this study demonstrates that tensile strength and modulus may remain comparatively stable even as impact resistance and elongation at break deteriorate. This behavior has been reported independently for several engineering thermoplastics and creates a significant risk of overestimating recyclate quality when qualification is based on tensile data alone. A robust evaluation should combine tensile, flexural, impact, rheological, thermal, and, where feasible, molecular characterization.

The simulated analysis reinforces this argument by showing a hypothetical material retaining 95% of virgin tensile strength after five reprocessing cycles while impact resistance falls to 76% and elongation-at-break retention falls to 63%. These values are illustrative rather than experimental. Future work should validate the framework using controlled repeated injection molding or extrusion of identified ABS, PA6, PC, and reinforced engineering-polymer grades, with consistent drying and process histories. Measurements should include mechanical performance, melt rheology, molecular weight, thermal behavior, fracture morphology, and, in reinforced systems, fiber-length distribution.

The broader engineering conclusion is that there is no universal maximum number of safe recycling cycles for engineering thermoplastics. The useful reprocessing window depends on polymer chemistry, grade, previous service exposure, processing conditions, moisture, additives, contamination, and application requirements. Circular manufacturing should therefore move toward property-based qualification, traceable feedstocks, controlled reprocessing, and deliberate matching of recycled polymers with applications capable of using their retained performance at the highest defensible value.

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