RECYCLING POTENTIAL OF END-OF-LIFE PVC FROM BATHROOM MAT APPLICATION: PROCESSING AND PERFORMANCE ANALYSIS

PUA SZE YANG

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature : 

Name : Pua Sze Yang

ID No. : 2102042

Date : 23/4/2026

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"RECYCLING POTENTIAL OF END-OF-LIFE PVC FROM BATHROOM MAT APPLICATION: PROCESSING AND PERFORMANCE ANALYSIS"** was prepared by **PUA SZE YANG** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Petrochemical Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature : Mathialagan a/l Muniyadi

Supervisor : Dr. Mathialagan A/L Munuyadi

Date : 23/4/2026

Signature : Yamuna a/p Munusamy

Co-Supervisor : Prof. Dr. Yamuna A/P Munusamy

Date : 23/4/2026

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ABSTRACT

This study investigates the optimisation of processing conditions and material performance of polyvinyl chloride (PVC) blended with scrap PVC (sPVC) for sustainable bathroom mat applications. The work focuses on addressing PVC waste challenges by enhancing recyclability while maintaining required material properties. Processing analysis identified 175 to 180 °C as the optimal temperature range, with improved melt behaviour, reduced torque, and effective fusion between virgin and recycled PVC. Mechanical results confirmed that all blends met standard requirements, while hardness criteria were only satisfied at ≥175 °C, highlighting the importance of sufficient processing temperature. Among the compositions studied, the 50/50 PVC/sPVC blend demonstrated the best balance of processability and performance, exhibiting the lowest torque and stable mechanical properties. Thermal and FTIR analyzes verified that the recycling process did not induce chemical degradation, while density, water absorption, and chemical resistance tests showed that samples processed at 180 °C possessed superior structural integrity and durability. Overall, the 50/50 blend processed at 180 °C is identified as the optimum condition, delivering a strong combination of performance and sustainability. The findings confirm that scrap PVC can be effectively recycled into high-value products without compromising quality, supporting the development of efficient and environmentally responsible polymer recycling solutions.

Keywords : PVC, scrap PVC, Polymer Recycling, Sustainable Materials, PVC Blending, Processing Temperature Optimization, Mechanical Properties, Thermal Stability, Water Absorption, Circular Economy.

Subject Area : TP1120-1135 (Plastic Engineering and Recycling)

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LIST OF SYMBOLS / ABBREVIATIONS

DBP	Dibutyl Phthalate
DEHP	Di(2-ethylhexyl) Phthalate
DIBP	Diisobutyl Phthalate
DTG	Derivative Thermogravimetry
FTIR	Fourier Transform Infrared Spectroscopy
NR	Natural Rubber
PC	Polycarbonate
PS	Polystyrene
PET	Polyethylene Terephthalate
PP	Polypropylene
PVB	Polyvinyl Butyral
PVC	Polyvinyl Chloride
RPVC	Recycled Polyvinyl Chloride
RPVB	Recycled Polyvinyl Butyral
SEM	Scanning Electron Microscope
sPVC	Scrap Polyvinyl Chloride
T_{50}	Temperature at 50% mass loss
Tc	Crystallisation Temperature
T_g	Glass Transition Temperature
TGA	Thermogravimetric Analysis
T_m	Melting Temperature
T_{max1}	Maximum Degradation Temperature (1st Peak)
T_{max2}	Maximum Degradation Temperature (2nd Peak)
TPU	Thermoplastic Polyurethane
UTS	Ultimate Tensile Strength

CHAPTER 1

INTRODUCTION

1.1 Background of Study

A polymer is a material made of macromolecules built by linking many small, repeating units (monomers) into long chains or networks (Bin Bakri et al., 2020). This chain-like architecture underpins the way polymers behave and why they're so useful. In practice, polymers are popular because their chemistry and processing can be tuned to make them flexible or rigid, transparent or opaque; they're lightweight and corrosion-resistant; and they can be shaped efficiently at scale by extrusion, moulding, and related methods.

Polymers exist in two broad origins, which are natural and synthetic. Natural polymers are produced by living organisms. For example, cellulose from plants, proteins such as silk, and natural rubber. Synthetic polymers are human-made by chemically linking monomers through polymerisation, and their properties can be designed by choosing the monomers and processing route.

The three most widely used polymers today are polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC). Based on **Figure 1.1**, the latest global demand for polymers reflects the highest demand for PE-based polymers with 26.2%, followed by PP (19.0%) and PVC (12.8%) (Plastics Europe, 2024). Besides that, other polymers such as polystyrene (PS), polyethylene terephthalate (PET), and polycarbonate (PC) are also widely used in polymer production. These families span films and bags (PE), food tubs and nonwovens (PP), rigid profiles and pipes (PVC),

appliance housings and foams (PS/EPS), beverage bottles and fibres (PET), and impact-resistant glazing and lenses (PC).

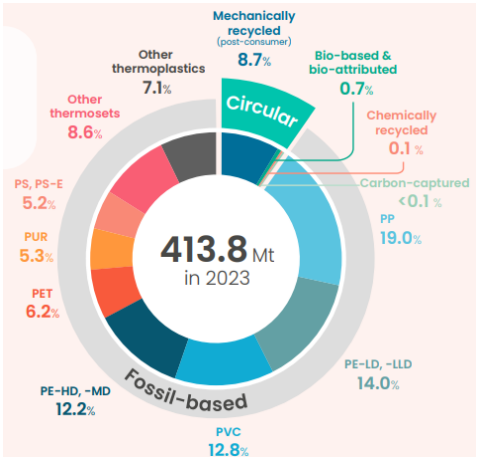

Figure 1.1: Pie Chart of Polymer Usage (Plastics Europe, 2024).

Polyvinyl chloride (PVC) is a synthetic thermoplastic made by linking many molecules of vinyl chloride into long chains. It belongs to the large family of polymers and is one of the world's most widely used plastics. In short, PVC is the polymerisation product of vinyl chloride monomer (VCM). Industrial PVC production begins upstream with its two key feedstocks, which are chlorine and ethylene. These are reacted to make the intermediate 1,2-dichloroethane (EDC) by two complementary routes: direct chlorination and oxychlorination. Purified EDC is then thermally cracked to vinyl chloride monomer (VCM), generating hydrogen chloride that is looped back to oxychlorination. Finally, VCM is polymerized, most commonly by suspension polymerisation and, for certain applications, emulsion polymerization to yield a white, odourless PVC resin powder (Chemanalyst, 2025). VCM handling is done in closed systems under strict safety controls, and the resin is subsequently dried and sieved before formulation.

After polymerisation, manufacturers compound the resin with stabilizers, plasticizers, and other additives to achieve the required stiffness, weatherability, colour, and processing behaviour, creating either rigid PVC or flexible PVC for different end uses. This ability to fine-tune properties from the same base resin is why PVC spans both structural building products and soft goods in healthcare,

electrical, and flooring markets. Polyvinyl chloride (PVC) is used across several major sectors, with products tailored to whether the resin is formulated in rigid or flexible form. In building and construction, PVC can be applied in long-life components such as water and sewer pipes and fittings, window and door profiles, claddings, siding, roofing and waterproofing membranes, and interior floor and wall coverings (Abdallah Ahmed Elgharbawy, 2022). Trade and association overviews consistently list this sector among the largest outlets for PVC due to its durability, weathering resistance, and processability. In electrical and electronics, flexible or semi-rigid PVC is widely formulated as insulation and sheathing for low-voltage power, appliance, telecom, and automotive cables.

When PVC is plasticized, its flexibility and weldability open additional applications. In healthcare, medical-grade flexible PVC remains a mainstay for tubing and flexible containers (e.g. blood and dialysis bags) owing to softness with strength, reliable sealing, and sterilisation compatibility (ECVM, 2025). In flooring and interiors, flexible PVC supports resilient surfaces and wall coverings, while coated fabrics and synthetic leather use PVC as a durable, cleanable substrate. Importantly for wet environments, flexible PVC bathroom and shower mats are widely specified as extruded or modular slip-resistant matting designed to self-drain and dry quickly. Collectively, these applications reflect that the proper compounding of one base resin can provide rigid structural roles and soft goods in hygiene-critical and wet-area settings.

PVC is a major economic driver in global manufacturing, recognised for its ability to replace more expensive or less durable materials in a variety of applications. Beyond its utility in specific sectors, PVC also supports millions of jobs worldwide through its extensive supply chain, from raw material processing to product manufacturing. As a result, PVC remains a vital component of the global economy, driving economic growth, trade, and employment in numerous industries. As production continues to expand, especially in emerging economies, PVC is expected to maintain its significance in the global supply chain.

1.2 Problem Statements

Global PVC output is best inferred from polymer-share data. PlasticsEurope's latest one-pager reports total world plastics production of 413.8 Mt in 2023, with PVC accounting for 12.8%, which is approximately 53.0 Mt. Specifically in Europe, 2.5 - 2.9 Mt of PVC waste is generated annually, and about 75% is disposed of via incineration or landfill, with 25% of it being recycled (Plastics Europe, 2024). With the current rate of increasing PVC production, the waste can be considered tremendous even with the normal end-of-life period. This situation could lead to serious environmental issues if the waste is not managed properly.

The environmental challenges associated with PVC waste are due to its high chlorine content and extensive usage of fossil-based additives such as plasticizers, including phthalates (used in flexible PVC), stabilizers, and plasticizers, which are often not fully removed during recycling. Improper disposal of PVC, particularly through open burning or poorly controlled incineration, toxic compounds such as hydrogen chloride (HCl) and dioxins/furans are released into the atmosphere. These pollutants are associated with severe health risks, including respiratory diseases, cancer, and reproductive toxicity. While modern incinerators equipped with acid-gas removal technologies can minimize these harmful emissions, many regions still rely on open burning or poorly controlled combustion, leading to significant environmental degradation and public health concerns. This underlines the urgent need for better waste management and advanced incineration technologies that ensure safe and efficient PVC disposal

Furthermore, when PVC waste is sent to landfills, the polymer itself persists in the environment for decades or even centuries, creating long-term pollution risks. Over time, PVC additives such as phthalates and lead can migrate from landfill sites into surrounding soils and groundwater, contributing to landfill leachate contamination. Multiple studies, including those from the European Chemicals Agency (ECHA), have documented the migration of phthalates in landfill leachates, with DEHP (di(2-ethylhexyl) phthalate) found at levels of environmental concern. This migration of additives poses a substantial threat to ecosystems, contaminating water sources and harming aquatic life. The presence of PVC microparticles in the

environment has also become a critical issue, as these particles can act as carriers for harmful additives, further spreading contamination across different ecosystems. The ECHA has recommended measures to minimize PVC dust and microparticle emissions during the entire lifecycle of PVC, including waste-handling facilities, emphasising the need for effective control measures to limit the release of harmful substances

As part of the European Union's (EU) commitment to a more sustainable future, there has been increasing pressure on industry stakeholders to comply with stricter environmental regulations aimed at improving the recyclability and circularity of PVC materials. The Waste Framework Directive (2008/98/EC) and the Circular Economy Action Plan (2020) set ambitious goals to reduce waste, promote recycling, and ensure that PVC waste is diverted from incineration and landfill. These frameworks prioritize the prevention, re-use, and recycling of PVC over energy recovery and disposal, and incorporate extended-producer responsibility (EPR) schemes that encourage manufacturers to improve product design for recyclability and increase collection rates (Hermann et al., 2024). The EU’s Circular Economy Action Plan further pushes for the safe and circular use of materials and the control of problematic waste shipments, signalling that manufacturers must adopt practices that keep PVC in circulation and out of landfills

However, despite these regulations, PVC recycling is much complicated due to the presence of additives that are embedded in many products. The EU REACH Regulation (Registration, Evaluation, Authorisation, and Restriction of Chemicals) has already restricted four phthalates (DEHP, DBP, BBP, DIBP) in most PVC products and recently introduced further restrictions on lead content in PVC materials (effective November 2024), limiting lead levels to less than 0.1% by weight in PVC articles (Intertek, 2018). These restrictions present a challenge for companies that wish to incorporate recycled PVC (RPVC) into new plasticized products, as the additive content in recycled material must be carefully managed to avoid regulatory non-compliance. Additionally, the mechanical properties and processing requirements of new PVC products must still be met, further complicating the use of RPVC in the manufacturing of flexible PVC products. These regulatory

complexities create significant barriers to increasing PVC recycling rates, particularly for products that require plasticizers, which are often phthalate-based.

In Malaysia, PVC waste is also subject to strict environmental control under the Environmental Quality Act 1974 and the Environmental Quality (Scheduled Wastes) Regulations 2005 (Department of Environment, 1974; Department of Environment, 2005). These regulations classify PVC waste that contains or is contaminated with hazardous substances as scheduled wastes, which necessitates strict cradle-to-grave handling, recovery, and disposal controls. This regulatory landscape further underscores the need for more effective PVC recycling solutions, as the improper disposal of hazardous PVC waste could lead to severe environmental and public health risks, as well as legal consequences for manufacturers that fail to comply.

Therefore, to address these pressing environmental challenges, PVC recycling stands as one of the most promising solutions. Such efforts would not only help to minimize harmful emissions like dioxins and HCl but also contribute to the achievement of Sustainable Development Goal (SDG) 12: Responsible Consumption and Production, by reducing waste and promoting circularity. Furthermore, enhancing the recyclability of PVC would align with global efforts to create more sustainable manufacturing processes and promote a cleaner environment for future generations.

1.3 Objectives of Study

The objectives of the thesis are shown as following:

i) To determine the optimum processing temperature for blending neat PVC and scrap PVC (sPVC) using an internal mixer based on processability and properties that meet standard specifications.
ii) To investigate the effect of different PVC/sPVC blend ratios at the optimized temperature on physico-mechanical properties, thermal stability, water absorption, and chemical resistance.

iii) To identify the optimum PVC/sPVC blend ratio and processing conditions suitable for bathroom mat applications.

1.4 Scope of Study

The scope of this study revolves around the development of PVC/sPVC blends for potential use in bathroom mat applications. The research is divided into three distinct phases. In Phase 1, PVC and sPVC will be blended in a 50:50 ratio using an internal mixer at varying processing temperatures. The blends will be assessed for processability through processing torque obtained from the internal mixer, along with hardness, tensile properties such as tensile strength, elongation at break, and elastic modulus. Thermal stability will be evaluated using thermogravimetric analysis (TGA). The outcome of this phase is to determine the processing temperature that produces blends with comparable or superior properties relative to the standard specifications for PVC applications shown in **Table 1.1**.

Table 1.1: Standard Specification for PVC Applications.

Property	Typical Range
Hardness (Shore A)	70-90 Shore A
Tensile Strength	≥ 10-15 MPa
Elongation at Break	≥100%
Plasticizer Migration	< 1-2% weight loss
Water Absorption	< 0.5%

In Phase 2, the temperature range identified in Phase 1, which yields PVC/sPVC blends with comparable or better properties, will be further explored. Blends with varying ratios of PVC and sPVC (100/0, 75/25, 50/50, 25/75, 0/100) will be prepared. These blends will undergo extensive evaluation, including processability, FTIR (Fourier Transform Infrared Spectroscopy), density, tensile properties, thermal stability, hardness, water and chemical resistance, plasticizer

migration, and morphological analysis using scanning electron microscopy (SEM). The primary objective of this phase is to identify the optimal PVC/sPVC ratio and processing conditions that achieve the required performance characteristics for the intended application.

The final phase of the study, Phase 3, will involve a comprehensive analysis and comparison of the evaluated properties against the standard specification values for bathroom mat applications. The optimal PVC/sPVC blend ratio and processing temperature will be identified, aiming to maximize the performance characteristics while adhering to the requirements for bathroom mat use. This study aims to optimize the material properties for practical applications, ensuring the blends meet or exceed the necessary standards.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

2.1.1 Structure Properties and Applications of PVC

Polyvinyl chloride (PVC) is a vinyl polymer produced by free-radical polymerisation of vinyl chloride monomer (VCM). The backbone carries a chlorine on every other carbon, and chains grow predominantly in a head-to-tail manner, as shown in **Figure 2.1**. The typical degrees of polymerisation are on the order of 500 to 1500 repeat units, and industrial resins are obtained mainly by suspension and emulsion routes (Shashoua, 2001). Besides that, commercial PVC is essentially atactic and more amorphous. The strong C-Cl dipoles drive interchain attractions. In practice, PVC's apparent structure is tuned by formulation. For example, it becomes flexible only when plasticized, and thermal stabilizers are added to suppress backbone dehydrochlorination.

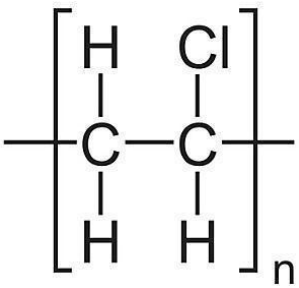

Figure 2.1: Structural formula of PVC (Mohamed, Tuhaiwer and Razzaq, 2016).

Unplasticized PVC is inherently rigid and stiff because of its polar C-Cl backbone, giving good short-term strength and modulus but only moderate toughness. It holds dimensions well in humid environments, like most thermoplastics. Referring to **Table 2.1**, the PVC properties table obtained from Vinidex and Ipolymer, it exhibits a tensile strength of 7,500 psi and a tensile modulus of 411,000 psi, along with a high Rockwell R hardness of 115, all characteristics consistent with a rigid material. The 24-hour water absorption reported as 0 % supports the expectation of low moisture uptake and good dimensional stability.

Table 2.1: Property of PVC (Vinidex, 2024; IPolymer, 2025).

Property	Value	Test Method
Density	0.051 lb/in³ (1.41 g/cm³)	ASTM D792
Water Absorption (24 h)	0 %	ASTM D570
Tensile Strength	7,500 psi	ASTM D638
Tensile Modulus	411,000 psi	ASTM D638
Hardness	115 (Rockwell R)	ASTM D785
Melting Temperature	160°C - 210°C	-
Glass Transition Temperature	70°C - 90°C	-
Thermal Conductivity	0.90 (BTU-in/ft²-hr-°F)	-

Additionally, PVC exhibits a glass transition temperature well above room temperature. However, it does not show a clean equilibrium melting point. Instead of melting directly, it will be softened and begin to dehydrochlorinate if overheated. Therefore, the processing temperature is crucial for PVC production. Referring to **Table 2.1**, a glass-transition range of 70 - 90 °C explains the room-temperature rigidity and softening with heat, while the listed melting temperature of PVC at 160 - 210 °C reflects the practical processing range rather than a true melt. The low thermal conductivity at 0.90 BTU·in/ft²·hr·°F further supports PVC's role as a thermal insulator.

Polyvinyl chloride (PVC) is a highly versatile material, and it is classified in two primary forms, rigid and flexible PVC, where each fulfils distinct roles across industries. For rigid PVC, it dominates the building and construction sector,

accounting for around 70% of PVC usage in Europe (European Council Vinyl Manufacturer, 2025). It is extensively employed in windows and doors, pipes and plumbing systems (water supply, sewer, drainage), vinyl flooring, roofing membranes, electrical conduits, and gutters/downpipes. This wide application of rigid PVC shows the versatility of the material.

On the other hand, flexible PVC, which is treated with plasticizers, is essential where flexibility or softness is required. It can be used as cable insulation, hosing and tubing, flexible flooring membranes, medical-grade products, resilient films and coatings (TLDVietnam, 2025). In everyday consumer contexts, particularly in wet and safety-oriented areas, flexible PVC bathroom and shower mats are widely used. This includes fine-grade vinyl bathroom mats designed for traction and comfort, manufactured from PVC for flexibility and non-slip performance.

As mentioned in the introduction, the production output of the PVC is approximately 53 Metric tons. There are also reports indicating rising demand and capacity expansion. ChemAnalyst projects the PVC market size in volume terms to be 53.82 million tonnes in 2025, growing to 65.48 million tonnes by 2030, reflecting a compound annual growth rate of about 4% (Mordor Intelligence, 2025). This shows that there is still a high demand for PVC in the future.

2.2 End-of-Life PVC Source and Characteristics

2.2.1 Types of PVC Waste

PVC waste is generally categorised by its form, rigid PVC or flexible PVC and by its origin, including end-of-life products, post-consumer waste, and industrial scrap. These distinctions are critical in assessing the most suitable recycling or disposal pathways.

Rigid PVC waste originates primarily from durable applications such as construction and infrastructure. Common examples include pipes, window frames,

siding, profiles, and bottles (PMC, 2023). These products have long service lifespans, which means rigid PVC waste often enters the waste stream as end-of-life products following demolition, renovation, or replacement. Rigid PVC is relatively easier to recycle mechanically due to its higher purity and absence of plasticizers. Therefore, rigid PVC is more frequently recovered from construction and demolition waste streams.

Flexible PVC waste, by contrast, incorporates significant amounts of plasticizers and other additives to impart softness, elasticity, and durability. This category includes flooring, wire and cable insulation, upholstery, medical products, and consumer goods like bathroom mats (Mohan, Cherian and Jayasree Joshi, 2022). Flexible PVC waste is more complex to recycle because additives can degrade during processing and complicate the recovery of clean resin. Bathroom mats in particular represent a typical post-consumer waste stream, where contamination from household use, for example, soap, moisture and dirt can increase the difficulty for recycling.

PVC waste can also arise as industrial scrap, generated during manufacturing and processing. Examples include offcuts from calendering or extrusion, trimmings from film production, rejected or defective profiles, and byproducts of injection moulding. Industrial scrap is usually clean and homogeneous, making it more suitable for direct mechanical recycling back into production.

2.2.2 Additives for Polymers

The performance of PVC is highly dependent on the addition of additives. Table 2.2 shows the types of additive and its function. Firstly, plasticizers, which lower the glass transition temperature and impart flexibility to an otherwise rigid polymer. Common examples such as DOP (DEHP), DINP, DIDP, and DOTP are widely used to produce soft, elastic products like flooring, cables, and bathroom mats (Merlin, 2025). Besides that, stabilizers are essential to prevent degradation during processing

and service life. Stabilizers such as calcium-zinc, lead, barium-cadmium and others can ensure thermal stability and extend product durability (Carroll et al., 2017).

To balance cost and performance, fillers such as calcium carbonate, talc, clay, and silica are frequently incorporated (Merlin, 2025). These not only reduce material cost but also enhance stiffness, wear resistance, and dimensional stability (Polymerupdate, 2024). In applications requiring enhanced safety, flame retardants such as phosphates and aluminium hydroxide are added to suppress ignition and reduce smoke emission (Merlin, 2025). In addition, antioxidants like hindered phenols and phosphite help to inhibit oxidative chain scission, thereby preventing discolouration and maintaining mechanical properties during long-term use.

Protection against UV degradation is achieved through UV absorbers, including HALS , benzotriazoles, and benzophenones (Merlin, 2025). These additives mitigate the effects of UV radiation, delaying surface cracking and yellowing. During manufacturing, lubricants such as paraffin wax, stearic acid, and metallic stearates play a vital role by reducing friction, improving melt flow, and ensuring smooth surface finishes (Carroll et al., 2017).

Finally, pigments and processing aids complete the formulation. Titanium dioxide, carbon black, and iron oxides are widely used not only for colour but also for opacity and UV protection (Polymerupdate, 2024). Meanwhile, processing aids such as acrylic modifiers, CPE, and MBS copolymers improve melt viscosity control, reduce frictional heat, and enhance die flow during compounding (Polymerupdate, 2024). Together, these additives transform PVC from a basic resin into a versatile material that can be tailored for diverse applications ranging from rigid construction profiles to soft consumer goods like bathroom mats.

Table 2.2: Summary of PVC Additives (Polymerupdate, 2024; Merlin, 2025; Carroll et al., 2017).

Additives	Functions	Examples	References
Plasticizers	Increase the flexibility of polymers and enhance processability	DOP (DEHP), DINP, DIDP, DOTP	Polymerupdate, 2024; Merlin, 2025; Carroll et al., 2017
Stabilizers	Prevent thermal and UV degradation	Lead salts, calcium-zinc, barium-cadmium	Polymerupdate, 2024; Merlin, 2025
Fillers	Reduce cost, enhance stiffness/wear resistance, improve dimensional stability	Calcium carbonate, talc, clay, silica	Polymerupdate, 2024; Merlin, 2025
Flame Retardants	Increase fire resistance and reduce smoke emission	Phosphates chlorinated paraffins	Merlin, 2025; Carroll et al., 2017
Antioxidants	Prevent oxidative chain scission and discolouration	Hindered phenols, phosphites	Merlin, 2025;Carroll et al., 2017
UV Absorbers	Shield against UV-induced degradation	Hindered amine light stabilisers (HALS)	Merlin, 2025
Lubricants	Improve melt flow, reduce processing friction, enhance surface finish	Paraffin wax, metallic stearates	Polymerupdate, 2024

Pigments	Essential for achieving opacity, UV protection, and desired colors in PVC compounds	Titanium Dioxide	Merlin, 2025
Processing Aids	Help control melt viscosity, frictional heat, and die flow in PVC compounding	Acrylic, CPE, MBS, and ABS polymers	Merlin, 2025

2.2.3 Degradation of PVC

Polyvinyl chloride (PVC) is a widely used thermoplastic polymer due to its favourable balance of mechanical properties, durability, and versatility. However, PVC is susceptible to degradation when exposed to environmental conditions such as heat, light, and mechanical stress. These degradation processes compromise its performance and can limit its lifespan, especially when used in applications like bathroom mats, where frequent exposure to moisture, friction, and cleaning agents accelerates wear and tear. Figure 2.4 shows the degradation of PVC occurs through several pathways, each affecting the material in distinct ways.

One of the primary degradation mechanisms for PVC is dehydrochlorination, an autocatalytic reaction in which chlorine atoms are removed from the polymer chains. This reaction initiates with a tertiary chloride (Cl) and leads to the generation of hydrogen chloride (HCl) and benzene as the main byproducts (Wu et al., 2024). Dehydrochlorination is often the result of thermal or oxidative stress, where heat or UV radiation breaks the C-Cl bond. This degradation usually occurs when PVC is exposed to high temperatures, such as in long-term applications or during industrial processing. The removal of chlorine atoms disrupts the polymer chain structure, making the material more susceptible to further degradation. In the context of bathroom mats, exposure to the high humidity and temperature fluctuations typical of bathroom environments may trigger this reaction, leading to a loss of strength and flexibility.

Another common pathway for PVC degradation is UV-induced degradation, where ultraviolet (UV) radiation from sunlight or artificial lighting breaks the C-Cl and C-C bonds within the polymer (Alahapperuma and Samarasekara, 2019). The energy from UV radiation creates free radicals, which initiate chain scission and lead to embrittlement, cracking, and material failure. PVC exposed to UV radiation undergoes changes in its molecular structure, which contribute to surface damage such as discolouration and surface cracking. For example, bathroom mats are often exposed to natural and artificial light during their use. This prolonged exposure to UV rays can cause the material to degrade, reducing the aesthetic appearance and mechanical properties, such as tensile strength and flexibility, which are essential for comfort and durability in bathroom mats.

On the other hand, oxidative degradation occurs when PVC undergoes chemical reactions with oxygen, typically in the presence of heat or UV light. This process involves the splitting off of a chlorine atom, leading to the formation of a ketone (Zhang et al., 2024). As a result, the molecular weight of the PVC decreases, which compromises its mechanical properties, such as tensile strength and elasticity. This type of degradation is common in outdoor or high-temperature applications where PVC is exposed to oxygen and heat for extended periods. When relating to bathroom mats, which are frequently exposed to moist environments with varying temperatures, oxidative degradation can contribute to the gradual weakening of the material, making it prone to cracks and tears over time.

Mechanical degradation refers to the physical breakdown of PVC due to repetitive stress, abrasion, grinding, and re-extrusion (Nazdaneh Yarahmadi, Jakubowicz and Gevert, 2001). In this process, the polymer chains experience mechanical forces that cause chain scission and the formation of microcracks, leading to a reduction in the tensile strength of the material. Bathroom mats, which are often subjected to frequent foot traffic, bending, and scrubbing during cleaning, are particularly vulnerable to mechanical degradation. Over time, these repeated mechanical stresses can lead to the failure of the mat, causing it to lose its original functionality and appearance.

Table 2.3: Types of Degradation Pathway.

Degradation Pathway	Description	Reference
Dehydrochlorination	An autocatalytic reaction that starts with a tertiary chloride (Cl) and generates hydrogen chloride (HCl) and benzene as the main products	Wu et al., 2024
UV-Induced	UV radiation breaks C–Cl and C–C bonds, generating radicals; it leads to chain scission, embrittlement, cracking, and material failure	Alahapperuma and Samarasekara, 2019
Oxidative Degradation	Decomposition occurs by splitting off a chlorine atom with the formation of a ketone, which accounts for the observed decrease in molecular weight of the oxidised PVC	Zhang et al., 2024
Mechanical Degradation	Repeated stress, abrasion, grinding, and re-extrusion cause chain scission and microcracks, lowering tensile strength.	Achukwu et al., 2020

2.3 PVC and sPVC Processing and Blending

2.3.1 Processing Method of PVC

PVC is a highly versatile material that can be processed using various methods to create products suited to specific applications, including bathroom mats. There are several types of PVC processing methods, which are extrusion, injection moulding,

calendaring, compression moulding, and blow moulding. Each of these techniques is tailored to create distinct forms and structures that meet the specific functional and aesthetic needs of the final product.

Extrusion is one of the most widely used methods for processing PVC, particularly in applications such as pipes, sheets, and flooring materials. In the extrusion process, PVC is heated until it melts and is then forced through a die to create continuous shapes, such as sheets or rolls (Drobny, 2014). This method is often employed in the production of PVC bathroom mats, where large sheets or mats are extruded and then cut to the desired size. The flexibility and strength of the material, combined with the ease of shaping through extrusion, make it ideal for producing mats that can withstand frequent exposure to water, moisture, and foot traffic.

Injection moulding involves melting polymers and injecting it into a mould under high pressure (Ashby, 2013). This method is ideal for producing precise, complex shapes and is commonly used for creating small and intricate parts and components. While injection moulding is less common for large products like bathroom mats, it is occasionally used to produce mats with intricate patterns or designs. The ability to mould detailed shapes makes this process suitable for applications where specific texture or patterns are required in the mat's surface, adding to both its functionality and appearance.

Calendaring is a processing method where polymers are passed through a series of heated counter-rotating rollers to create thin sheets or films (E. Mitsoulis, 2009). This technique is widely used for the production of films, coatings, and flooring materials. In the context of bathroom mats, calendaring is an essential method for producing thin, flexible PVC sheets that can be further processed into mats. The material's flexibility, combined with its resistance to water and wear, makes calendared PVC well-suited for use in bathroom environments, where mats must endure moisture and frequent cleaning.

Compression moulding is a process where PVC is placed into a heated mould cavity, and pressure is applied to form the desired shape (Alam, Maniruzzaman and

Morshed, 2014). This method is used for creating thicker, more durable products, making it suitable for producing bathroom mats that require extra strength and support. Compression moulding is particularly effective when the mat is designed to have a thicker surface layer or a more rigid structure. This method ensures that the mats are durable, resistant to mechanical stresses, and capable of maintaining their shape over time.

Blow moulding is commonly used for creating hollow shapes, such as bottles or containers, by forcing the plastic against the mold walls through air pressure (Cantor and Watts, 2011). While blow moulding is not typically used for flat products like bathroom mats, it can be employed to create PVC mats with unique features, such as raised edges or padding. This method may be used for specialised bathroom mats designed to offer extra cushioning or water drainage capabilities.

In conclusion, among these various methods, extrusion and calendaring are the most commonly used for producing PVC bathroom mats due to their ability to efficiently create large, flexible sheets that are well-suited to withstand the conditions of bathroom environments.

Table 2.4: Type of Processing Method.

Processing Method	Description	References
Extrusion	A continuous process where PVC is melted and forced through a mould to create products like pipes and sheets.	Drobny, 2014
Injection Moulding	PVC is melted and injected into a mould under high pressure to create precise and complex shapes, often for consumer goods.	Ashby, 2013
Calendaring	PVC is passed through a series of rollers to create thin sheets or films. Often used for flooring and wallpaper.	E. Mitsoulis, 2009

Compression Moulding	PVC is placed into a heated mould cavity and compressed to form the final shape. It is typically used for thicker parts.	Alam, Maniruzzaman and Morshed, 2014
Blow Moulding	A process where melted PVC is inflated into a mould to form hollow shapes like bottles or containers.	Cantor and Watts, 2011

2.3.2 Process and Blending

The ratio of mixing for PVC and sPVC plays a crucial role in determining the performance, quality, and cost-effectiveness of the final product. Recycled PVC is often sourced from post-industrial scraps or end-of-life products that may exhibit degradation in thermal stability due to prior processing and aging. Therefore, the ratio of blending must be carefully optimized to achieve an acceptable range of mechanical, thermal and aesthetic properties.

A higher proportion of sPVC can significantly reduce the material cost and achieve more sustainable manufacturing practices by fulfilling SDG 12, also known as responsible consumption and production. However, without proper control on blending ratio, it can cause poor product performance, such as reduced flexibility, poor tensile strength and surface finish. Consequently, a review has been conducted to select a range of blending ratios that may achieve the desired product performance while maintaining the desired properties.

A study on the mechanical properties of recycled plasticized PVB (RPVB) and neat plasticized PVC was done by Michael and several researchers. The PVC is prepared in a Brabender internal mixer, and the temperature and ratio of blending are varied. Referring to **Figure 2.2**, the increment in recycled PVB ratio from 0% to 40% shows a drastic decrease in elongation at break and then started to increase slowly from 40% to 100% of recycled PVB. Considering the higher elongation at break, the

PVB/PVC blends have better properties when the PVB ratio is between 0% to 20%. The research has also stated that when the ratio of recycled PVB is above 60%, the mechanical properties become stable because it has become the main component in the blend (Tupý et al., 2014). The same concept can be applied back to PVC and sPVC blending, where SPVC that undergoes thermal and mechanical stress will affect the properties of the PVC/sPVC blend.

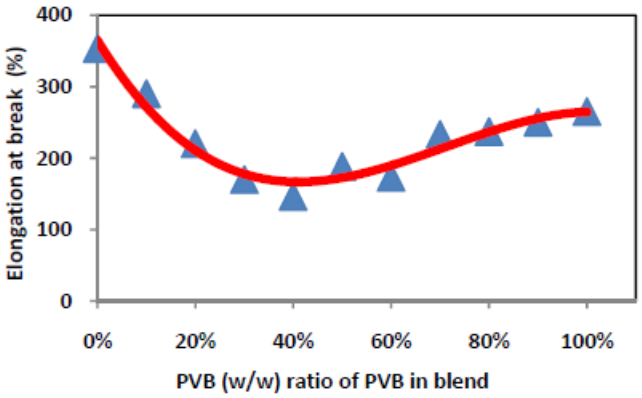

Figure 2.2: Elongation at Break of Various PVC/RPVB Blends (Tupý et al., 2014).

Besides that, the changes in temperature from 130 °C to 160 °C also affect the properties of the PVC/RPVB blend. The researchers stated that at 130°C to 140°C the PVC is not melted after 10 minutes of kneading. However, at process temperatures more than 160°C, the PVC can be easily melted (Tupý et al., 2014). At higher temperatures, more than 170°C, a slight polymer yellowing is observed. This is due to the thermal oxidative degradation caused by high temperature. At a 50/50 ratio blend, the effect of process temperature on the RPVB/PVC blend is also investigated. Referring to **Figure 2.3 (a) and (b)**, the tensile strength and elongation at break of 50/50 of RPVB/PVC are shown. The trend of the tensile strength and elongation both show an increasing trend and decrease significantly after 170°C. This further proves the statement that thermal oxidative degradation occurs after 170°C, causing a decrease in mechanical properties.

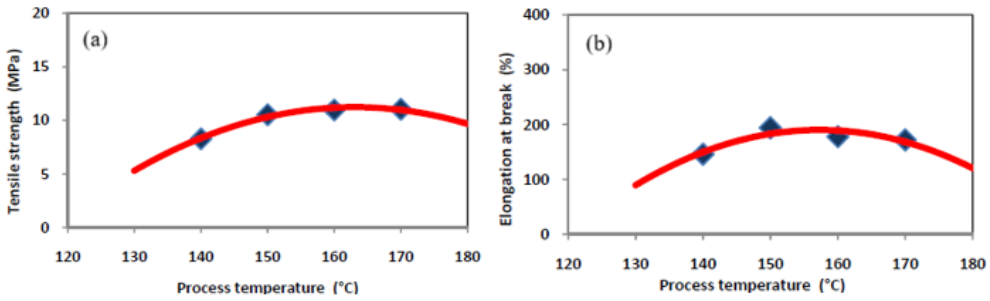

Figure 2.3: (a) Tensile Strength at Break and (b) Elongation at Break of 50/50 Blend in Various Temperatures (Tupý et al., 2014).

In addition, another study on the mixing of pipe-grade PVC and Recycled PVC (RPVC). The study investigates the blending of different ratios of VPVC and RPVC from chopped oil bottles (Popovska-Pavlovska et al., 2000). **Table 2.5** shows the blending ratio of VPVC/RPVC and the testing results. The results above show a slight decrement in mechanical properties, and Fredrick and others also stated that the blending properties still show acceptable mechanical properties until a 50/50 blending ratio. Although the main focus of the investigation is on Rigid PVC, the blending ratio of the PVCs can be referred to as a reference for the optimal point.

Table 2.5: Mechanical Properties of PVC/RPVC Blends (Popovska-Pavlovska et al., 2000).

VPVC/RPVC	E (MPa)	σ_y (MPa)	σ_r (MPa)	ε_r (MPa)
100/0	1400	27.2	22.7	312
90/10	1380	25.5	20.4	237
80/20	1370	21.2	19.5	227
70/30	1370	20.0	17.8	216
50/50	1320	19.5	17.5	210
0/100	1180	18.7	17.2	204

A study was done by Norazlina, Firdaus and Hafizuddin on the enhanced properties from mixing natural rubber (NR) with recycled polyvinyl chloride (RPVC)

by melt blending using a two-roll mill. The study aims to revalue the PVC by recycling it and mixing it with natural rubbers. Referring to **Table 2.6**, when the NR/RPVC blend is at the ratio 40/60, the blend achieves the highest hardness. However, the elongation at break and tensile strength tend to decrease as the RPVC ratio increases in the blend. On the other hand, when the RPVC ratio increases in the blend, the crystallisation temperature and melting temperature show an upward trend and peak at a 40/60 NR/RPVC ratio (Norazlina, Firdaus and Hafizuddin, 2015). Both results indicate that there is a trade-off between flexibility and thermal durability of the mixture. From this study, the ratio of PVC/sPVC blend can range from 80/20 to 40/60 to examine the change in mechanical properties caused by the ratio of blending.

Table 2.6: Mechanical Properties of NR/RPVC Samples (Norazlina, Firdaus and Hafizuddin, 2015).

NR/RPVC	Hardness (Shore A)	Elongation at Break (mm)	Tensile Strength (MPa)	Tensile Modulus (MPa)
100/0	10.8	349	20	1.9
80/20	22.3	380	24	2.0
60/40	32.5	153	24.5	4.7
40/60	49.5	87.8	20	8.6
20/80	33.3	17.5	18.4	8.8

Moreover, the study “From Recycled PVC and Its Blends to Eco-Friendly Materials for the Footwear Industry in Brazil” investigates the mechanical performance of blending virgin thermoplastic polyurethane (TPU) with RPVC. The blending is done through extrusion for each blending ratio from 100/0, 33/67, 50/50, 67.33, and 0/100 (wt%). Marsura et. al. stated that the blending of TPU/RPVC is optimum at 50/50, proven by the outstanding tensile strength for each 10%, 100% and 300% strain (Marsura et al., 2023). From the results obtained, Marsura et. al. also deduced that the best range of blending ratio for TPU/RPVC will be between 70/30 to 50/50.

The research papers provide insights into the mechanical properties of different blending ratios. The best optimal ratio after reviewing each study ranges between 80/20 to 40/60, which can possibly be applicable for PVC/sPVC blending. Even though some of the papers do not investigate the blending of plasticized PVC and sPVC, they also provide concepts on the mixing of PVC with recycled polymers or vice versa, as all of it involves the interaction of materials with differing mechanical properties.

2.3.3 Mixing Techniques

Polymer blending is a critical process in polymer engineering to obtain materials with desired mechanical, thermal, and chemical properties. Several blending techniques are mentioned in **Section 2.3.2**, including Brabender internal mixers, two-roll mills, and injection moulding. The technique involves combining two or more polymers, or a polymer with additives, to enhance performance or tailor characteristics for specific applications. Therefore, it is important to choose a suitable blending technique depending on the type of polymer, desired property, and production scale.

Internal mixers, such as Brabender or Banbury mixers, are widely used for melt blending of polymers. In this technique, the polymer is heated and mechanically sheared between rotors in a closed chamber to achieve homogeneity (Drobny, 2016). One major advantage of internal mixers is the excellent control over temperature, shear, and mixing time, which ensures uniform dispersion of fillers and additives (Drobny, 2016). They are suitable for small-to-medium scale lab and industrial applications. However, they have limited throughput compared to continuous processes and may require additional steps for shaping the final product. Therefore, internal mixers are most suitable for lab-scale production (batch process) as they provide good homogeneity and excellent control over processing parameters, ensuring accurate final products.

Two-roll mills consist of two counter-rotating rolls where polymers are sheared, spread, and compounded (Drobny, 2016). This method is commonly used for rubbers and some thermoplastics. Advantages include good control over mixing intensity and the ability to incorporate fillers and plasticizers efficiently, especially for sheet products. Additionally, it allows for continuous monitoring of the polymer sheet thickness. However, since it is an open system, the polymers are exposed to the environment, increasing the risk of contamination and oxidative degradation. It is also labour-intensive as the operator is required to manually feed and collect the materials to control the thickness, prevent air trapping and the formation of non-uniform sheets of polymers (Drobny, 2016). These disadvantage makes them less practical for large-scale blending of polymers.

Moreover, extrusion is a continuous process where the molten polymer is forced through a shaped die to produce profiles, sheets, or tubes (Drobny, 2014). It provides good dispersion due to the high shear applied to the melted polymer through the screw in the extruder and is suitable for high-volume production. However, extrusion requires precise control of residence time, temperature, and screw speed to prevent thermal degradation of PVC/sPVC blends. It is also less flexible for small-scale production.

Lastly, focusing on the blending of PVC/sPVC, the internal mixer is a more preferred blending method for lab-scale processing due to its precise parameter control and uniform blending. Although it can only process in batches with a small amount of blending, it is still able to produce enough final product for lab testing purposes.

2.4 Property Evaluation of PVC Blends

The evaluation of material properties is a fundamental aspect of understanding the performance and suitability of polymers for specific applications. In the context of PVC and its blends, property analysis offers critical insights into the mechanical, thermal, and chemical behaviours that directly influence the processing, durability,

and end-use performance of products such as bathroom mats. Accurate characterisation of these properties enables researchers to assess the effects of blending PVC with sPVC, the incorporation of additives, and the impact of processing techniques on the final material's performance.

2.4.1 Mechanical Properties

Mechanical properties, such as tensile strength, elongation at break, and hardness, are commonly evaluated to determine the polymer's resistance to deformation, wear, and stress during usage. These properties are particularly important for PVC bathroom mats, which are exposed to repetitive stress, moisture, and abrasion. Therefore, evaluations are done to have a quick view of the mechanical properties of PVC/sPVC blends.

Firstly, from the research paper "Rheological behaviour of PVC/RPVC blends", the mechanical properties are evaluated on different blending ratios of PVC and RPVC from chopped oil bottles (Popovska-Pavlovska et al., 2000). Referring to **Figure 2.4**, When the PVC/RPVC ratio is at 100/0, which is neat PVC, the tensile stress is 27.2 MPa. When the RPVC ratio increases from 0 to 50, the tensile stress decreases to 19.5 MPa. Additionally, the elongation at break at a 100/0 PVC/RPVC ratio is 312%. As the RPVC ratio increases, the elongation at break eventually decreases, and at a 50/50 PVC/RPVC ratio, the elongation at break is 210%. The incorporation of recycled PVC into PVC has a negative effect on the mechanical properties of the final product. As the proportion of RPVC increases, both tensile stress and elongation at break decrease, indicating that the material becomes weaker and less ductile.

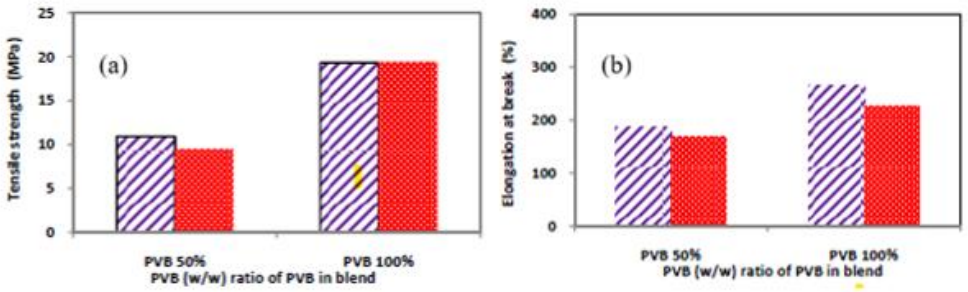

Figure 2.4: (a) Tensile Strength and (b) Elongation at Break for 50/50 PVC/RPVC (dotted), 50/50 PVC/PVB (dashed) Blend, 100% PVB (dashed) and 100% RPVC (dotted) (Tupý et al., 2014).

The results presented in **Figures 2.4 (a) and (b)** provide a comparison of the tensile strength and elongation at break between original and recycled polyvinyl butyral (RPVB), both used individually and in blends with polyvinyl chloride (PVC) in a 1:1 ratio. In terms of tensile strength, **Figure 2.4 (a)** shows the tensile strength for both the original and RPVB when blended with PVC. For the 50% RPVB blend, the tensile strength of the RPVB blend is clearly lower than that of the original PVB blend. However, it is observed in the 100% PVB samples, where the tensile strength of 100% recycled PVB is the same when compared to its 100% original PVB. On the other hand, the elongation at break shows a clear distinction between the two materials. The recycled PVB demonstrates a notable reduction in elongation when compared with the original PVB for 50% blend and 100% PVB, suggesting that the recycled material is less ductile and more prone to fracture under strain. Although the material blending is PVC/RPVB instead of PVC/RPVC, it still provides the concept of a decrease in mechanical properties when the ratio of recycled materials increases.

Besides that, a study by Norazlina et al. on the topic “Enhanced Properties from Mixing Natural Rubber with Recycled Polyvinyl Chloride by Melt Blending” evaluated the mechanical properties, as shown in **Table 2.6**. In terms of hardness, there is a clear increasing trend as the proportion of RPVC rises. Pure NR exhibits the lowest hardness (10.8 Shore A), while hardness steadily increases with higher RPVC content, reaching 49.5 Shore A at 40/60 and maintaining a relatively high value (33.3) even at 20/80. This indicates that RPVC contributes rigidity and resistance to indentation, counteracting the soft and elastic nature of NR.

The elongation at break shows the opposite trend. Pure NR has a very high elongation (349 mm), which increases slightly in the 80/20 blend (380 mm), suggesting some compatibility at lower PVC loadings. However, as RPVC content increases further, elongation drops drastically from 153 mm at 60/40, 87.8 mm at 40/60, and only 17.5 mm at 20/80. This sharp decline reflects the reduced elasticity and chain mobility caused by the higher RPVC fraction, which makes the blends more brittle and less capable of sustaining deformation before breaking.

For tensile strength, the effect is more complex. Pure NR shows moderate tensile strength (20 MPa), and the tensile strength increases until RPVC content is increased up to 60%, where the maximum tensile strength of 24.5 MPa is observed (Norazlina, Firdaus and Hafizuddin, 2015). This suggests some reinforcement effect due to PVC's rigidity at intermediate ratios. However, at higher PVC contents (40/60 and 20/80), tensile strength declines again to around 20 and 18.4 MPa, respectively. This drop indicates that excessive r-PVC reduces the balance between strength and flexibility, leading to embrittlement.

This review section refers to the study "From recycled PVC and its blends to eco-friendly materials for the footwear industry in Brazil: Insight into the process and evaluation of the mechanical properties.". The paper compares thermoplastic polyurethane (TPU), virgin PVC (PVC), recycled PVC (RPVC), and their blends across composition.

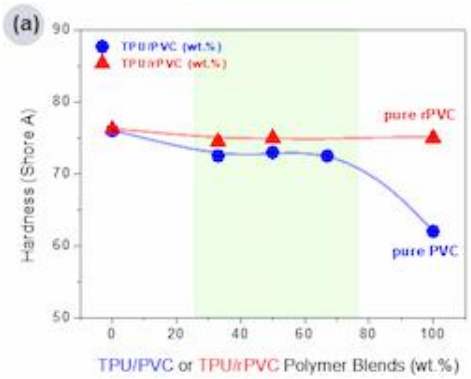

Figure 2.5: Shore A Hardness of TPU/PVC Blends and TPU/RPVC Blends (Marsura et al., 2023).

Referring to **Figure 2.5**, the Shore A hardness of TPU/PVC blends exhibits a distinctly non-linear trend with composition. Adding a small fraction of PVC to TPU results in only a slight decrease in hardness, and from TPU-rich compositions down to approximately TPU/PVC 67/33 (wt.%), the hardness remains nearly constant. Beyond this composition, the matrix of the polymer blend becomes PVC-dominated. Therefore, the hardness drops sharply toward the lower value of pure PVC.

In contrast, RPVC is inherently harder than virgin PVC. TPU/RPVC maintains an almost similar hardness of 74 - 76 Shore A across the series. The study attributes the higher RPVC hardness primarily to reprocessing effects, which is the thermal history that reduces molar mass via chain scission and promotes plasticiser loss, leading to limited chain mobility and increased stiffness. The practical consequence is that TPU/RPVC blends can match the hardness of pure TPU over a wide composition window, offering designers a robust hardness target without tight composition control.

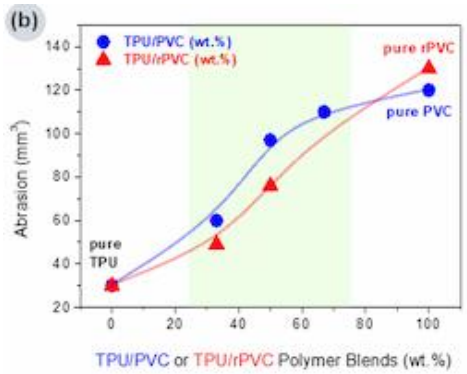

Figure 2.6: Abrasion of TPU/PVC Blends and TPU/RPVC Blends (Marsura et al., 2023).

In the abrasion test of this study, increasing TPU content systematically improves abrasion resistance for both blends (PVC and RPVC). At similar compositions, blends made with PVC exhibit approximately 10% better abrasion resistance than those with RPVC, as shown in **Figure 2.6**. In addition, pure RPVC has a higher volume loss than pure PVC. This is caused by reprocessing-induced degradation that diminishes resistance to micro-cutting and fatigue wear despite higher hardness.

Overall, the addition of recycled polymers will cause a decrease in mechanical properties. This is caused by thermos-oxidative and shear-induced chain scission, leading to a shorter chain. This chain degradation will lead to poorer processability and lower mechanical properties. Relating the literature to the PVC/sPVC blending, the increase in sPVC can lead to a reduction in the mechanical properties of the final product.

2.4.2 Thermal Properties

The thermal properties of natural rubber (NR) and recycled polyvinyl chloride (RPVC) blends, as presented in **Table 2.7**, reveal the impact of RPVC incorporation on the glass transition temperature (T_g), crystallisation temperature (T_c), and melting point (T_m) of the composites. Referring to **Table 2.7**, it shows that T_g remains relatively stable across all compositions, ranging narrowly from -60.98°C to -63.80°C. This indicates that the addition of r-PVC does not significantly affect the mobility of polymer chains within the NR matrix (Norazlina, Firdaus and Hafizuddin, 2015). This behaviour is expected because NR is amorphous and highly flexible, while PVC has a much higher T_g (around 80°C), meaning that recycled PVC exerts minimal influence on the T_g of NR at the molecular level.

In contrast, the crystallisation temperature (T_c) increases noticeably with higher r-PVC content. Pure NR exhibits the lowest Tc at 198.08°C, while the 40/60 blend reaches 286.84°C. This rise is attributed to the presence of r-PVC, which acts as nucleating sites and restricts the chain mobility of NR, thereby raising the crystallisation temperature. However, at very high r-PVC content (20/80 blend), Tc slightly decreases to 272.40°C, likely due to phase separation and aggregation of PVC domains, which reduces compatibility and uniform crystallisation within the matrix. Similar effects have been reported in polymer blend systems where excessive filler or secondary polymer disrupts efficient chain packing.

The melting point (T_m) also shows the effect of the varying r-PVC loading. Pure NR has a Tm of 377.08°C, which initially decreases at 80/20 and 60/40

compositions, which is 340.57°C and 360.17°C, respectively. Subsequently, the 40/60 blend exhibits the highest Tm at 416.20°C, highlighting the stabilising and fire-resistant nature of PVC at this ratio. This suggests that an intermediate PVC content enhances thermal stability by reinforcing the NR matrix and reducing molecular mobility (Norazlina, Firdaus and Hafizuddin, 2015). At 20/80 loading, however, Tm drops again to 333.35°C, which can be explained by poor interfacial compatibility and aggregation, reducing the effectiveness of PVC reinforcement. These non-linear variations in T_m are typical in heterogeneous polymer blends, where miscibility plays a critical role.

Overall, the DSC analysis confirms that T_g is unaffected by PVC loading, but T_c and T_m are strongly dependent on the blend ratio. Moderate PVC incorporation improves crystallisation and enhances thermal stability, while excessive PVC leads to phase incompatibility, aggregation, and a decline in thermal performance. This balance between reinforcement and compatibility is crucial for optimizing NR/PVC blends for practical applications where both flexibility and thermal resistance are required.

Table 2.7: Thermal Properties of NR/RPVC Blends (Norazlina, Firdaus and Hafizuddin, 2015).

NR/RPVC	Glass Transition, T_g (°C)	Crystallization Temperature, T_c (°C)	Melting Point, T_m (°C)
100/0	-60.98	198.08	377.08
80/20	-61.46	266.51	340.57
60/40	-62.33	270.51	360.17
40/60	-62.03	286.84	416.20
20/80	-63.80	272.40	333.35

From the study, “From recycled PVC and its blends to eco-friendly materials for the footwear industry in Brazil: Insight into the process and evaluation of the mechanical properties”, TGA has been done, and the thermal properties are evaluated. All compositions decompose in four steps, starting from a small loss at 100 - 145°C, a dominant loss of 79% of mass across 145 - 367°C, then additional losses over 365 -

480°C and 480 - 530°C. In TPU/PVC, the curves largely follow PVC around 250°C and 390°C, and the blends show poor miscibility as each component shows individual thermal response. In TPU/rPVC, the temperature of maximum degradation shifts to lower values as PVC/rPVC content increases due to the extra interaction with TPU, as stated by the author.

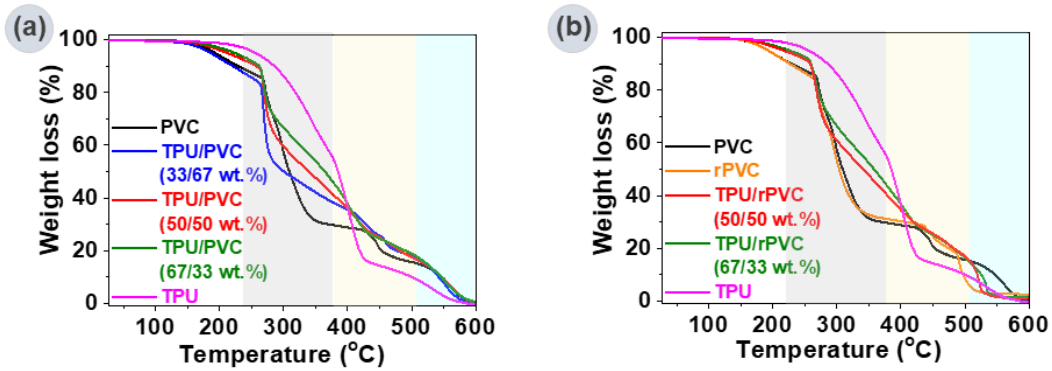

Figure 2.7: TGA Results of PVC and TPU Blends (Marsura et al., 2023).

In conclusion, for NR/r-PVC blends, DSC results show that the glass transition temperature (T_g) remains essentially unchanged, since it is governed by the NR phase. However, the crystallisation (T_c) and melting (T_m) temperatures shift in a non-linear way: moderate r-PVC content enhances crystallisation and thermal stability, whereas excessive r-PVC leads to phase separation, reducing T_c and T_m. Similarly, TGA of TPU/r-PVC blends confirms that PVC largely controls the degradation behaviour, with multi-step weight loss. Increasing r-PVC content shifts maximum degradation to lower temperatures due to residual defects and additives, and weaker miscibility, though the presence of PVC improves flame resistance. Relating back to PVC/RPVC blends, the T_g is expected to remain stable, but thermal stability strongly depends on the r-PVC fraction and its associated impurities or additive residues. The best balance is usually achieved at intermediate r-PVC levels, provided stabilizers are refreshed, and good dispersion is obtained.

2.4.3 Water Absorption and Chemical Absorption

Water absorption in polymers is the uptake of water molecules into the polymer matrix when it is exposed to moisture, liquid water, or humid environments. It is typically measured as the percentage increase in weight of the polymer after being immersed in water for a defined period. Excessive water absorption can cause swelling, softening, reduced mechanical strength, and dimensional instability (SpecialChem, 2025). Over time, this can cause cracking, microstructural damage, and premature failure of the polymer, particularly in applications where the material is in constant contact with moisture.

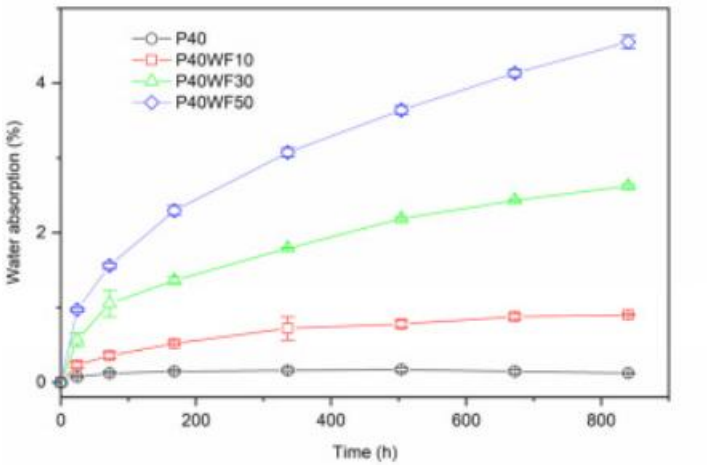

Figure 2.8: Water Absorption of Plasticised PVC/Wood (Lewandowski et al., 2024).

From the paper "Mechanical and Processing Properties of Plasticized PVC/Wood Composites", the water absorption was tested on pure PVC. The paper reports that pure plasticised PVC (P40) shows negligible water uptake, rising quickly at first and then slowing toward a diffusion-limited plateau, with just 0.12% absorption after 840 h of immersion at 22°C. When wood flour (WF) is introduced, it markedly increases moisture uptake because the hydrophilic cellulose and interfacial capillaries draw and transport water (Lewandowski et al., 2024).

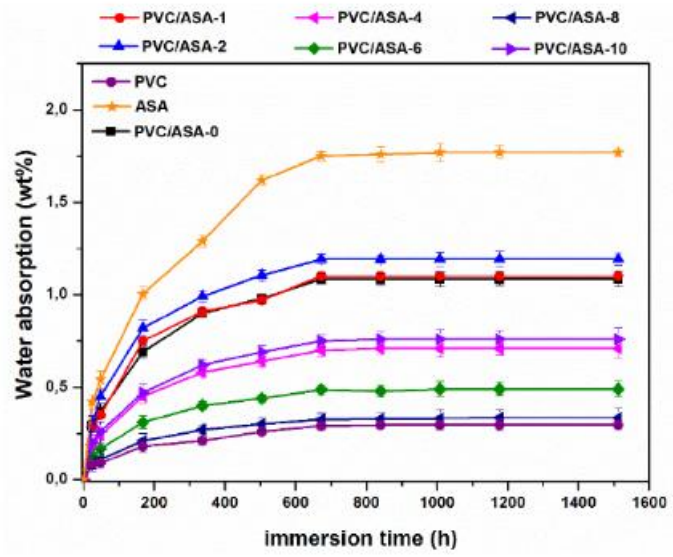

Figure 2.9: Water Absorption of PVC/Acrylonitrile Styrene Acrylate (ASA) (Lewandowski et al., 2024).

From the study, "Effect of o-MMT content on properties of Poly (vinyl chloride)/Poly (acrylonitrile styrene acrylate) blends", the authors measured uptake gravimetrically by letting it dry at 80 °C for 24 hours, weighing the PVC, then immersing it in distilled water and reweighing until a constant mass is obtained. Baselines show very low uptake for neat PVC (0.08 wt%) after 24 h and a higher value for the PVC/ASA (70/30) blend (0.29 wt%), where this high water absorption is attributed to the ASA phase's polarity, proven by the water absorption of pure ASA of (0.42 wt%) (KÖKÇAN and TAMER, 2020). These time-dependent curves reflect a fast initial gain that slows toward near-equilibrium, consistent with diffusion-limited sorption.

Besides that, by referring to the study of recycled polyvinyl chloride powder on the properties of cementitious composite, the water absorption is studied for the addition of RPVC powder to cementitious composite. The water absorption results for R-PVC-CC (Recycled PVC Cement Composite) highlight a trend of increased water absorption with higher RPVC aggregate content. The data indicate a 15% increase in absorption at a 50% replacement ratio, which is a significant rise (Lv et al., 2024). This increase can primarily be attributed to the higher porosity of the composite matrix, particularly in the cement paste. The study emphasizes that the

poor bonding between the hydrophobic PVC aggregates and the cement paste plays a crucial role in this behaviour.

When you consider PVC/sPVC blending, a similar trend might occur. The addition of sPVC in the blends can lead to poorer interfacial bonding between PVC. As a result, the polymer matrix may exhibit increased porosity and greater water absorption, especially in blends with higher RPVC content, much like what is observed with cementitious composites.

On the other hand, chemical absorption can also affect the properties of the PVC. Chemical absorption in polymers occurs when liquids such as acids, bases, solvents, or oils penetrate the polymer structure. For PVC, this is especially significant because plasticizers and stabilizers can migrate or leach out upon exposure, altering the polymer's mechanical and thermal properties. Excessive chemical absorption can cause swelling, softening, reduced hardness, and loss of elasticity, as plasticizers are removed from the polymer matrix (SpecialChem, 2025). Over time, this can lead to surface crazing, microcracks, and discolouration, ultimately compromising durability and safety.

The Plastex Chemical Resistance Statement outlines the chemical resistance properties of PVC, particularly in relation to the role of plasticisers. According to the document, PVC demonstrates excellent resistance to diluted acids and alkalis at room temperature, with minimal effects (Plastex, n.d.). However, when exposed to higher temperatures, there may be some hydrolysis of the plasticizer and extraction at elevated temperatures. If PVC is in continuous contact with solvents, the extracted plasticizer can be replaced by the solvent, maintaining some flexibility. However, once the solvent evaporates, the material stiffens and does not regain its original flexibility when re-immersed in the liquid. This underscores the significant impact that solvents and plasticizers can have on PVC's properties.

In conclusion, both water and chemical absorption are important factors to consider when blending VPVC and RPVC. The increased porosity in RPVC and the potential for plasticiser migration or poor interfacial bonding can lead to higher water and chemical absorption in the final blend. This understanding is crucial for

designing PVC/RPVC blends for applications that require low moisture uptake and high chemical resistance, particularly in harsh environmental conditions. Therefore, careful consideration of the RPVC content and plasticizer levels is essential for optimising the performance of PVC/RPVC blends in such applications.

2.4.4 Aging (Migration)

The migration of plasticisers from PVC materials was investigated in a study focused on environmentally friendly plasticizers synthesised from renewable sources like succinic acid, oleic acid, and propylene glycol. The test involved placing PVC samples that were plasticized with these synthesised plasticizers in contact with polyethene discs, which acted as absorbing materials. The migration was assessed over a period of seven days, during which the plasticiser that migrated from the PVC material into the absorbing material was measured. The results showed that the synthesised plasticisers exhibited excellent resistance to migration, with migration levels being significantly lower than those of commercial plasticizers such as DEHP and DINP. Specifically, the migration resistance of the synthesised plasticizers was found to be 70% better than DEHP and DINP (Ledniowska et al., 2022). This indicates that the new plasticizers not only provided comparable plasticization efficiency but also significantly reduced the potential for harmful leaching over time, making them a safer and more sustainable alternative to traditional plasticizers.

2.5 Case Studies on sPVC on Flooring and Matting Applications

sPVC has increasing applications in flooring and mat products due to its durability, cost-effectiveness, and environmental benefits. For instance, NoTrax produces industrial anti-slip mats made entirely from recycled PVC, which are widely used in commercial and industrial settings to provide safety and reduce fatigue in high-traffic areas. In the commercial vinyl flooring sector, Gerflor incorporates approximately 22% recycled PVC in its products, demonstrating that sustainable material

integration can coexist with high-performance flooring solutions in offices, schools, and healthcare facilities (Gerflor, 2023). Similarly, Tarkett utilizes up to 40% recycled materials in its vinyl floorings and emphasizes that these products are fully recyclable at the end of their service life, aligning with circular economy principles and promoting resource recovery (Tarkett, 2023). For floor matt application, Artsy Mats manufactures RPVC flooring mats and doormats, highlighting the feasibility of using recycled PVC in residential and decorative applications while maintaining functionality and aesthetic appeal (Artsy Mats, 2025). These examples illustrate that RPVC is effectively applied across a range of flooring and mat applications, from industrial safety solutions to commercial and domestic flooring products, underscoring its versatility and environmental value.

Although there are no publicly posted experimental results specifically for RPVC flooring or mats from these companies, their products are designed and manufactured according to recognized industry standards to ensure performance, durability, and safety. NoTrax industrial anti-slip mats, made entirely from recycled PVC, are designed following ASTM D2047 for slip resistance and undergo rigorous durability testing to withstand heavy foot and machinery traffic in industrial settings (NoTrax, 2023). In the commercial flooring sector, Gerflor incorporates approximately 22% recycled PVC in its vinyl floors, which are produced in compliance with EN 660-2 for abrasion resistance and EN 13893 for slip resistance, ensuring suitability for high-traffic commercial and healthcare environments (Gerflor, 2023).

In addition, Tarkett vinyl flooring, containing up to 40% recycled materials, is manufactured according to ISO 10582 / EN 649, with additional testing for recyclability through its ReStart program and indoor air quality compliance via ISO 16000 for VOC emissions (Tarkett, 2023). Lastly, Artsy Mats produces RPVC mats and doormats, claiming that their products are tested for durability, flexibility, and resistance to wear in residential and decorative settings, though detailed test results are not publicly available (Artsy Mats, 2025). These companies demonstrate that even in the absence of publicly posted product testing data, RPVC mats and flooring are developed in accordance with recognized durability, safety, and environmental

standards, ensuring reliable performance across industrial, commercial, and residential applications.

2.6 Gaps and Limitation

The blending of PVC and sPVC plays a crucial role in determining the final properties of flexible PVC products, such as bathroom mats. PVC contains fresh plasticizers and stabilizers that provide optimum flexibility, tensile strength, and processability, while sPVC often experiences partial plasticizer loss, chain scission, and degradation due to previous processing and thermal history. When PVC is blended with sPVC, migration of plasticizers from PVC domains to sPVC domains can partially restore flexibility and improve the homogeneity of the blend. However, incomplete mixing or insufficient plasticizer migration may result in localized stiffness, heterogeneous mechanical properties, and reduced elongation at break, reflecting one of the main limitations in recycling post-consumer PVC products. Flexible PVC waste from bathroom mats is particularly challenging to reuse due to contamination from household use, residual moisture, and the presence of additives that may degrade during processing.

Research opportunities exist in addressing these issues through improved blend compatibility and processing strategies. While incorporating sPVC into new mats reduces production cost and environmental burden, the variability in plasticizer content and prior thermal exposure limits the consistency of mechanical and thermal properties in the final product. For instance, hardness and thermal stability can vary non-linearly depending on the PVC/sPVC ratio and the efficiency of mixing, which may compromise the durability and flexibility required for bathroom mat applications. The use of compatibilizers, tailored plasticizers, and stabilizers can enhance interfacial adhesion and reduce phase separation, while optimising laboratory-scale mixing techniques, such as internal mixing, can provide better parameter control for consistent mechanical and thermal properties. Additionally, replenishment of lost additives and careful control of processing conditions could

restore flexibility and durability, making recycled blends more suitable for bathroom mat applications.

Beyond material performance, studies can explore environmental sustainability and life-cycle assessments, evaluating the energy efficiency, carbon footprint, and recyclability of PVC/sPVC mats. Finally, developing standardized testing protocols for hardness, elongation, water resistance, and chemical resistance can ensure that recycled mats meet performance benchmarks comparable to virgin PVC products, supporting a more circular and sustainable use of PVC in household applications.

2.7 Summary of Literature Review

This literature review has reviewed the structure, applications, and recycling importance of polyvinyl chloride (PVC), with a focus on its potential use in bathroom mats. PVC is a versatile polymer that exists in rigid and flexible forms, while rigid PVC is dominant in construction, whereas flexible PVC, produced by incorporating plasticizers, is widely applied in consumer goods such as mats and flooring. Its wide application of use makes recycling critical for reducing landfill burden and minimising environmental impacts such as dioxin release during disposal.

PVC degradation occurs through several pathways, including dehydrochlorination, UV-induced breakdown, oxidative degradation, and mechanical degradation. These processes reduce strength, elasticity, and durability, especially when it is exposed to moisture-rich, high-use environments like bathrooms or any other outdoor application. Additives such as plasticizers, stabilizers, fillers, lubricants, antioxidants, UV absorbers, flame retardants and pigments play a central role in tailoring PVC's performance and prevent degradation, but they also complicate recycling due to variability and potential migration during service life.

In addition, processing methods such as extrusion, calendaring, and internal mixing enable PVC to be formed into sheets and products, with extrusion and

calendaring most relevant for bathroom mats. Blending of PVC/sPVC offers both economic and sustainability benefits. However, the blending ratio strongly influences performance. Studies suggest that ratios between 80/20 and 40/60 PVC/sPVC can retain acceptable mechanical properties, while excessive RPVC reduces tensile strength and elongation. Processing temperature is equally critical. From the study above, stable properties of PVC are achieved around 170°C, but higher temperatures trigger oxidative degradation and loss of strength.

To have a better view of the properties of the PVC/sPVC blend, property evaluations from other studies are referred to in this literature review. It can be confirmed that increasing sPVC content generally lowers tensile strength and ductility, though hardness may rise. Thermal studies show that glass transition is unaffected, but crystallisation and melting behaviour shift non-linearly with sPVC content. Water and chemical absorption tests indicate higher uptake with recycled content due to porosity and additive migration. SEM analysis further reveals phase separation in blends, highlighting challenges in interfacial compatibility.

Overall, blending PVC with sPVC demonstrates potential for sustainable bathroom mat production but faces limitations in consistency, durability, and chemical resistance. Contamination and additive loss in post-consumer sPVC remain barriers to large-scale application, and there is limited research specifically addressing bathroom mat waste streams. Future studies should focus on optimising blending ratios, improving processing control, and applying compatibilizers or additive replenishment to enhance performance while meeting sustainability goals.

Focusing back to the objective of this experiment, the literature review can provide some insight into the design of the experimental plan. Firstly, the blending ratio that is deduced for PVC/sPVC is between 80/20 to 40/60. However, the PVC blend used in the studies is different from the source of PVC used in this experiment. Therefore, it is recommended to test the PVC/sPVC blend in a larger range, for example, 100/0, 75/25, 50/50, 25/75, 0/100. Moreover, the blending techniques that are more suitable for this experiment are deduced to be the internal mixer. This is because the internal mixer shows a better compatibility for lab-scale production when compared to the extruder and provides better homogeneity by mixing in a

closed chamber rather than exposing the polymers to external environments. Lastly, the temperature that will be selected for processing will be 165°C and 175°C. These temperatures are deduced to investigate the performance of PVC blends above the optimal temperature obtained from the literature review.

CHAPTER 3

METHODOLOGY

3.1 Materials

The two main materials used for the research are the PVC pellets was supplied by Hsing Lung Sdn. Bhd. Malaysia, the specification sheet is shown in **Table 3.1**, and the sPVC obtained from CY Handee Rubber Moulding Sdn. Bhd. Malaysia as the industrial scrap from anti-slip bathroom mat production. Besides that, rigid PVC sheets, distilled water, and toluene from Sigma Aldrich (≥ 99.5%) will be used during testing and characterization.

Table 3.1: Specification Sheet of PVC Pellets Provided By Hsing Lung Sdn. Bhd.

Physical Description	Test Method	Specification	Test Results
Appearance	Visual	Smooth surface	Pass
Form	Visual	Granular	Pass
Tensile Strength (N/mm^2)	ASTM D-638	Min 8.5	12.6
Elongation at Break (%)	ASTM D-638	Min 400%	438%
Specific Gravity (g/cc)	ASTM D-792	1.16 ± 0.03	1.16
Hardness (Shore A)	JIS K 7215	57 ± 3	57

3.2 Preparation of Virgin PVC/Scrap PVC Blend

3.2.1 Preliminary

In the preliminary phase of the study, the blending ratio of PVC and sPVC was fixed at 50/50, with a total mass of 55 g for each blend. The primary objective of this phase was to assess the effect of varying processing temperatures on the blend's processability and overall properties. Four different processing temperatures, 165°C, 170°C, 175°C, and 180°C, were applied during the mixing process.

The blending of PVC and sPVC was carried out using a Brabender internal mixer (Plastograph EC 815652, Brabender GmbH & Co. KG, Germany), as shown in **Figure 3.1**, with the rotor speed set at 60 rpm to maintain consistency throughout the blending procedure. Both PVC and sPVC were introduced into the internal mixer simultaneously to ensure an even distribution of the components.

Figure 3.1: Brabender Internal Mixer (Plastograph EC 815652, Brabender GmbH & Co. KG, Germany).

During the mixing process, processing torque values were continuously monitored and recorded. These values served as key indicators of the blend's processability, providing insight into how the materials interacted under different temperature conditions. The entire mixing process was conducted for a period of 4

minutes, after which the blend was carefully removed from the internal mixer chamber.

Once removed, the blend was allowed to cool to room temperature. Special care was taken during this cooling phase to prevent any contamination from external particles, ensuring that the final blend retained its integrity for subsequent testing. This phase provided valuable data on the optimal processing conditions for the PVC/sPVC blends and set the foundation for the subsequent experimental phases.

The blended compounds from the internal mixer were converted into 1.0 mm sheets using a hydraulic moulding press (GOTECH GT-7014-H, GOTECH Testing Machines Inc., Taiwan) as shown in **Figure 3.2**. The sheet preparation process involved a three-stage cycle. Initially, the machine was pre-heated to 175°C for 8 minutes without applying pressure, allowing the compound to soften. Following this, the PVC/sPVC blends were hot-pressed at 175°C for 4 minutes under pressure to ensure the mould was fully filled. Finally, the compound was cold-pressed for 3 minutes with chilled-water circulation at 2°C, a step aimed at minimizing warpage and shrinkage. This process was repeated as necessary to prepare sufficient sheets for all subsequent tests.

Figure 3.2: Hydraulic Moulding Press (GOTECH GT-7014-H, GOTECH Testing Machines Inc., Taiwan).

3.2.2 Preparation of PVC/sPVC Blend at Optimized Temperature

In the next phase, the preparation of PVC/sPVC blends at the optimized temperatures was conducted. With the two selected optimized temperatures, the PVC/sPVC blend ratio was varied at different levels, specifically (100/0, 75/25, 50/50, 25/75, and 0/100). These variations were mixed using the internal mixer at a consistent rotor speed of 60 rpm. The entire mixing process was conducted for a period of 4 minutes, after which the blend was carefully removed from the internal mixer chamber. The process aimed to assess the impact of different blend ratios at the optimized processing temperatures on the overall properties of the blends.

Following the preparation of the PVC/sPVC blends at the optimized temperatures, the blends were compressed into 1.0 mm thin sheets using a hydraulic moulding press. The same three-stage cycle, as described previously, was applied to ensure uniform sheet formation. The machine was initially pre-heated to the appropriate temperature for 8 minutes without pressure to soften the compound. Then, the PVC/sPVC blends were hot-pressed at the optimized temperature for 4 minutes under pressure to fill the mould. Finally, the blend was cold-pressed for 3 minutes with chilled-water circulation at 2°C to minimize warpage and shrinkage. This process was repeated as necessary to produce sufficient sheets for further testing and analysis.

3.3 Characterization and Testing

3.3.1 Fourier Transform Infrared Spectroscopy (FTIR)

Chemical fingerprints of PVC, RPVC and all blends were collected by ATR-FTIR (diamond ATR). Spectra were recorded from 4000-600 cm^{-1} at 4 cm^{-1} resolution with 32 scans per specimen. Key PVC backbone bands and plasticiser/stabiliser peaks were used to confirm composition prior to property testing. Each spectrum was baseline-corrected and normalised for comparison.

3.3.2 Density Test

Each PVC sheet is cut into small rectangular pieces (1 cm × 1 cm). The initial mass of each sample was measured with the Precisa density determination kit, as shown in **Figure 3.3**. The sample is then put into the water medium in the density tester, where the density of the medium is set. The density will then be obtained from the density tested, and the results are recorded.

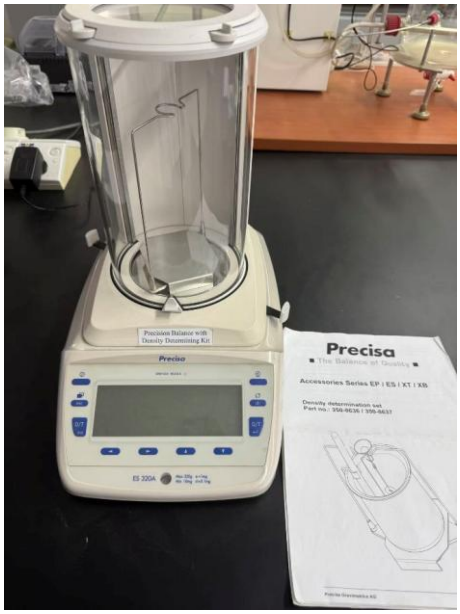

Figure 3.3: Precisa Density Determination Kit.

3.3.3 Water Absorption

Water uptake was evaluated following ASTM D570. Dumbbell shaped specimens were oven-dried at 60°C for 2 h, cooled in a desiccator, and weighed to obtain the conditioned mass. Samples were then immersed in distilled water at room temperature for 72 h. After 72 h, specimens were removed, gently patted dry with a lint-free cloth, and weighed (wet mass). The formula is shown below:

$$Water\ absorption\ (\%) = \frac{Wet\ mass - Conditioned\ mass}{Conditioned\ mass} \times 100\% \qquad (3.1)$$

3.3.4 Chemical Absorption

Chemical absorption was evaluated following ISO 175. Dumbbell specimens were oven-dried at 60 °C for 2 h, cooled in a desiccator, and weighed to obtain the conditioned mass. Samples were then immersed in toluene at room temperature for 72 h. After 72 h, specimens were removed, gently patted dry with a lint-free cloth, and weighed (wet mass). The formula for chemical absorption is similar to the water absorption and is shown below:

$$Chemical\ absorption\ (\%) = \frac{Wet\ mass - Conditioned\ mass}{Conditioned\ mass} \times 100\% \quad (3.2)$$

3.3.5 Thermogravimetric Analysis (TGA)

The PVC sheets were then sent to the Mettler Toledo TGA/DSC 3+, as shown in **Figure 3.4**, for thermogravimetric analysis (TGA) to determine their thermal stability and degradation behavior. The TGA analysis was conducted to evaluate the weight loss of the PVC/sPVC blends as a function of temperature, providing insights into the materials' thermal resistance and the decomposition temperatures of the components. This data is essential for understanding the thermal performance of the blends and identifying any potential issues related to stability under elevated temperature conditions.

Figure 3.4: Mettler Toledo TGA/DSC 3+.

3.3.6 Tensile Test

Uniaxial tensile properties were measured in accordance with ASTM D638. Type-V dog-bone specimens were die-cut from 1.0 mm sheets. Tests were performed on a Tinius Olsen H10KS universal tester (Leader Technology Scientific, Malaysia) with a 500 N load cell and a crosshead speed of 50 mm min^{-1}, as shown in **Figure 3.5**. For each composition and processing temperature, five replicates were tested, and the average ultimate tensile strength, elastic modulus, and elongation at break were reported. Fracture surfaces from representative broken specimens were retained for SEM purposes.

Figure 3.5: Tinius Olsen H10KS Universal Tester.

3.3.7 Scanning Electron Microscopy (SEM)

Microstructures were examined using Field Emission Scanning Electron Microscopy (FESEM) model JOEL JSM 6701F supplied by JOEL, USA. Inc. at various magnifications. Fracture surfaces from tensile specimens are used as the sample for SEM analysis. Three selected regions were analysed to correlate morphological features with mechanical behaviour.

3.3.8 Hardness Test

Indentation hardness was determined using a Shore A durometer in accordance with ASTM D2240 (Type A). To reach the minimum thickness requirement (≥ 3 mm), sheets were stacked when necessary. Five readings were taken at different locations on each sample and averaged.

3.3.9 Migration Test

Sheets from each formulation were cut into flat rectangular and the initial mass of each sample was measured. Then, the dry, rigid PVC sheets were prepared as receptor surfaces. The samples were sandwiched between the two dry PVC sheets, and a constant compressive load was applied to ensure intimate, uniform contact across both faces of the specimen. Assemblies were placed in a forced-air oven at 60°C for 32 days. After 32 days, the samples were removed from the oven, and the mass of the sample was measured again. Migration percentage was calculated by the formula below:

$$Migration\ (\%) = \frac{Final\ mass - Initial\ mass}{Initial\ mass} \times 100\% \qquad (3.3)$$

3.4 Procedure Flow Sheet

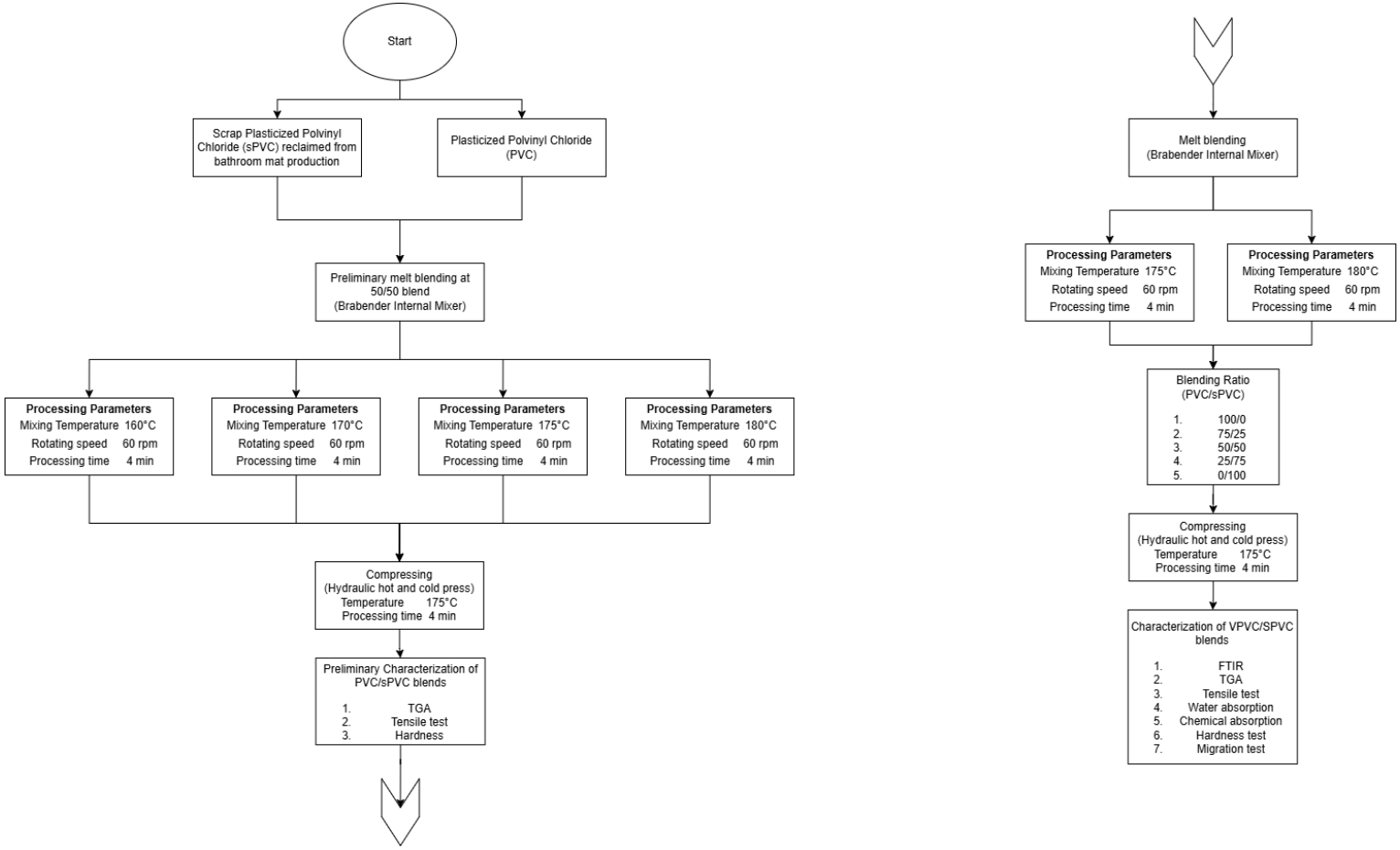

Figure 3.6: Procedure Flow Sheet.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Preliminary

4.1.1 Process Characterization

The processing characteristics of PVC and sPVC blends at a constant ratio of 50:50, as evaluated from the processing torques at different processing temperatures, are tabulated in **Table 4.1**. Loading torque refers to the peak frictional resistance when the solid polymer is discharged into the hopper, marking the highest torque before melting and fusion between PVC and sPVC begin. Stabilization torque, in contrast, represents the torque when the polymer is fully melted, and the mixture becomes homogeneous, indicating a well-mixed blend. Stabilization torque is typically lower than loading torque, signifying a consistent polymer blend essential for optimal material properties (Alias, Ismail and Ku Ishak, 2020). At 165°C, the material exhibits moderate resistance, giving a loading torque of 31.3 Nm and a stabilisation torque of 6.4 Nm. However, upon increasing the temperature to 170°C, the loading peak reaches its highest value at 44.6 Nm, accompanied by the highest recorded stabilisation torque of 6.5 Nm. These results suggest that at 170°C, the PVC and sPVC blend has a quick gelation, where the particles are sufficiently sticky to generate high friction but have not yet reached a fluid state that facilitates easy flow, leading to a higher loading torque (Tomaszewska et al., 2022).

At temperatures of 175°C and 180°C, a significant transition in the material's behaviour can be observed. The loading torque at 175°C decreases sharply to 25.5

Nm, and the stabilisation torque decrease to 4.1 Nm. This reduction in both torque marks the temperature as a critical point for the material's processing efficiency. While the loading torque rises slightly at 180°C, to 29.5 Nm, the stabilisation torque hits its lowest value of 4.0 Nm. This suggests that, although there is a minor increase in the loading torque, the overall melt behaviour becomes more stable and efficient at these higher temperatures.

The contrast between 165°C - 180°C is notable. While 165°C and 170°C are characterised by relatively high resistance and higher torque values throughout the processing cycle, temperatures of 175°C and 180°C facilitate a more efficient transition from solid loading to a stabilized melt. This indicates that at these higher temperatures, the thermal incorporation of scrap PVC into the virgin matrix is more effective, leading to better material homogeneity.

Table 4.1: Processing Torque of 50/50 Blending at Different Processing Temperatures.

Temperature (°C)	**Loading Torque (Nm)**	**Stabilisation Torque (Nm)**
165	31.3	6.4
170	44.6	6.5
175	25.5	4.1
180	29.5	4.0

In summary, 175°C and 180°C are identified as the most optimal processing temperatures for the PVC/sPVC blend. 175°C is preferred for its lowest loading torque performance, which indicates its low energy consumption for faster polymer melting and fusion at low torque. In contrast, 180°C is selected for its lowest and comparable stabilisation torque to 175°C. It signifies a low melt viscosity as desired for better processability and producing a homogeneous polymer melt with lower internal friction. The lowest torque values are crucial as they reflect optimal melt viscosity, allowing polymer chains to overcome intermolecular forces for a more homogeneous melt. Minimising torque not only improves thermal efficiency but also prevents excessive shear stress and local overheating, which can degrade or discolour

the material (Horechyy et al., 2026). Thus, 180°C ensures better processing with minimal energy consumption and reduced risk of degradation, leading to high-quality recycled plastic products.

In conclusion, the optimal processing temperatures for the 50/50 PVC/sPVC blend are identified as 175°C for its favourable loading peak and 180°C for its low stabilisation torque. These parameters not only optimize the material's thermal and mechanical processing efficiency but also contribute to the sustainability and quality of the final recycled product.

4.1.2 Mechanical Properties

Figure 4.1 represents the hardness values of the PVC/sPVC blends at different ratios of PVC:sPVC, comparable to the standard specification values desired for bathroom mat applications, which is a shore A hardness value between 70 - 90. Referring to **Table 4.2**, at 165°C and 170°C, the hardness values are below the required threshold. However, as the temperature increases to 175°C, the hardness increases above 70, indicating an improvement in the polymer's cohesion. The superior results observed at 175°C and 180°C, suggest that as the temperature increases, the fusion level improves, leading to a more cohesive polymer matrix. This enhanced fusion is particularly important for recycled blends, as it ensures that the sPVC is fully incorporated into the virgin matrix, thus eliminating voids caused by poor interaction that could compromise the hardness and overall material integrity (Zinatlou Ajabshir et al., 2026).

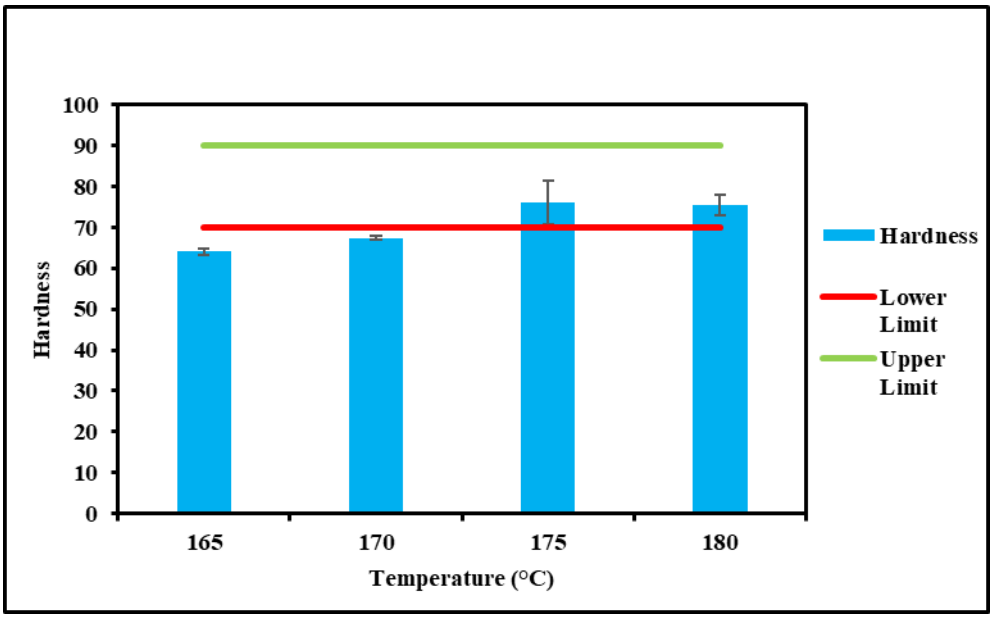

Figure 4.1: Hardness of PVC and sPVC Blends at a 50/50 Blend Ratio at Various Processing Temperatures.

Table 4.2: Hardness of PVC and sPVC Blends at a 50/50 Blend Ratio at Various Processing Temperatures.

Temperature (°C)	Hardness			Average Hardness	Standard Deviation (+/-)
	1	2	3		
165	64	63	65	64	0.8
170	68	67	67	67	0.5
175	70	75	83	76	5.4
180	76	72	78	75	2.5

The inability of the PVC/sPVC blends to reach the minimum hardness threshold at 165°C and 170°C further demonstrates that processing temperatures below 170°C do not facilitate adequate fusion between PVC and sPVC, making them unsuitable for optimal blending of these materials. Consequently, for a reliable recycling process, processing windows centred around 175°C to 180°C are preferred, as they maintain stable mechanical properties and ensure compliance with industry standards.

The consistently high ultimate tensile strength (UTS) values across all samples at various temperatures suggest that the 50/50 PVC/sPVC blend allows for effective molecular entanglement, as shown in **Table 4.3**. During the melting process, the polymer chains from the scrap PVC successfully diffuse into the virgin PVC matrix. This molecular interaction of polymer chains is critical in providing the material with the ability to resist being pulled apart under tension. Notably, even the lowest UTS value recorded (18.24 MPa) has shown well tensile properties above the 15 MPa threshold, when referring to **Figure 4.2**, reinforcing that the recycling process does not compromise the structural integrity of the PVC blend.

Table 4.3: UTS of PVC and sPVC Blends at a 50/50 Blend Ratio at Various Processing Temperatures.

Temperature	UTS (MPa)					Average
(°C)	1	2	3	4	5	(MPa)
165	18.42	19.57	19.40	17.34	18.18	18.58
170	20.42	19.96	20.38	20.08	20.45	20.26
175	17.31	19.26	18.02	18.39	18.22	18.24
180	21.21	18.47	18.95	17.20	18.15	18.79

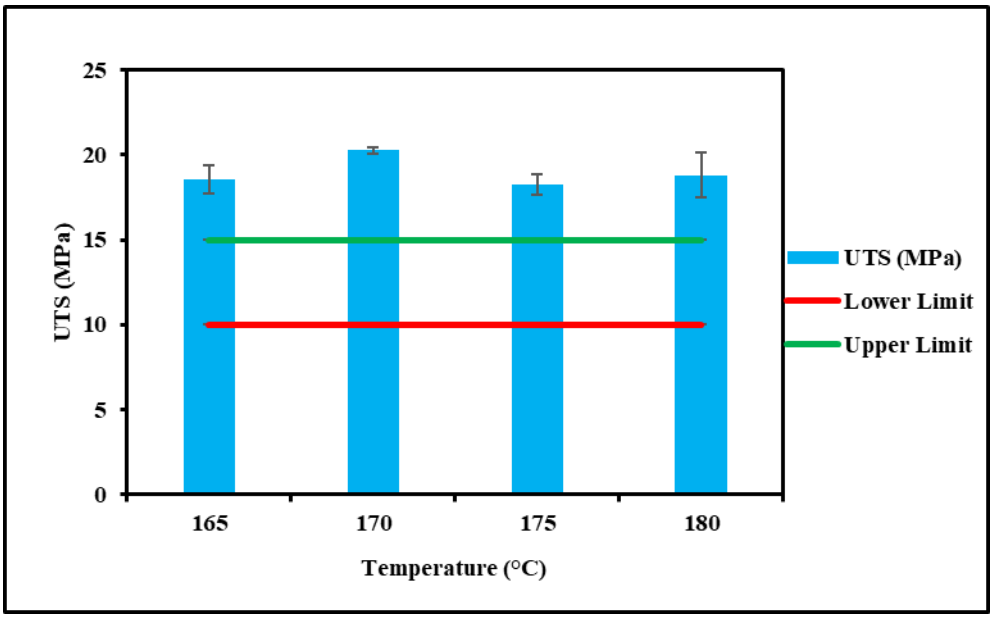

Figure 4.2: UTS of PVC and sPVC Blends at a 50/50 Blend Ratio at Various Processing Temperatures.

The consistency of these results, with ultimate tensile strength (UTS) values remaining within a narrow range of approximately 18 to 20 MPa, further highlights the robustness of the processing window for this blend. This finding is particularly significant for the project, as it indicates that minor fluctuations in processing temperature will not compromise the material's ability to meet its mechanical requirements. This stability offers flexibility in the recycling process, making the blend suitable for a range of applications while maintaining reliable mechanical performance. All four processing temperatures tested are deemed acceptable, as their average Ultimate Tensile Strength (UTS) values are higher than the desired standard specification values of 10-15 MPa.

The peak performance observed at 170°C suggests a good performance for UTS and elongation at break. At this temperature, it proves that the increase in elongation leads to a reduction in the stiffness of the material. Referring to **Table 4.4**, the slight decline in elongation values at 175°C and 180°C could be attributed to a higher degree of gelation or molecular entanglement. At higher processing temperatures, the polymer chains gain more kinetic energy, allowing them to move more freely and form a more uniform and integrated structure (Lion and Johlitz, 2026). This will cause more entangled polymer chains at higher temperatures. Therefore, their ability to slide freely over one another during stretching is slightly reduced, leading to a marginal decrease in elongation.

These results further demonstrate that the reprocessing or recycling of PVC effectively preserves the plasticizer efficiency. Since elongation is primarily influenced by plasticizers, which reduce intermolecular forces, the high elongation percentages recorded indicate that the scrap PVC used in this blend still contains active plasticising agents. These plasticizers are successfully integrated into the new matrix, ensuring that the blend maintains its ductile properties despite the incorporation of sPVC. All four processing temperatures studied, ranging from 165 °C to 180 °C are acceptable, with every sample comfortably exceeding the 100% minimum elongation requirement, as shown in **Figure 4.3**. The high elongation values, ranging from 317% to 359%, confirm that the inclusion of 50% sPVC does not influence the molecular structure and affect the flexibility of PVC.

Table 4.4: Elongation at Break of PVC and sPVC Blends at a 50/50 Blend Ratio at Various Processing Temperatures.

Temperature (°C)	Elongation at Break (%)					Average (%)
	1	2	3	4	5	
165	349.2	380.0	355.0	309.0	334.2	345.5
170	350.8	353.3	361.3	370.0	360.8	359.2
175	308.3	339.6	317.7	308.3	315.0	317.8
180	370.0	299.7	325.3	289.7	311.0	319.1

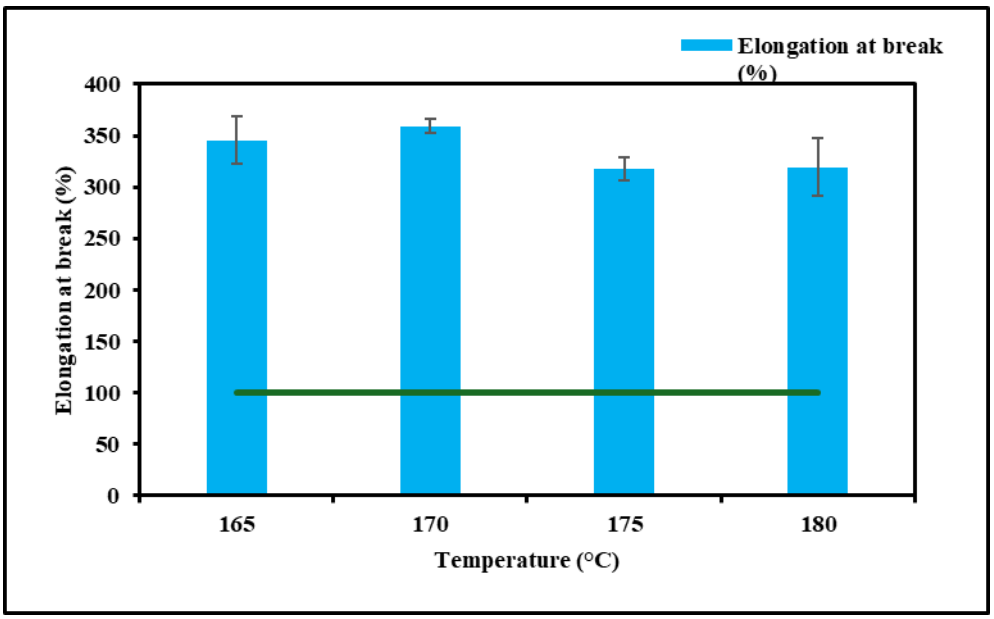

Figure 4.3: Elongation at Break of PVC and sPVC Blends at a 50/50 Blend Ratio at Various Processing Temperatures.

The increase in elastic modulus with temperature is directly related to the degree of gelation and fusion between the PVC and the sPVC. In a 50/50 blend, it is crucial that the scrap particles are fully integrated into a continuous matrix. Referring to **Table 4.5**, at 165°C, the elastic modulus is the lowest at 6.82. The low elastic modulus is caused by incomplete fusion, leaving voids or weakly bonded interfaces between the virgin and scrap phases. This is supported by the high loading torque, which indicates hard fusion between PVC and sPVC. These incomplete connections

allow the material to yield more easily under low stress, resulting in a lower modulus and reduced rigidity (Li and Chang, 2025).

As the temperature increases above 170°C, the polymer chains gain sufficient mobility to interpenetrate and form a more cohesive, dense network. This enhanced interfacial adhesion contributes to an increase in the material's stiffness. Based on these criteria, processing at 170°C, 175°C, and 180°C is considered acceptable, while 165°C is deemed insufficient for applications requiring this specific level of rigidity, as shown in **Figure 4.4**.

Table 4.5: Elastic Modulus of PVC and sPVC Blends at a 50/50 Blend Ratio at Various Processing Temperatures.

Temperature (°C)	Elastic Modulus (MPa)					Average (MPa)
	1	2	3	4	5	
165	6.62	6.28	6.75	7.46	6.99	6.82
170	7.49	7.39	7.18	7.19	7.36	7.32
175	8.23	7.41	7.39	7.75	7.95	7.75
180	7.41	8.06	7.76	8.09	7.65	7.79

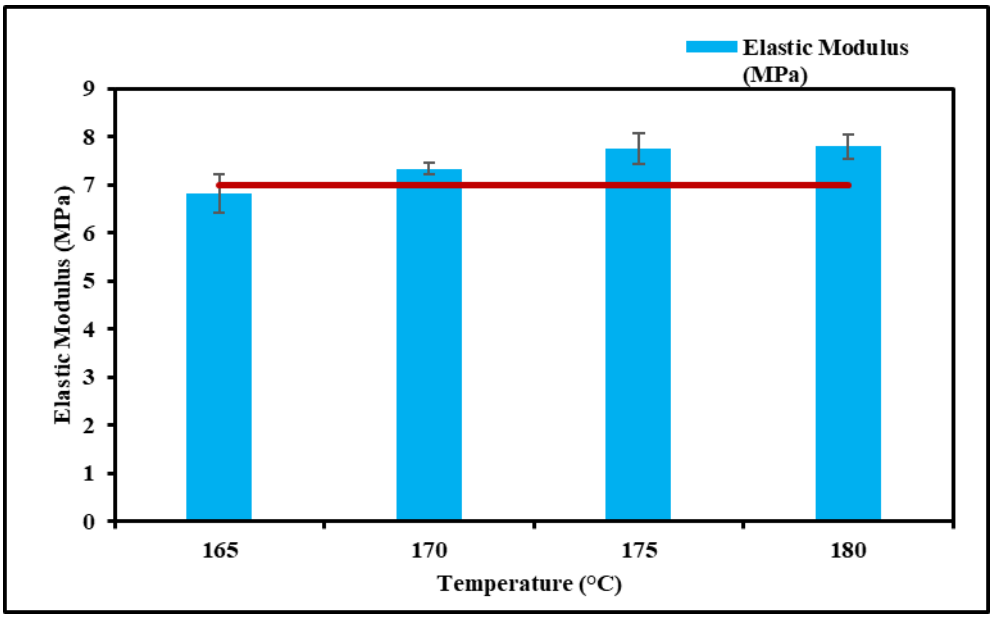

Figure 4.4: Elastic Modulus of PVC and sPVC Blends at a 50/50 Blend Ratio at Various Processing Temperatures.

4.1.3 Thermal Properties Analysis

The TGA of the raw materials reveals a distinct difference between PVC and sPVC, which can be attributed to the thermal history of the scrap material. Referring to **Table 4.6**, the sPVC exhibits a higher T50 value of 310.26°C, compared to 302.71°C for the virgin resin. This increase in the 50% mass loss temperature suggests that prior processing cycles may have led to the removal of more volatile, shorter polymer chains, leaving behind a more thermally resistant bulk structure (Sadat-Shojai and Bakhshandeh, 2011).

Table 4.6: Thermal Gravimetric Analysis of Raw PVC and sPVC.

Sample	T_{50} (°C)	Total Mass Loss at 900 °C (%)
PVC	302.71	94.70
sPVC	310.26	90.38

When evaluating the impact of different processing temperatures on the 50/50 blends, the temperature parameter effect on the blending is comparable, as shown in **Table 4.7**. This could be due to regional mixing between PVC and sPVC, which leads to insignificant thermal stability readings. At the lowest processing temperature of 165°C, the mass loss is significant at 0.52%. As the temperature rises to 170°C, the mass loss decreases to 0.26%, although the T_{50} value remains moderate. This trend demonstrates that at lower processing temperatures, PVC will not have enough kinetic energy, leading to a reduced mobility of the chain, causing incomplete fusion (Summers, 2005).

Therefore, the selection of 175°C and 180°C as optimal processing temperatures is supported by the significant improvements in both processing stability and final thermal robustness. Sample processed at 175°C, achieves the lowest mass loss at the processing temperature (0.14%) among all the blends, indicating that this temperature provides the cleanest and most stable processing window with minimal immediate degradation. On the other hand, sample processed at 180°C, yields the highest T_{50} value of 307.15°C, signifying that the resulting material has the greatest resistance to major thermal decomposition. By choosing the

175°C to 180°C range, it ensures that the material undergoes sufficient thermal treatment to minimize volatile emissions while maximising the thermal endurance of the final product, effectively overcoming the instability issues observed at 165°C and 170°C.

Table 4.7: Thermal Gravimetric Analysis of 50/50 PVC/sPVC Blends at Various Processing Temperatures.

Process Temperature (°C)	Temperature at 50% Mass Loss, T_{50} (°C)	Mass Loss at Process Temperature (%)	Total Mass Loss at 900°C (%)	Residual Weight
165	304.10	0.52	94.33	5.67
170	305.38	0.26	90.99	9.01
175	303.05	0.14	91.81	8.19
180	307.15	0.18	91.37	8.63

4.1.4 Selection of Process Temperature

Based on the integrated analysis of the processing torque, mechanical performance and thermal properties of the 50/50 PVC and sPVC blends, the justification for selecting 175°C and 180°C as the optimal experimental temperatures becomes clear. From a processing standpoint, these two temperatures exhibited the most efficient rheological behaviour. Specifically, 175°C yielded the lowest loading peak, while 180°C achieved the lowest stabilisation torque. This reduction in torque suggests a significant decrease in melt viscosity, which minimizes mechanical wear on the equipment and reduces energy consumption. In contrast, the lower temperatures (165°C and 170°C) exhibited higher resistance and torque instability, indicating that the thermal energy provided was insufficient to overcome the internal friction of the polymer chains, leading to a more difficult and less efficient mixing process.

The mechanical evaluation further supports the selection of the higher temperature range, as 175°C and 180°C were the only conditions that met all

industrial criteria. While all samples demonstrated high tensile strength and ductility, the 165°C and 170°C samples were rejected due to specific property failures. The 165°C sample failed to meet the required elastic modulus, recording an elastic modulus of 6.82 MPa, which is below the 7 MPa threshold. Similarly, the 165°C and 170°C samples failed the hardness test, with a value of 64 and 67 respectively, which is below the 70 Shore limit. These results indicate that processing at these lower temperatures results in insufficient fusion between the virgin and scrap phases, leading to a lack of structural integrity and surface resistance.

The selection of 175°C and 180°C as optimal processing temperatures is supported by significant improvements in both processing stability and thermal robustness. At 175°C, sample S3 achieves the lowest mass loss, indicating that this temperature provides a stable processing environment with minimal degradation. Conversely, sample S4, processed at 180°C, yields the highest T_{50} value, demonstrating the material's superior resistance to thermal decomposition. By choosing the 175°C to 180°C range, the material undergoes sufficient thermal treatment to minimize volatile emissions while enhancing its thermal endurance.

Ultimately, the selection of 175°C and 180°C is based on the achievement of superior gelation and interfacial bonding. At these temperatures, the polymer matrix achieves sufficient kinetic energy to allow the molecular chains from the scrap PVC to fully interpenetrate and fuse with the virgin PVC. This leads to a stabilised material that is simultaneously hard, stiff, and strong, ensuring that the final blended product is both technically viable and compliant with industrial standards.

4.2 Evaluation of Properties at Optimal Processing Temperatures

4.2.1 Processing Torque

Referring to **Figures 4.5 and 4.6**, the processing torque-time profiles at 175°C and 180°C show distinct differences in the behaviour of the polymer blend during processing. At 175°C, the torque initially rises sharply as the polymer begins to melt,

peaking at the start of the mixing process. Following this peak, the torque declines, indicating that the fusion of the polymer is not as rapid. The torque stabilizes at a lower value after a short period, suggesting a more gradual transition to a homogeneous molten state. This decline in torque highlights the fusion of PVC and sPVC at this temperature.

In contrast, the 180°C curve displays a similar initial sharp rise in processing torque, followed by a comparable decline time. The torque reaches a lower, stable plateau, with a comparable decline time, indicating similar efficient fusion of the polymers. Overall, the data suggest that 175°C and 180°C both offer comparable fusion of the polymer blend, showing an efficient mixing process.

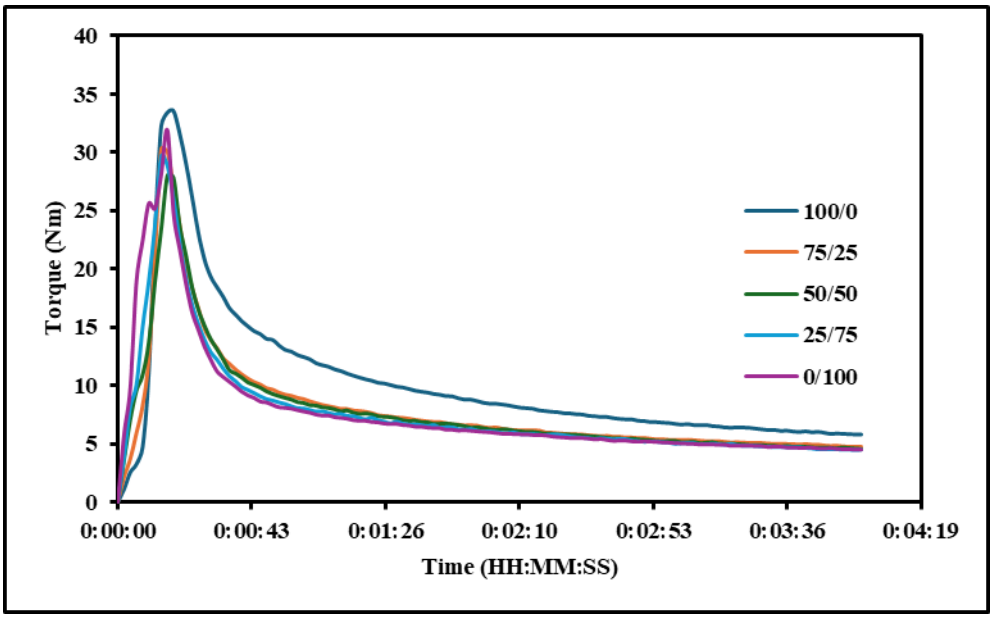

Figure 4.5: Torque-Time Plot for Composition with 175°C Processing Temperature.

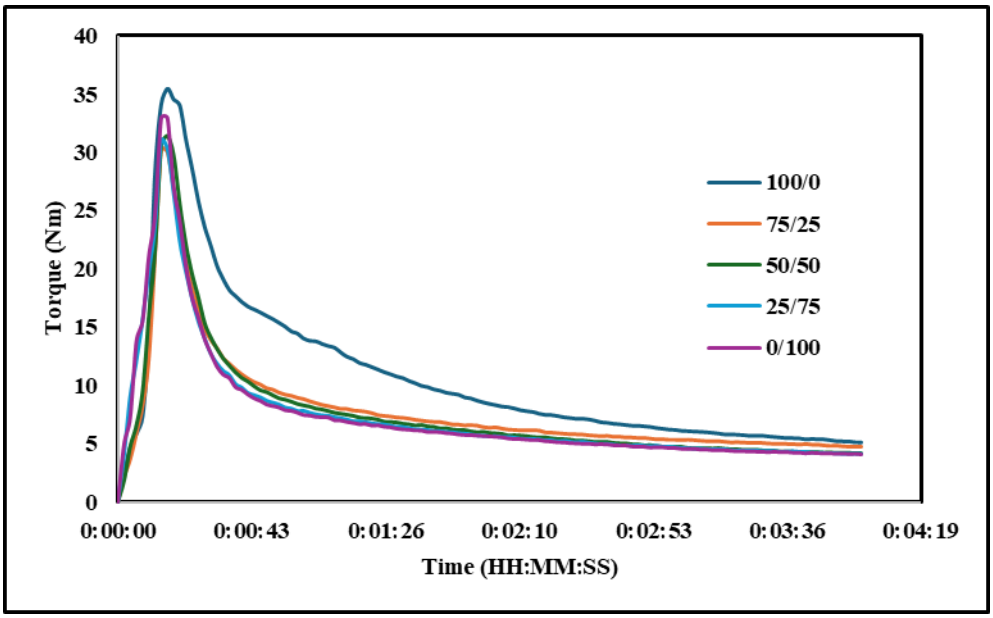

Figure 4.6: Torque-time Plot for Composition with 180°C Processing Temperature.

Referring to **Figure 4.7**, the 100/0 sample exhibited the highest resistance, with a loading peak of 33.5 Nm. As the scrap PVC content increased, a notable reduction in resistance was observed. The 75/25 blend showed a decrease to 30.3 Nm, and the lowest loading peak of 25.5 Nm was recorded at the 50/50 composition. However, as the scrap content is over 50%, the loading peak increases. The 25/75 blend recorded a loading peak of 29.7 Nm, while the 0/100 sample reached 31.9 Nm. Despite this late-stage increase, the pure scrap PVC still required less energy to load than the pure virgin resin.

A similar trend was observed in the stabilisation torque, which represents the material's viscosity once it reaches a homogeneous melt state. Referring to **Figure 4.8**, the 100/0 PVC required the highest torque to maintain flow at 5.8 Nm. This value decreases to 4.8 Nm for the 75/25 blend and reaches its lowest point of 4.1 Nm for the 50/50 blend. In higher scrap compositions, the torque stabilised at 4.5 Nm for both the 25/75 and 0/100 samples. Overall, the data suggests that the 50/50 blend provides the most efficient processing window in terms of energy consumption and melt fluidity.

The observed trends can be explained by the molecular characteristics of the blends. The high torque values seen in the 100/0 PVC are primarily attributed to its high molecular weight. PVC chains are highly entangled with a uniform molecular weight distribution, creating significant internal friction and resistance to shear during processing. In contrast, the 0/100 sPVC has already undergone at least one thermal processing cycle, leading to chain scission and the formation of shorter polymer chains. These shorter chains will lead to a reduction in entanglements compared to PVC, therefore reducing the melt viscosity, which is why pure sPVC exhibits lower torque values than PVC (Litvinov et al., 2020).

The reducing and increasing trend is observed, where the 50/50 blend shows the lowest overall torque, which is likely due to the difference in molecular weight between the two materials. When PVC and sPVC are blended, the shorter chains from the scrap material act as an internal lubricant for the longer, more entangled virgin chains. This broadening of the molecular weight distribution allows the chains to slide past one another more easily, significantly reducing intermolecular friction, providing easier molecular disentanglement and alignment (Simunec et al., 2026). At the 50/50 ratio, the balance between high-molecular-weight structural integrity and low-molecular-weight mobility is optimized, resulting in the lowest energy requirement for both fusion and stable processing. For 75/25 and 25/75 blending, they both exhibit the same condition where they are both dominant, either PVC or sPVC and have a narrower molecular weight distribution compared to 50/50 blending. Therefore, it will behave more towards the PVC or sPVC, which both have a higher loading and stabilisation torque compared to 50/50 blending.

Referring to **Figure 4.7** and **Figure 4.8**, at 180 °C, the 100/0 virgin PVC continues to exhibit the highest resistance, with a loading peak of 35.5 Nm and a stabilisation torque of 5.2 Nm. As scrap PVC is introduced, both torque values decrease significantly. The loading peak drops to 31.4 Nm for the 75/25 blend and reaches its minimum of 29.5 Nm at the 50/50 ratio. Similarly, the stabilisation torque for the 50/50 blend reaches a low of 4.0 Nm. Beyond the 50% sPVC threshold, the torque values begin to rise again, with the 25/75 blend showing a loading peak of 31.0 Nm and the pure scrap (0/100) reaching 32.9 Nm. Both the 25/75 and 0/100 samples maintain a consistent stabilisation torque of 4.1 Nm.

The internal trend at 180°C remains a reducing and increasing trend, reinforcing that the 50/50 blend provides the most efficient processing profile. This can be attributed to the difference in molecular weight between the two materials, where the shorter, degraded chains from the scrap PVC act as a processing aid for the longer, more entangled virgin chains. This interaction allows for a more homogeneous melt with reduced internal friction, offering better flow properties than either component could achieve on its own.

However, the loading torque is higher at 180°C compared to 175°C, with the virgin PVC showing a loading peak of 35.5 Nm at 180°C versus 33.5 Nm at 175°C. This can be explained by the accelerated fusion rate at higher temperatures. At 180°C, heat transfer into the PVC particles occurs much more rapidly, causing the polymer to soften and tack together almost instantly upon entering the mixing chamber (Hyvärinen, Jabeen and Kärki, 2020). As the material transitions from a solid state to a highly viscous, partially melted mass more quickly, the rotors experience a concentrated resistance within a shorter window of time. Due to the resistance, it creates a higher instantaneous pressure and torque peak before the material fully melts.

Once the material has fully fused into a stable melt, the stabilisation torque follows the standard principles of polymer rheology, where higher temperatures lead to lower viscosity. At 180°C, the polymer chains have increased kinetic energy and more free volume, which reduces the intermolecular forces holding them together. As a result, the melt flows more easily under shear, leading to lower stabilisation values.

Both 175°C and 180°C appear to be optimal processing temperatures. At 175°C, the blend exhibits the lowest loading torque, indicating excellent fusion between PVC and sPVC at relatively low torque, which suggests efficient mixing and minimal resistance during the early stages of processing. Meanwhile, at 180°C, the lowest stabilization torque is observed, reflecting improved melt flow and enhanced processability, which ensures the polymer achieves a homogeneous and stable molten state more quickly. Together, these findings demonstrate that both

temperatures offer advantageous processing characteristics, with 175°C excelling in fusion and 180°C in ease of melt flow and processability.

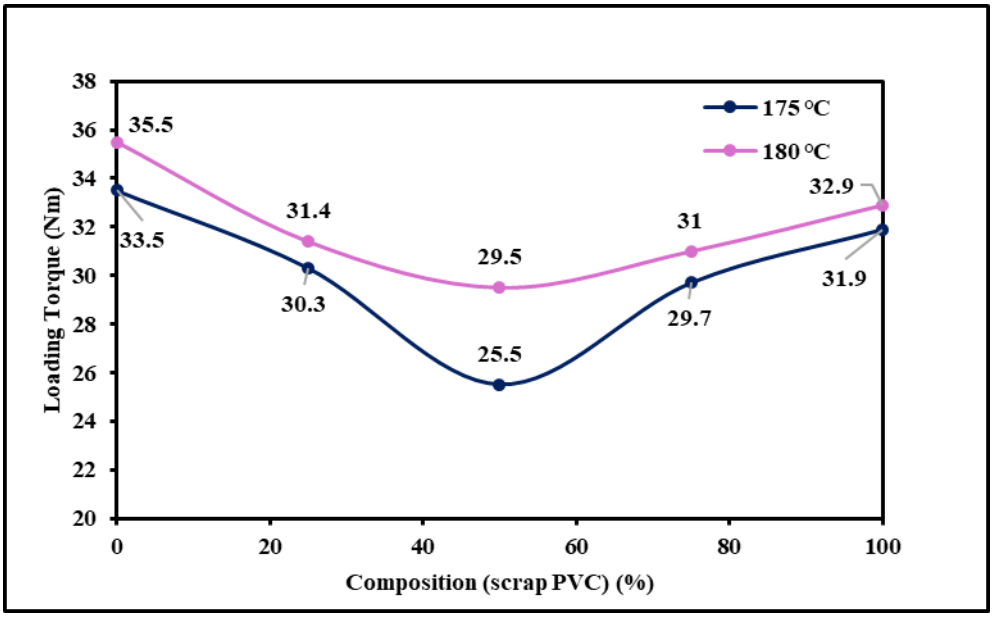

Figure 4.7: Loading Torque of 175°C and 180°C Processing at Various Composition.

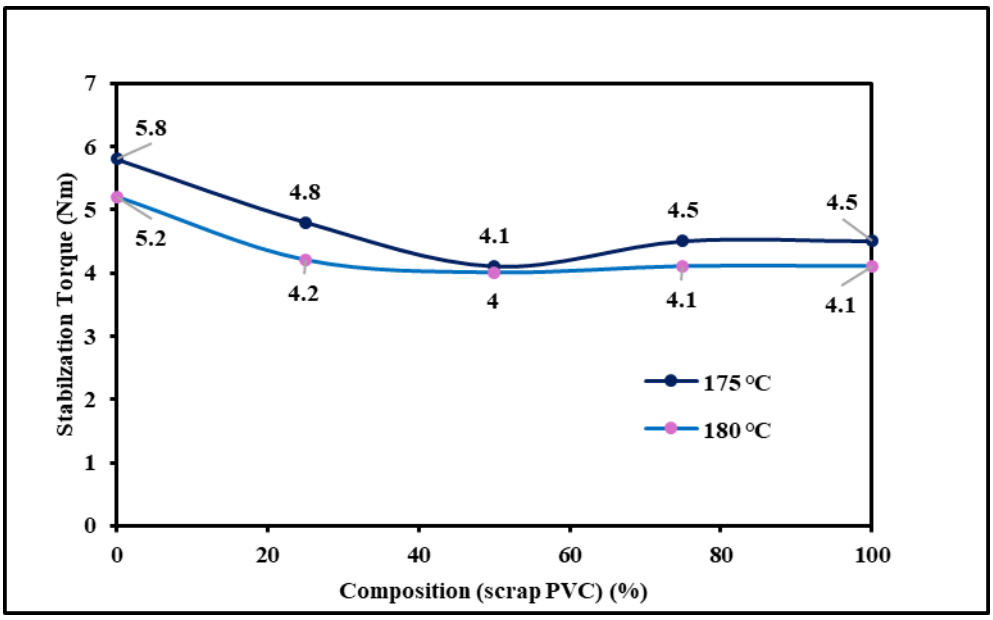

Figure 4.8: Stabilization Torque of 175°C and 180°C Processing at Various Composition.

4.2.2 Fourier Transform Infrared Spectroscopy (FTIR)

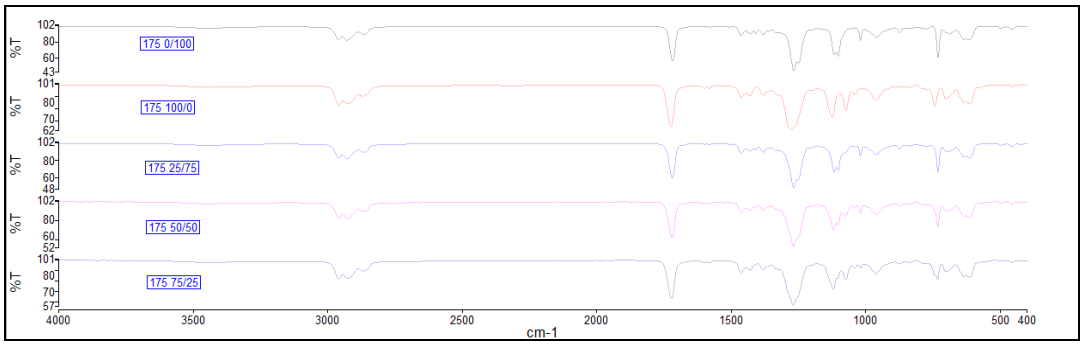

Figure 4.9: FTIR Spectra of PVC/sPVC at Loading Ranging from 100:0 to 0:100, Respectively at 175°C.

The FTIR spectra for the samples processed at 175°C reveal several characteristic functional groups associated with plasticized PVC across all blend compositions, from 100/0 to 0/100. Referring to **Figure 4.9**, a prominent peak at approximately 1720-1730 cm^{-1} corresponds to the C=O (carbonyl) stretching vibration, indicative of the ester groups in the plasticizers, likely phthalates, used in both the virgin and scrap PVC. In the high-frequency region, the C-H stretching vibrations of the polymer backbone and plasticizer alkyl chains are observed between 2850 cm^{-1} and 2960 cm^{-1}. Within the fingerprint region, a peak around 1425 cm^{-1} is attributed to CH_2 bending, while signals near 1250-1270 cm^{-1} correspond to C-H wagging near chlorine atoms. A distinct set of peaks between 1000 cm^{-1} and 1150 cm^{-1} represents C-O stretching from the ester linkage of the plasticizer. The signature of PVC itself is observed as a sharp peak between 600 cm^{-1} and 700 cm^{-1}, corresponding to the C-Cl stretching vibration. These peaks are confirmed by the studies "Thermal degradation and plasticising mechanism of poly(vinyl chloride) plasticized with a novel cardanol derived plasticizer" (Chen et al., 2018).

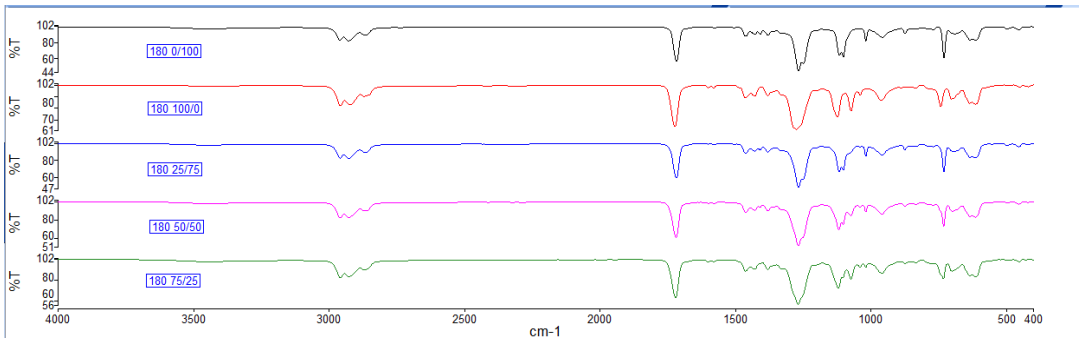

Figure 4.10: FTIR Spectra of PVC/sPVC at Loading Ranging from 100:0 to 0:100, Respectively at 180°C.

The FTIR spectra for the 180°C series show nearly identical profiles to those obtained at 175°C, with no new functional groups emerging, as shown in **Figure 4.10**. The C-H stretching (2850-2960 cm^{-1}), C=O carbonyl (1725 cm^{-1}), and CH_2 bending (1425 cm^{-1}) remain dominant features, and the C-O-C and C-H wagging bands in the 1000-1300 cm^{-1} range are consistently present across all blend ratios. The C-Cl stretch (615 cm^{-1}) retains its intensity and position. These results indicate that, even at the higher processing temperature of 180°C, the chemical skeleton of the material remains intact, with the plasticizer signals remaining strong and well-defined.

When comparing the FTIR results from the 175°C and 180°C series across all compositions, the most significant observation is the chemical consistency between the two temperatures. Despite the differences in processing torque and physical resistance observed in earlier data, the FTIR spectra are virtually indistinguishable. This suggests that the blending of virgin and scrap PVC is a purely physical process, with no evidence of new chemical. The fact that the 50/50 blend, which showed the lowest torque, shares the exact same peaks as the pure components confirms that its improved flow is due to physical lubrication and molecular weight distribution, rather than a chemical reaction.

Moreover, the comparison between the two processing temperatures indicates that increasing the temperature from 175°C to 180°C did not trigger detectable thermal degradation. If significant dehydrochlorination had occurred, we would

expect to see the emergence of a peak around 1600-1650 cm^{-1}, representing the formation of C=C double bonds (Amraoui et al., 2025). The absence of such a peak, along with the lack of broad hydroxyl (O-H) peaks around 3400 cm^{-1}, which would indicate degradation of PVC films, suggests that both temperatures are within the safe processing window for these specific plasticized PVC formulations (Amer Adnan Hasan et al., 2022).

In conclusion, while the torque rheometer indicated that 180°C and specific blend ratios significantly affect the physical processability, the FTIR analysis confirms that the chemical integrity of the PVC remains stable throughout the processing range. This ensures that the recycling process has been successful, preserving the chemical structure of the PVC without inducing premature thermal breakdown. This finding is vital for your FYP, as it demonstrates that the material has been successfully recycled without compromising its chemical properties.

4.2.3 Density Test

The initial characterisation of the raw materials reveals a baseline difference between the two components. Referring to **Table 4.8**, The virgin PVC pellets have an average density of 1147 kg/m^3, while the scrap PVC exhibits a slightly higher average density of 1154.3 kg/m^3. This higher density in the scrap material is typical of recycled plastics, as they have lost some of their lighter, low-density plasticizers during their reprocessing.

When comparing the compositions at 175°C and 180°C, a clear upward trend in density is observed as the scrap PVC content increases. Referring **Table 4.9**, at 175°C, the 100/0 sample has a density of 1136 kg/m^3, and the 75/25 blend shows a slight increase to 1138.7 kg/m^3. A more significant rise occurs at the 50/50 ratio, reaching 1148 kg/m^3, and the density continues to increase sharply for the 25/75 blend to 1169.3 kg/m^3 before peaking at 1177.3 kg/m^3 for the 0/100 scrap PVC. This trend indicates that the higher-density scrap PVC is the primary contributor to the overall density of the blend.

Referring to **Table 4.10**, at 180°C, the same upward trend is evident, but with significantly higher starting values and overall densities. The 100/0 virgin PVC starts at 1178.7 kg/m³, which is notably higher than the pure scrap PVC processed at 175°C. The density increases further with higher scrap content: 1181 kg/m^3 for 75/25, 1187.7 kg/m^3 for 50/50, 1188 kg/m^3 for 25/75, and peaking at 1193.3 kg/m^3 for the 0/100 scrap sample. Across all compositions, the material processed at 180°C is consistently denser than that processed at 175°C.

Table 4.8: Density of PVC and sPVC.

Composition	Density (kg/m^3)			Average Density (kg/m^3)
	1	2	3	
PVC Pellets	1184	1153	1104	1147
Scrap PVC	1169	1163	1131	1154

Table 4.9: Density of Blends in All Compositions for 175°C.

Composition (175°C)	Density (kg/m^3)			Average Density (kg/m^3)
	1	2	3	
100/0	1139	1132	1137	1136
75/25	1139	1142	1135	1138
50/50	1191	1119	1134	1148
25/75	1181	1124	1203	1169
0/100	1173	1198	1161	1177

Table 4.10: Density of Blends in All Compositions for 180°C.

Composition (180°C)	Density (kg/m^3)			Average Density (kg/m^3)
	1	2	3	
100/0	1165	1185	1186	1178
75/25	1187	1176	1180	1181
50/50	1176	1212	1175	1187
25/75	1195	1179	1190	1188
0/100	1201	1158	1221	1193

The higher density observed at 180°C, as shown in **Figure 4.11**, can be attributed to the improved fusion efficiency and the reduction of free volume. At 180°C, as indicated by the torque data, the melt viscosity is lower, allowing the polymer chains to move more freely and pack more tightly together during the stabilisation phase. A more fluid melt effectively displaces air trapped between pellets or flakes during the loading stage (Pang et al., 2025). In contrast, at 175°C, the higher viscosity likely causes voids to remain trapped within the matrix, as the material is too stiff to fully consolidate, resulting in a lower measured density.

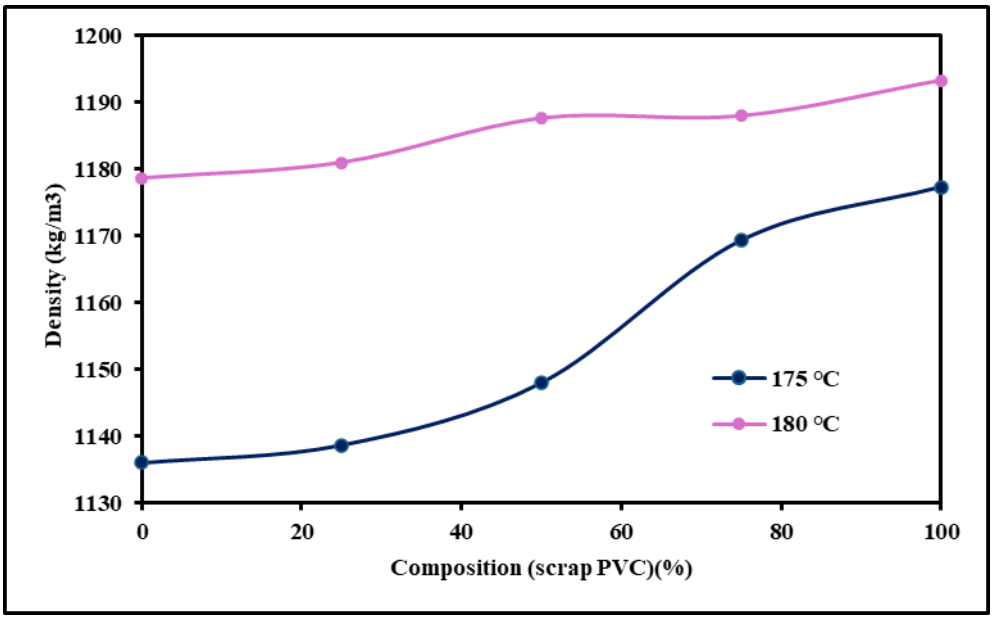

Figure 4.11: Density of PVC Blends at Different Processing Temperatures.

4.2.4 Water Absorption

The water absorption test is a critical evaluation of the physical integrity of the PVC blends, providing insight into the material's porosity and the quality of the interfacial bonding between the virgin and scrap phases. The percentage of weight gained after 72 hours of immersion serves as a direct measure of the material's susceptibility to moisture penetration.

Referring to **Table 4.11**, at a processing temperature of 175°C, the average water absorption rate increases with the addition of scrap PVC. The 100/0 sample exhibited the lowest absorption at 0.167%, while the 0/100 sample showed the highest absorption at 0.474%. Among the blends, the 50/50 composition experienced a notable spike in absorption at 0.382%, significantly higher than the 75/25 blend at 0.221% and the 25/75 blend at 0.197%. The higher absorption in pure scrap PVC compared to virgin PVC can be attributed to the presence of pre-existing micro-voids or impurities from its previous processing. The peak observed in **Figure 4.12** at the 50/50 ratio likely indicates a poor interfacial bond between the virgin and scrap PVC at this temperature, creating micro-voids at the boundaries where the two materials meet.

At 180°C, the water absorption behaviour follows a similar trend, but with a significantly lower overall absorption magnitude. The virgin PVC (100/0) demonstrated the highest resistance to water absorption, with a weight gain of only 0.036%, as shown in **Table 4.12**. The absorption increases with scrap content, reaching 0.301% for the 50/50 blend and peaking at 0.365% for the pure scrap PVC (0/100). Similar to the 175°C series, the 50/50 blend at 180°C exhibited a higher absorption rate than the 25/75 blend (0.164%), suggesting a recurring morphological trait at that specific mixing ratio.

When comparing the two temperatures, it is clear that processing at 180°C significantly improves the water resistance of the PVC across all compositions. For instance, the virgin PVC absorption decreased from 0.167% at 175°C to a nearly negligible 0.036% at 180°C. This indicates a more compact material structure when processed at the higher temperature. This improvement is logically linked to the density results, as discussed earlier. At 180°C, the lower melt viscosity enables a more complete fusion of the PVC particles (Bekker et al., 2022). This enhanced fusion eliminates micro-voids and free volume that were present at 175°C. When a material is more densely packed and better fused, there are fewer voids or pores for water molecules to penetrate. As a result, even though the chemical nature of the scrap PVC remains unchanged, the physical consolidation achieved at 180°C creates a more impermeable barrier.

Table 4.11: Water Absorption of Blends in All Compositions for 175°C.

Composition (175°C)	Weight Gained (%)					Average (%)
	1	2	3	4	5	
100/0	0.0485	0.1618	0.1702	0.1282	0.3265	0.1670
72/25	0	0.1646	0.1339	0.2260	0.5784	0.2206
50/50	0.6893	0	0	0.1194	1.1025	0.3822
25/75	0.0379	0.0703	0	0.4895	0.3875	0.1970
0/100	0.7492	0.3039	0.7299	0.0466	0.5386	0.4736

Table 4.12: Water Absorption of Blends in All Compositions for 180°C.

Composition (180°C)	Weight Gained (%)					Average (%)
	1	2	3	4	5	
100/0	0.0424	0	0.0938	0	0.0414	0.0355
72/25	0.0538	0	0.0516	0.2087	0.2428	0.1114
50/50	0.1721	0.0642	0.3916	0.1371	0.7404	0.3011
25/75	0.0579	0.0284	0	0.3144	0.4198	0.1641
0/100	0.0330	0.4868	0.5050	0.2881	0.5131	0.3652

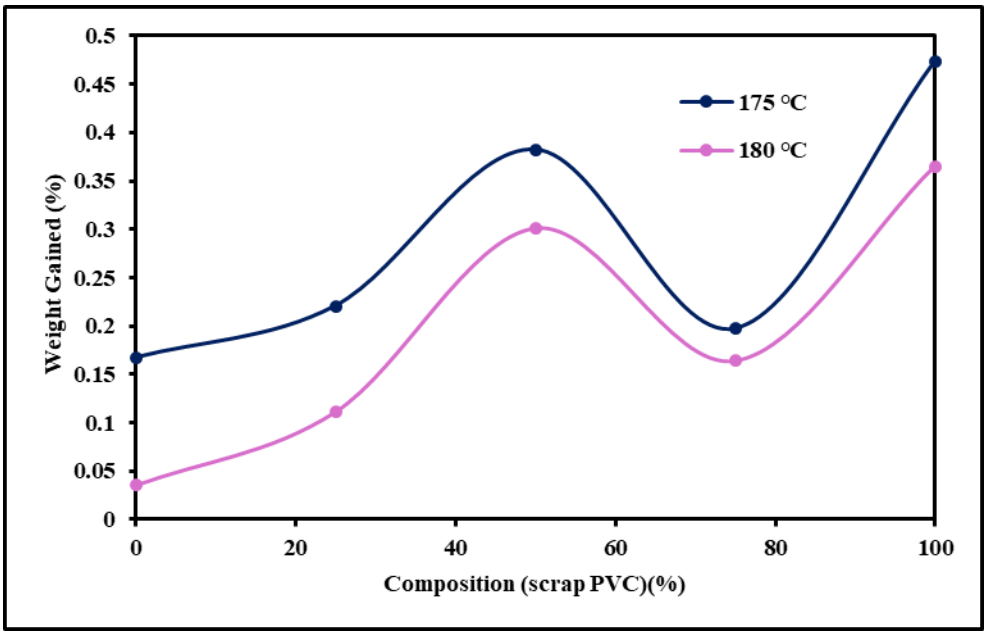

Figure 4.12: Water Absorption of PVC Blends at Different Processing Temperatures.

4.2.5 Chemical Stability

The chemical stability test in toluene is an important evaluation for your project, as it measures the resistance of the PVC compounds to solvent extraction. In plasticized PVC, the primary mechanism of weight loss when exposed to a solvent like toluene is the leaching of plasticizers from the polymer matrix into the surrounding fluid.

At a processing temperature of 175°C, all samples experienced significant weight loss, ranging from approximately 28% to 31% as shown in **Table 4.13**. The pure sPVC (0/100) showed the highest average weight loss at 31.06%, indicating it is the most vulnerable to solvent extraction. The 100/0 virgin PVC followed closely with a loss of 29.65%. Interestingly, the blends showed slightly improved resistance, with the 50/50 blend achieving the lowest weight loss in this series at 28.34%. Following the weight loss of the 75/25 blend at 28.6552% and the 25/75 blend at 30.3712%. The higher weight loss in the 0/100 sPVC can be attributed to the presence of shorter polymer chains resulting from its previous thermal history, which causes chain scission. These shorter chains create more free volume within the material, making it easier for toluene molecules to penetrate the matrix and for plasticizers to migrate out.

At 180°C, the samples exhibited a similar trend but with an overall improvement in chemical resistance compared to the lower temperature series. The virgin PVC (100/0) showed a weight loss of 29.19%, while the pure scrap PVC (0/100) lost 29.62% as tabulated in **Table 4.14**. Once again, the 50/50 blend proved to be the most stable composition, recording the minimum weight loss of 26.51%. The 75/25 (28.51%) and 25/75 (27.00%) blends also performed better than their respective pure counterparts. The consistency of the 50/50 blend as the top performer across both temperatures reinforces the idea that this specific ratio achieves the most optimized physical structure. At 180°C, the improved flow and molecular integration allow the virgin and scrap chains to interweave more effectively, leading to a successful reduction of the plasticizer lost (G. Cunha and Robbins, 2020).

Referring to **Figure 4.13**, When comparing the two processing temperatures, the samples processed at 180°C consistently show lower weight loss than those

processed at 175°C. This increase in chemical stability at the higher temperature can be directly explained by the good fusion quality and higher density of the 180°C samples. As established in the previous density and water absorption results, the lower melt viscosity at 180°C facilitates a more complete fusion of the PVC particles, effectively eliminating micro-pores and reducing the free volume within the material. In contrast, poorly fused samples, such as those processed at 175°C, allow toluene to seep into internal voids, providing a larger surface area for the solvent to interact with the plasticizer. The more "solid" and well-consolidated matrix produced at 180°C acts as a more effective physical barrier, making it harder for the toluene to diffuse into the center of the sample. This ultimately reduces the total amount of plasticizer leached over the 72-hour period.

Table 4.13: Weight Loss of Blends in All Compositions for 175°C.

Composition	**Weight Loss (%)**					**Average Weight**
(175°C)	**1**	**2**	**3**	**4**	**5**	**Loss (%)**
100/0	29.63	28.94	29.13	31.02	29.55	29.65
72/25	27.96	29.45	29.11	28.46	28.30	28.66
50/50	28.94	28.61	27.89	30.12	26.13	28.34
25/75	30.79	29.73	31.15	29.07	31.12	30.37
0/100	30.60	31.19	30.56	32.14	30.78	31.06

Table 4.14:Weight Loss of Blends in All Compositions for 180°C.

Composition	**Weight Loss (%)**					**Average Weight**
(180°C)	**1**	**2**	**3**	**4**	**5**	**Loss (%)**
100/0	29.23	27.01	30.54	29.54	29.63	29.19
72/25	28.91	29.40	31.06	27.19	26.01	28.51
50/50	25.53	25.16	26.15	28.36	27.34	26.51
25/75	26.87	27.02	27.34	27.29	26.50	27.00
0/100	27.49	26.58	32.01	31.85	30.17	29.62

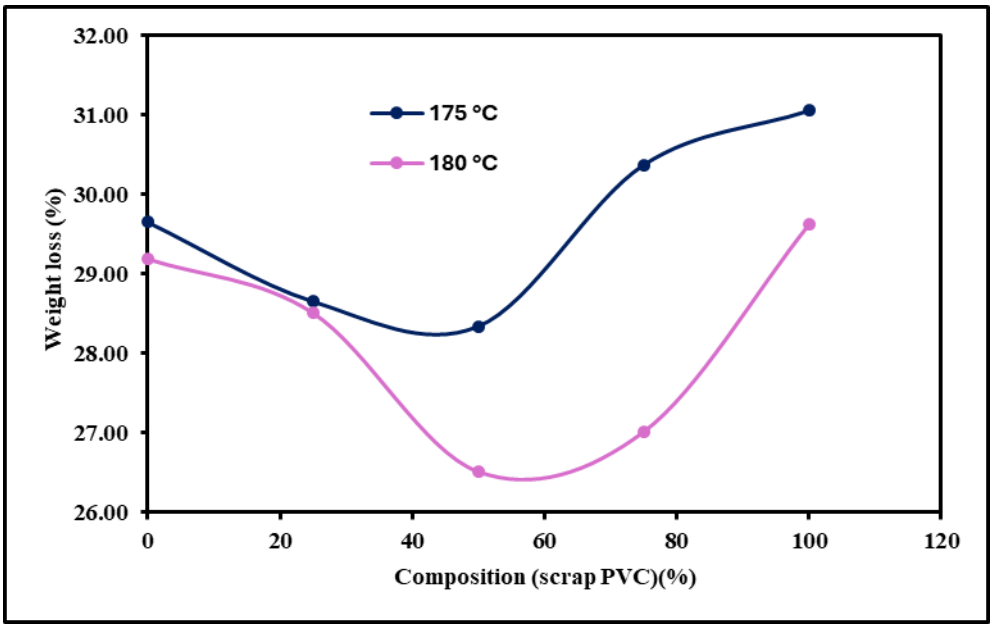

Figure 4.13: Weight Loss of PVC Blends at Different Processing Temperatures.

4.2.6 Thermal Stability

Referring to **Table 4.15 and Figure 4.14**, the TGA analysis at 175°C shows that the thermal stability of the PVC blends improves with increasing scrap PVC content. The temperature at which 50% mass loss occurs (T_{50}) rises from 303.97°C for the 100/0 blend to 305.51°C for the 75/25 blend and 307.81°C for the 50/50 blend. Although the 25/75 blend experiences a slight drop to 305.21°C, the pure scrap PVC achieves the highest thermal stability at 309.32°C. The mass loss at the processing temperature reveals that the 50/50 blend is the most resilient, with the lowest loss at 0.11%, followed by the pure sPVC at 0.11%, and the 100/0 blend at 0.14%. The 25/75 and 75/25 blends exhibit higher mass losses of 0.20% and 0.21%, respectively. At the end of the test, S3 retains the most residue (11.15%), indicating it was the most thermally stable, while S4 had the highest total mass loss at 92.30%.

Table 4.15: TGA Results of Blends for All Compositions at 175°C.

Composition	T_{50} (°C)	Mass Loss at Process Temperature (%)	Total Mass Loss at 900°C (%)	Residual Weight (%)
100/0	303.97	0.14	91.33	8.67
75/25	305.51	0.21	91.63	8.37
50/50	307.81	0.11	88.85	11.15
25/75	305.21	0.20	92.30	7.70
0/100	309.32	0.11	91.29	8.71

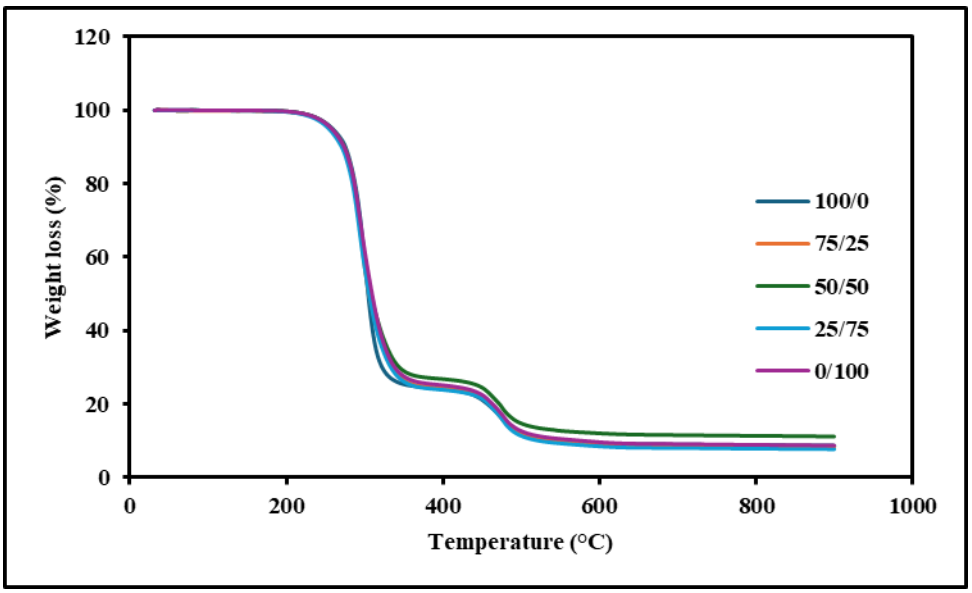

Figure 4.14: TGA of PVC Blends at Different Compositions at 175°C.

At 180°C, the thermal data exhibit higher variability as shown in **Figure 4.15**. The T_{50} values for the PVC and blends show a similar trend to those at 175°C, but with slightly higher values. Referring to **Table 4.16**, the 100/0 blend recorded a T_{50} of 303.93°C, and the stability increased in the 75/25 blend to 306.93°C, but dropped for the 50/50 blend to a study-low of 303.69°C. Stability recovered for the 25/75 blend at 308.19°C, and peaked with the pure sPVC at 309.00°C. Regarding mass loss at 180°C, PVC had the highest loss at 0.28%, while the scrap-containing blends showed notably better stability. The 75/25 blend had the lowest loss at 0.13%, followed by the 50/50 blend at 0.16%, and the 0/100 blend at 0.18%. The highest

residue retention was observed in the 25/75 blend at 87.57%, while S8 had the highest mass loss at 95.05%.

The comparison of the two processing temperatures clearly indicates that processing at 180°C results in higher mass loss than at 175°C. This is expected, as higher thermal energy accelerates the volatilisation of smaller molecules. However, the T_{50} values for pure scrap PVC remained consistently high regardless of the processing temperature. The total mass loss results also suggest that the higher temperature at 180°C, the improved melt flow at 180°C allows the polymer matrix to have more homogeneous mixing, creating a more stable residue compared to the less dense samples processed at 175°C (Summers, 2005).

Table 4.16: TGA Results of Blends for All Compositions at 180°C.

Composition	T_{50} (°C)	Mass Loss at Process Temperature (%)	Total Mass Loss at 900°C (%)	Residual Weight (%)
100/0	303.93	0.28	93.49	6.51
75/25	306.93	0.13	90.74	9.26
50/50	303.69	0.16	95.05	4.95
25/75	308.19	0.19	87.57	12.44
0/100	309.00	0.18	88.49	11.51

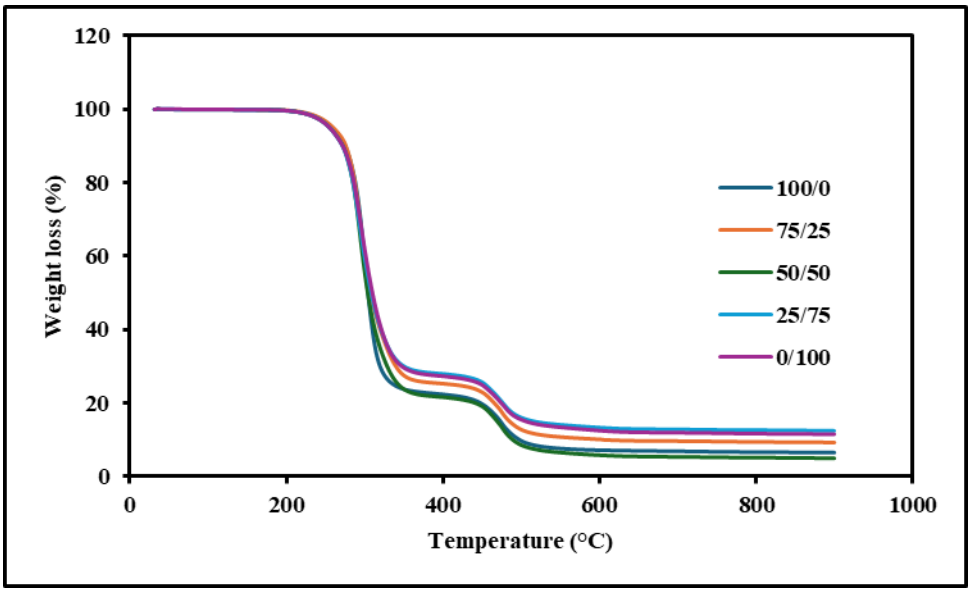

Figure 4.15: TGA of PVC Blends at Different Compositions at 180°C.

In addition to the temperature analysis, the DTG graph provides valuable insight into the degradation patterns of the PVC blends. **Figure 4.16** illustrates the rate of mass loss as a function of temperature at 175°C for each blend composition. The 100/0 composition exhibits a sharp and distinct degradation peak at 302.33°C, indicating a more pronounced and earlier onset of degradation compared to the blends containing sPVC. This peak is notably more defined, suggesting that pure PVC undergoes a more immediate and intense degradation process in the first stage.

For the blends containing sPVC, such as the 75/25, 50/50, and 25/75 compositions, the first degradation peak shifts to lower temperatures, with T_{max1} values ranging from 297.67°C to 298°C. These shifts are visible in the graph as a slight broadening of the degradation curve, indicating that the presence of sPVC accelerates the degradation process at the onset. The 0/100 (pure sPVC) composition shows a similar trend, with the degradation peak occurring at 300°C, reflecting the early onset of degradation due to the defect sites inherent in sPVC.

Despite these differences in the first degradation stage, the Stage 2 degradation peak for all blends remains relatively consistent, with values ranging from 471.67°C to 475.45°C. On the graph, this results in a more uniform and stable degradation curve in the second stage, regardless of the blend composition. This

indicates that the final breakdown of the polymer backbone is an inherent characteristic of PVC, and its degradation behavior in this stage is largely unaffected by the amount of sPVC in the blend. Overall, the graph visually confirms that the incorporation of sPVC leads to earlier degradation in the first stage but does not influence the stability of the polymer backbone during the final degradation stage (Wu and G., 2020).

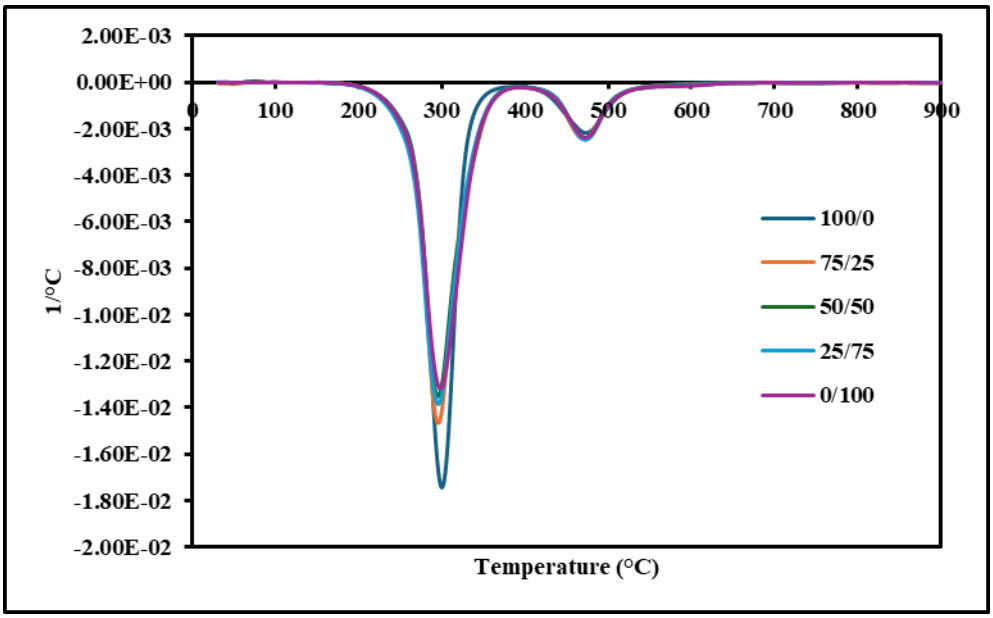

Figure 4.16: DTG of PVC Blends at Different Compositions at 175°C.

At 180°C, the situation changes due to the higher thermal energy. This temperature increases molecular mobility and leads to more instability. The shift to 180°C introduces more difference into the data, as seen by the decrease in S8. This is primarily because 5°C is a significant increament in terms of viscosity and molecular mobility. The 100/0 PVC experiences the most mass loss due to the higher volatility of its original components, which were not removed in previous heat cycles. The 50/50 blend shows a drop in T_{50} due to phase morphology at 180 °C. The viscosity of both phases (virgin and scrap PVC) drops, leading to a co-continuous phase, where neither phase dominates. This creates a high surface area of interfaces between the two phases. If these interfaces are weak, they become hot spots for degradation, leading to the lower stability observed. 25/75 and 0/100 have good thermal stability at 180°C is due to the loss of plasticizers. Due to the reprocessing, the volatile

plasticizers have leached out, leading to a smaller degradation peak. This results in higher residue and improved thermal stability.

The DTG analysis for PVC blends at a processing temperature of 180°C shows similar degradation trends to those observed at 175°C, with only slight differences in the degradation peaks, as shown in **Figure 4.17**. The 100/0 composition still exhibits the highest degradation temperature in Stage 1 at 302°C, indicating that pure PVC undergoes the most significant degradation in the first stage. This is consistent with the behavior observed at 175°C. The Stage 2 degradation peak for the 100/0 composition occurs at 475°C, again reflecting the inherent stability of the polymer backbone.

For the blends containing sPVC, such as the 75/25, 50/50, and 25/75 compositions, the Stage 1 degradation peak shifts slightly lower to temperatures around 297°C to 297.33°C, indicating that the presence of sPVC continues to accelerate the degradation process in the first stage. The 0/100 composition (pure sPVC) shows the lowest T_{max1} value of 299°C, indicating that sPVC begins to degrade earlier, as expected due to its prior thermal history.

The Stage 2 degradation peak remains relatively stable across all compositions, with values ranging from 473°C to 475°C, which is consistent with the behavior observed at 175°C. This suggests that the breakdown of the polymer backbone is an intrinsic property of PVC, largely unaffected by the processing temperature or the ratio of virgin PVC to sPVC in the blend (Wu and G., 2020).

Overall, the degradation behavior at 180°C is comparable to that at 175°C, with sPVC blends exhibiting earlier degradation at Stage 1 and the final polymer backbone degradation (Stage 2) showing minimal variation across all compositions.

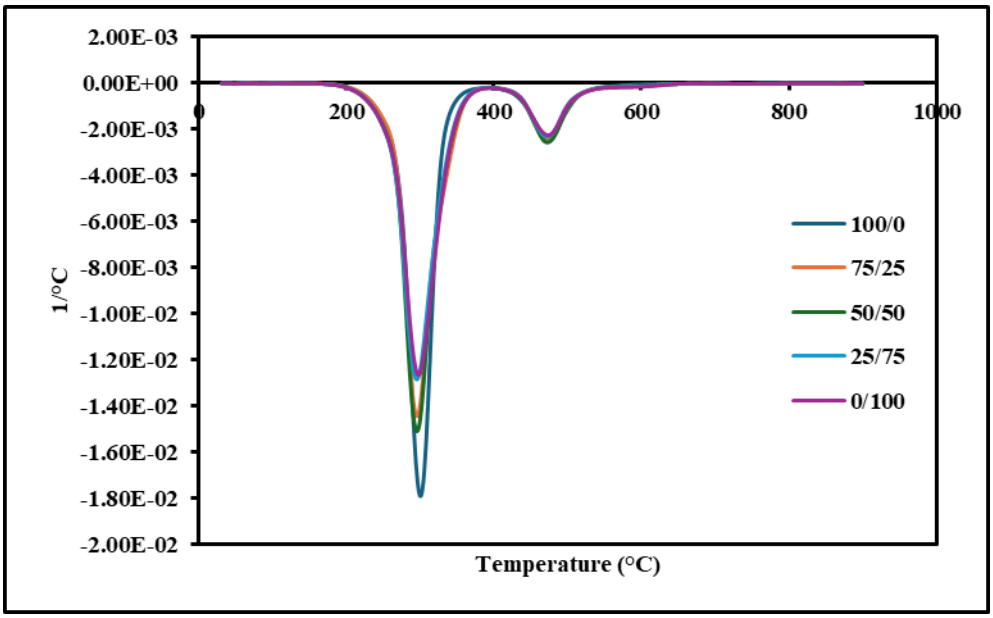

Figure 4.17: DTG of PVC Blends at Different Compositions at 180°C.

4.2.7 Tensile Strength and Morphology

At 175°C, the tensile properties of the PVC blends revealed some distinct trends related to the amount of scrap content. The Ultimate Tensile Strength (UTS) improved with higher scrap content, reflecting the reinforcement effect from the chain scission process. Referring to **Table 4.17**, the 100/0 composition exhibited a UTS of 18.58 MPa, while the 75/25 composition achieved 19.3 MPa, and the 50/50 blend showed a further increase to 19.64 MPa. The 25/75 composition reached its peak UTS at 20.05 MPa. However, the 0/100 pure SPVC showed a slight decline in UTS to 19.23 MPa. This decline suggests that the chain scission that occurs due to thermal history causes a reduction in the polymer's molecular weight, limiting the material's ability to bear load effectively, which can explain the drop in UTS for the pure scrap (Laycock et al., 2017).

Table 4.17: UTS of Blends in All Compositions for 175°C.

Composition (175°C)	UTS (MPa)			Average (MPa)
	1	2	3	
100/0	18.14	18.79	18.82	18.58
72/25	19.82	19.29	18.89	19.33
50/50	19.27	19.74	19.9	19.64
25/75	20.39	20.33	19.43	20.05
0/100	20.83	18.53	18.33	19.23

The elongation at break followed a consistent downward trend as scrap content increased. The 100/0 PVC blend, with an elongation at break of 346.9%, displayed high ductility. This value decreased as the scrap content increased, dropping to 334.7% for the 75/25 blend, 334.03% for the 50/50 blend, and 321.47% for the 25/75 blend, as shown in **Table 4.18**. The 0/100 composition exhibited the lowest elongation at break at 319.33%. This reduction in elongation is due to the rigid polymer chains and the thermal history of the material. As more sPVC is added, there is a decrease in plasticizer content due to plasticizer loss during previous processing, which typically serves to enhance polymer chain mobility (Pannico and Musto, 2024). The loss of plasticizer and the increased presence of chain scission restrict the mobility of PVC molecular chains, making the material stiffer and less ductile.

Table 4.18: Elongation at Break of Blends in All Compositions for 175°C.

Composition (175°C)	Elongation at Break (%)			Average (%)
	1	2	3	
100/0	322.70	361.70	356.30	346.90
72/25	326.70	310.70	366.70	334.70
50/50	333.30	332.30	336.50	334.03
25/75	327.00	330.70	306.70	321.47
0/100	305.30	336.70	316.00	319.33

The Elastic Modulus (E-modulus) confirmed the increased rigidity of the blends as more scrap PVC was added. Referring to **Table 4.19**, the modulus rose from 7.06 MPa for the 100/0 blend to 7.13 MPa for the 75/25 blend, 8.08 MPa for the 50/50 blend, and 8.47 MPa for the 25/75 blend. The modulus for the pure scrap PVC, 0/100, was 7.99 MPa, showing a slight decrease compared to the 25/75 blend. The increase in E-modulus is a result of the increased stiffness due to the loss of plasticizer content. As the plasticizer content decreases, the polymer chains become less flexible, resulting in a more rigid material. Additionally, the chain scission caused by the previous thermal history leads to shorter polymer chains of sPVC that are less capable of moving past each other, increasing the stiffness of the material (Laycock et al., 2017).

Table 4.19: Elastic Modulus of Blends in All Compositions for 175°C.

Composition	**E-Modulus (MPa)**			**Average**
(175°C)	**1**	**2**	**3**	**(MPa)**
100/0	7.35	6.95	6.87	7.06
72/25	7.16	7.79	6.45	7.13
50/50	7.14	7.18	7.52	7.28
25/75	7.58	7.37	7.99	7.65
0/100	8.17	8.03	7.77	7.99

At 180°C, the overall tensile properties improved compared to the 175°C series, indicating better material integration and fusion at this higher processing temperature. Referring to **Table 4.20**, the UTS started at 18.73 MPa for the virgin PVC and increased steadily through the compositions, reaching 19.6 MPa for the 75/25 blend, 19.8 MPa for the 50/50 blend, and peaking at 20.7 MPa for the 25/75 blend. The 0/100 pure scrap PVC showed a slight decrease in UTS to 20.23 MPa, but this was still higher than the 175°C results. The higher temperature at 180°C facilitates better fusion of PVC chains, improving the molecular alignment and leading to superior interfacial adhesion. This enhanced fusion helps in the better stress transfer within the material, resulting in higher peak strength.

Table 4.20: UTS of Blends in All Compositions for 180°C.

Composition (180°C)	UTS (MPa)			Average (MPa)
	1	2	3	
100/0	19.22	19.48	17.49	18.73
72/25	19.68	19.52	19.25	19.48
50/50	19.74	19.71	19.95	19.80
25/75	21.65	21.25	19.33	20.74
0/100	19.5	19.7	20.23	19.81

The elongation at break at 180°C was generally lower than at 175°C, although the trend with scrap content remained consistent. Referring to **Table 4.21**, the virgin PVC exhibited an elongation at break of 330.33%, which decreased to 325.29% for the 75/25 blend, 324.4% for the 50/50 blend, 314.33% for the 25/75 blend, and 309.67% for the 0/100 pure scrap PVC. The increase in temperature improves fusion, but it can also lead to thermal degradation. This thermal degradation reduces the material's ability to stretch, leading to a more brittle material and explaining why elongation at break is lower at 180°C compared to 175°C. Additionally, the plasticizer content could also degrade at higher temperatures, contributing to a reduction in flexibility and an increase in brittleness due to reduction in plasticizer content (Eslami et al., 2023).

Table 4.21: Elongation at Break of Blends in All Compositions for 180 °C.

Composition (180°C)	Elongation at Break (%)			Average (%)
	1	2	3	
100/0	327.00	340.00	324.00	330.33
72/25	332.00	321.17	322.70	325.29
50/50	328.30	323.30	321.60	324.40
25/75	319.70	325.00	298.30	314.33
0/100	296.00	323.00	310.00	309.67

The E-modulus at 180°C showed a consistent and linear increase across all compositions. Starting at 7.40 MPa for the virgin PVC, the modulus rose to 7.59 MPa for the 75/25 blend, 8.04 MPa for the 50/50 blend, and 8.47 MPa for the 25/75 blend, as shown in **Table 4.22**. The 0/100 pure scrap PVC showed the highest modulus at 8.67 MPa, indicating that the higher processing temperature allowed for better melt flow and integration of the polymer chains, leading to maximum rigidity. Unlike the 175°C set, the modulus did not decrease at 100% scrap at 180°C, suggesting that the higher temperature allowed the pure scrap PVC to fuse better, ensuring a more well-integrated polymer network and providing maximum rigidity.

Table 4.22: Elastic Modulus of Blends in All Compositions for 180°C.

Composition	E-Modulus (MPa)			Average
(180°C)	1	2	3	(MPa)
100/0	7.64	7.25	7.3	7.40
72/25	7.56	7.93	7.59	7.69
50/50	7.94	8.13	8.18	8.08
25/75	8.59	8.47	8.36	8.47
0/100	8.9	8.37	8.76	8.68

The tensile properties of PVC blends processed at 175°C and 180°C exhibit significant differences, reflecting the impact of the processing temperature on material integration, strength, ductility, and rigidity. While 175°C offers a more moderate thermal environment, 180°C facilitates enhanced fusion and interfacial adhesion, leading to improved mechanical performance.

Figure 4.18 shows the comparison of UTS at 175°C and 180°C. At 175°C, the Ultimate Tensile Strength (UTS) initially increases with scrap content, peaking at 20.05 MPa for the 25/75 blend. However, the 100% scrap PVC (0/100) shows a slight decline in UTS to 19.23 MPa, suggesting that at this lower temperature, insufficient virgin resin prevents proper chain entanglement and interfacial bonding. This reduction in strength is attributed to chain scission, which occurs at 175°C, leading to a decrease in molecular weight and reduced load-bearing capacity (Krzysztof Pielichowski and Njuguna, 2023).

In contrast, at 180°C, the UTS values are consistently higher across all compositions. The 25/75 blend reaches a peak of 20.7 MPa, and even the pure scrap PVC (0/100) maintains a strong 20.23 MPa. The higher temperature enhances polymer chain fusion, promoting better molecular alignment and superior interfacial adhesion. This improved fusion allows for more efficient stress transfer across the material, resulting in increased strength compared to 175°C.

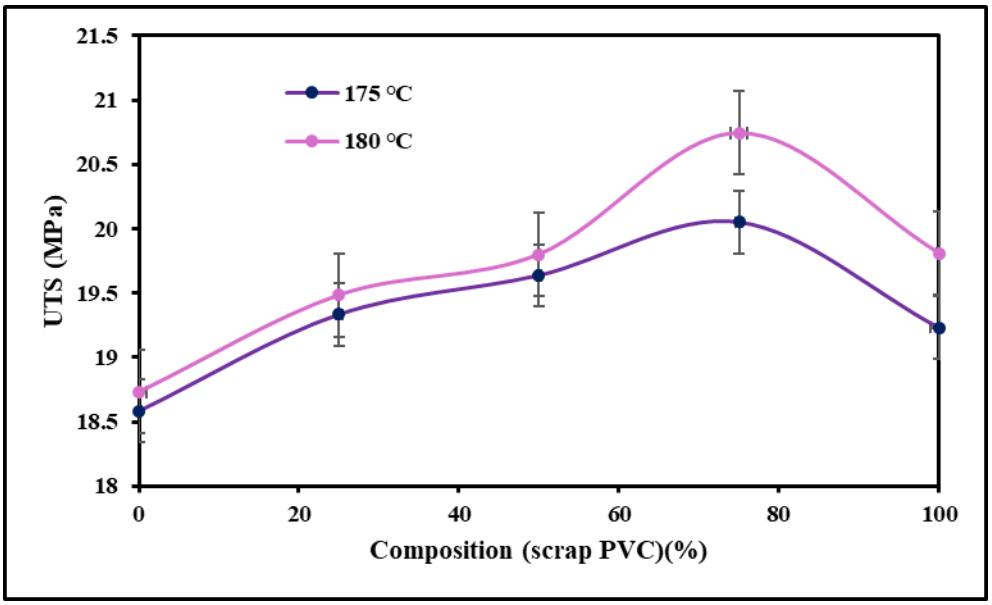

Figure 4.18: UTS of PVC Blends at Different Processing Temperatures.

The elongation at break followed a consistent downward trend as scrap content increased at both temperatures, indicating a shift towards more brittle behaviour, as shown in **Figure 4.19**. At 175°C, the virgin PVC exhibited high ductility, with an elongation at break of 346.9%, which decreased to 319.33% for the 0/100 pure scrap PVC. This reduction is linked to the decrease in plasticizer content and chain scission, which restricts the movement of PVC chains, making the material stiffer and less flexible. At 180°C, elongation values were consistently lower, with the virgin PVC showing 330.33% elongation, dropping to 309.67% for the pure scrap PVC. The higher processing temperature causes thermal degradation, which can shorten polymer chains or increase cross-linking, reducing the material's ability to stretch and making it more brittle. Additionally, the higher temperature accelerates the loss of plasticiser, contributing to the reduction in ductility.

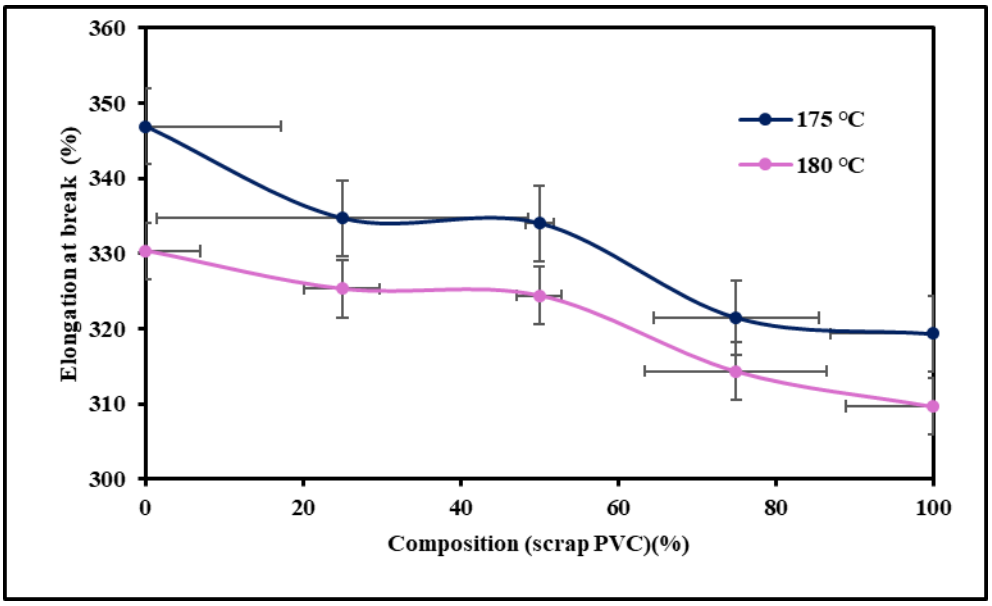

Figure 4.19: Elongation at Break of PVC Blends at Different Processing Temperatures.

The Elastic Modulus confirmed the increased rigidity of the blends as more scrap PVC was added, with the modulus steadily increasing at both temperatures. At 175°C, the modulus rose to 8.47 MPa for the 25/75 blend but reduced slightly to 7.99 MPa for the 0/100 pure scrap PVC, as shown in **Figure 4.20**. This drop suggests that incomplete fusion at 175°C leads to micro-voids or weak spots in the material structure, reducing stiffness. At 180°C, the modulus increased consistently across all compositions, peaking at 8.67 MPa for the pure scrap PVC. The higher temperature allows for better melt flow, ensuring a more complete integration of the polymer chains, even in 100% scrap PVC, which leads to the highest rigidity observed in the 180°C series. Unlike 175°C, where the modulus drops at 100% scrap, 180°C ensures a more uniform and rigid network due to superior fusion.

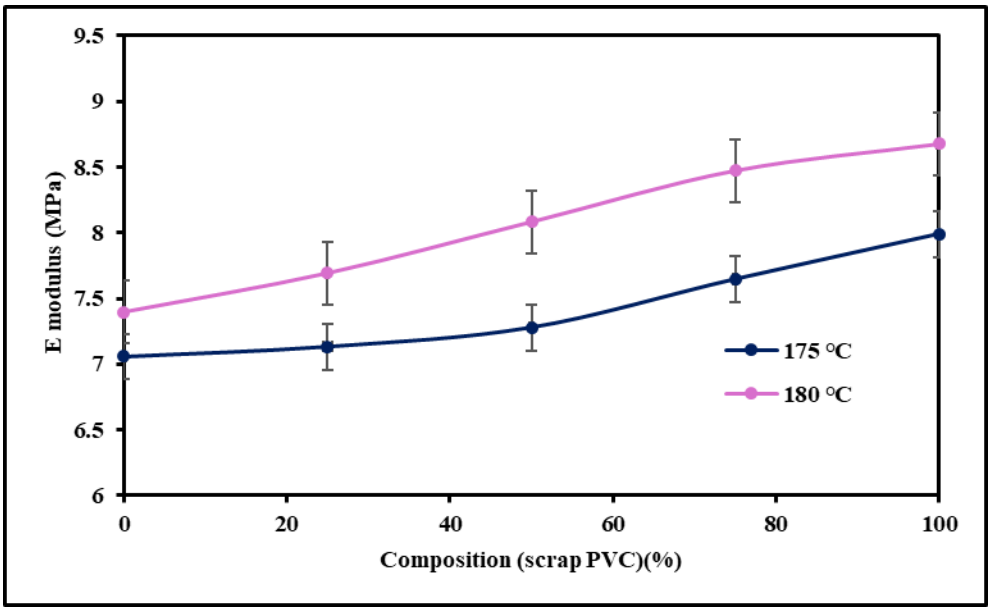

Figure 4.20: Elastic Modulus of PVC Blends at Different Processing Temperatures.

In conclusion, 180°C processing improves overall strength, rigidity, and material integration compared to 175°C. The higher temperature enhances fusion, resulting in better stress transfer and higher UTS and E-modulus. However, the trade-off is a reduction in elongation at break due to thermal degradation and plasticizer loss, making the material stiffer and more brittle. 175°C, while providing better ductility, results in lower strength and stiffness due to incomplete fusion and limited polymer chain entanglement, especially at higher scrap content. The processing temperature thus plays a crucial role in balancing strength, flexibility, and rigidity in PVC blends.

The FESEM image of pure PVC in **Figure 4.21 (a)** displays a highly textured surface with a pronounced layered appearance. This texture is indicative of significant plastic deformation occurring during the fracture process. The presence of visible matrix tearing, with polymer chains being pulled apart, suggests that the virgin PVC has high ductility, enabling it to undergo considerable elongation before failure. The irregularity of the fracture surface further supports the material's ability to deform extensively before breaking, which is typical for ductile materials. The rough fracture surface aligns with the tensile properties of virgin PVC, exhibiting a UTS of 18.58 MPa, which serves as the baseline for comparison. This ductile

behavior and the relatively soft matrix make pure PVC more susceptible to deformation compared to the blends with higher scrap content.

The FESEM image of the 75/25 blend in **Figure 4.21 (b)** reveals a smoother surface compared to pure PVC, reflecting a reduction in ductility as the scrap content increases. The fracture surface of this blend appears more uniform, with less pronounced matrix tearing, suggesting that the material is transitioning from a ductile behavior to more localized failure. The presence of a long, jagged crack in the surface further indicates that the failure mode is shifting. These observations correlate with the increased UTS of 19.3 MPa, which is higher than the virgin PVC, yet the material still shows signs of reduced ductility. The elongation at break of 334.7%, though higher than the pure PVC, is still lower, consistent with the decreased flexibility resulting from the higher scrap content.

The FESEM image of the 50/50 blend in **Figure 4.21 (c)** displays a fine-grained, homogeneous matrix, suggesting that the blend has reached a better integration between the virgin resin and the scrap material. The fracture surface appears more uniform and denser, with minimal matrix tearing, signaling that the material is becoming stiffer and less ductile compared to the 75/25 blend (Dorigato, 2021). The smooth texture, accompanied by small, embedded particles, likely results from the increased scrap content. The reduction in ductility, evidenced by the absence of large voids and deep fractures, is reflected in the higher E-modulus (8.08 MPa) and the reduced elongation (334.03%). This blend demonstrates improved matrix integration, which enhances rigidity while compromising flexibility, indicating a transition towards a more brittle behavior.

The 25/75 blend in **Figure 4.21 (d)** presents a step-like fracture pattern, characteristic of a more brittle material. The surface morphology exhibits distinct vertical relief, with smoother regions between fractures, indicating a transition from ductile to brittle behavior (Leone and Koroma, 2025). The polymer chains in this blend appear more rigid and less flexible, resulting in clearer fracture points. This shift in behavior is further confirmed by the increase in E-modulus (8.47 MPa) and the decline in elongation (321.47%), suggesting that the material is becoming stiffer but with reduced ability to stretch. The increased scrap content in this blend leads to

higher stiffness, but the reduction in ductility highlights the impact of scrap material on the mechanical properties.

The FESEM image of the 0/100 blend in **Figure 4.21 (e)** shows an irregular surface with elongated fibrils and small pits. These features suggest poor fusion between the scrap particles and a lack of effective interfacial bonding (Karthik et al., 2023). The matrix tearing and micro-voiding observed on the fracture surface further confirm that the absence of virgin PVC as a binder result in weak interfacial bonding, which impairs the overall material cohesion. These characteristics are mirrored in the reduction of UTS to 19.23 MPa and the lowest elongation at break of 319.33%, highlighting poor ductility and matrix instability. The rough texture is not due to high ductility but rather due to inadequate fusion between the two phases, leading to lower strength and poor mechanical performance. The slight decrease in E-modulus (7.99 MPa) suggests that the material's rigidity is compromised by the ineffective integration of the polymer chains.

In conclusion, as the scrap content increases in the PVC/sPVC blends, there is a clear progression from ductile to brittle behavior, as evidenced by the changes in the surface morphology and mechanical properties. The 100/0 blend (pure PVC) exhibits high ductility and a smooth fracture surface, while blends with higher scrap content, such as 50/50 and 25/75, show smoother and more rigid surfaces with reduced ductility. The 0/100 blend, with the highest scrap content, demonstrates the poorest fusion and mechanical properties, confirming that higher scrap content negatively impacts the material’s strength and flexibility.

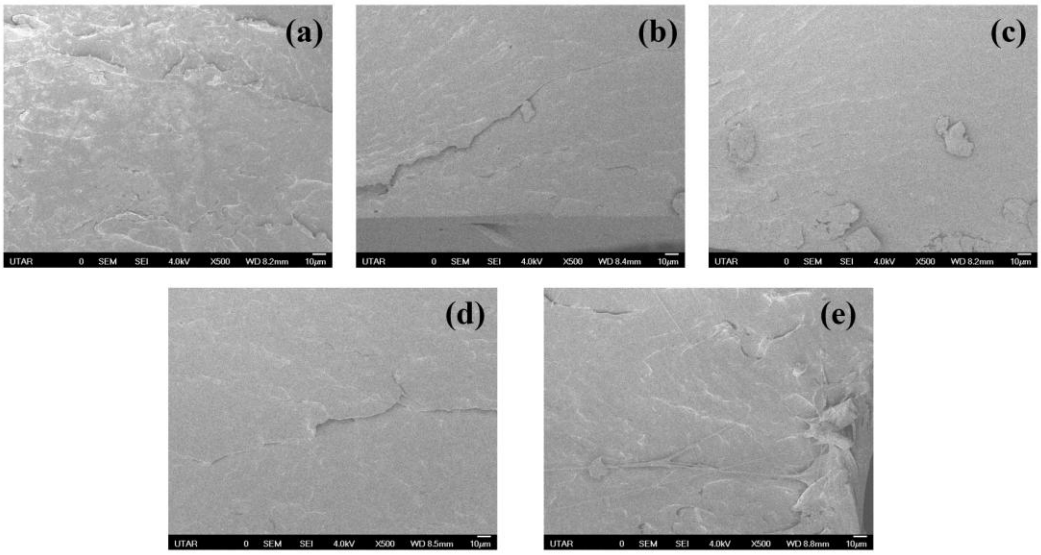

Figure 4.21: FESEM Image at each Composition under the Processing Temperature of 175°C; (a) 100/0; (b) 75/25 ; (c) 50/50 ; (d) 25/75 ;(e) 0/100.

The surface morphology of the virgin PVC at 180°C, shown in **Figure 4.22 (a)**, presents a uniform and featureless appearance, indicative of a fully homogeneous melt. The surface is the smoothest in the series, suggesting that the virgin resin reached a low viscosity, allowing it to flow and solidify into a dense, monolithic block. This smoothness correlates with the relatively lower elongation at break of 330.33%, which is still high but lower compared to the 175°C virgin sample. The lack of significant matrix tearing and only a faint, singular crack line suggests a brittle fracture, which is consistent with the lower elongation observed for the 180°C virgin sample. The surface is indicative of a material that stretched less before failure, which relates to the tensile result where the E-modulus of 180°C is higher than 175°C.

The surface of the 75/25 blend at 180°C, shown in **Figure 4.22 (b)**, exhibits a similar appearance to the virgin PVC, with a smeared or high-flow look. The smoothness of the surface suggests that the virgin resin still dominates the morphology and effectively integrates the scrap particles, resulting in a uniform melt (Dorigato, 2021). This is reflected in the high UTS of 19.6 MPa for this composition, indicating strong material cohesion. The smooth surface also suggests that, despite the increased scrap content, the material retains its ductile nature to some extent.

There is no obvious breaking point or phase separation, which indicates that the material remains cohesive and does not experience the brittleness observed at higher scrap content in this temperature range.

In **Figure 4.22 (c)**, the surface of the 50/50 blend at 180°C shows a plateau-like structure, with large, flat regions. This texture indicates that the material is becoming stiffer and more rigid due to the higher scrap content. The roughness is slightly more noticeable compared to the 75/25 blend, but the surface still appears relatively smooth. This is consistent with the increase in E-modulus (8.04 MPa), as the material is transitioning from ductile to more brittle behavior. The prominent breaking point seen on the surface suggests that the material is starting to fail in a more localized manner, with sharp edges visible at the fracture points. This indicates an increase in brittleness due to the higher temperature processing, which causes thermal degradation of the polymer chains, further contributing to the reduced elongation at break of 324.4% and higher elastic modulus.

The surface morphology of the 25/75 blend at 180°C, shown in **Figure 4.22 (d)**, reveals fine, horizontal striations and ripples, suggesting that the material is becoming more fibrous and less uniform. This surface texture indicates that the scrap content is now dominating the morphology, leading to higher rigidity and less flexibility (Nedjma Tazibt et al., 2023). The roughness is moderate, and the texture appears to reflect the fibrous nature of the material as it becomes stiffer and less flexible. The visible tearing lines are well-embedded within the matrix, suggesting that the higher temperature (180°C) facilitated better integration between the small amount of virgin resin and the scrap, resulting in a more solid and cohesive matrix. The elongation at break for this blend (314.33%) confirms this transition from ductile to more brittle behavior.

In **Figure 4.22 (e)**, the surface of the 0/100 pure scrap PVC at 180°C shows small, crescent-shaped dimples and ripples, suggesting a rougher surface compared to the 175°C pure scrap. Unlike the void-heavy and poorly fused surface at 175°C, the 180°C processing temperature allowed for better melt flow, ensuring that the material fused more effectively. This is confirmed by the fully fused, continuous network observed in the microstructure. The roughness is still significant, but is due

to the natural structure of the scrap material rather than the voids and poor fusion observed at 175°C. There are localized breaking points, but the micro-voids are significantly reduced compared to the 175°C pure scrap, confirming that the higher temperature allowed for better fusion and interfacial bonding. This improved fusion is reflected in the increase in E-modulus to 8.67 MPa and the UTS of 20.23 MPa. The fracture surface shows less matrix tearing, confirming that the material is more rigid and less prone to the void-induced failures observed at 175°C. This is a clear sign that the 180°C processing temperature helped the pure scrap PVC form a stronger and more cohesive material.

In conclusion, the tensile properties and SEM analysis of PVC blends at 175°C and 180°C demonstrate the significant impact of processing temperature on material performance. At 175°C, the material exhibits higher ductility with increased elongation, but poor fusion and weak interfacial bonding at higher scrap contents result in reduced strength and rigidity. The SEM images show rougher, more irregular surfaces with noticeable matrix tearing and micro-voids, particularly in the pure scrap PVC. In contrast, at 180°C, better molecular alignment and fusion lead to improved strength and stiffness, with a linear increase in the E-modulus. However, this comes at the expense of ductility, as thermal degradation and plasticizer loss reduce elongation. The SEM images at 180°C reflect smoother, more cohesive surfaces with reduced tearing and micro-voids, confirming better material integration and enhanced mechanical properties overall.

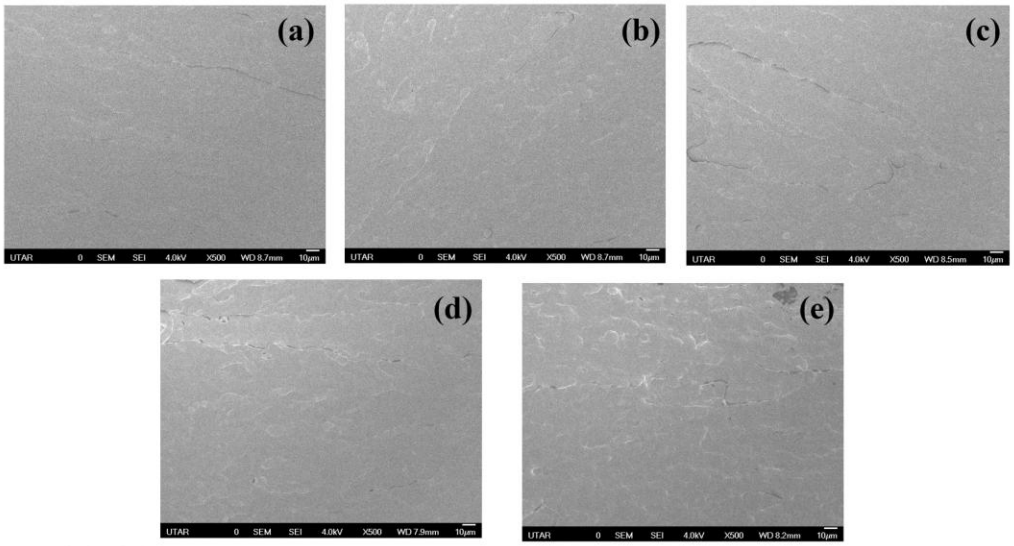

Figure 4.22: FESEM Image at each Composition under the Processing Temperature of 180°C ; (a) 100/0; (b) 75/25 ; (c) 50/50 ; (d) 25/75; (e) 0/100.

4.2.8 Hardness Test

At a processing temperature of 175°C, the Shore hardness of the PVC blends increased steadily with higher scrap content. Referring to **Table 4.23**, the 100/0 had an average hardness of 74.9, which rose to 77.0 for the 75/25 blend, 77.6 for both the 50/50 and 25/75 compositions, and peaked at 78.8 for the 0/100 pure scrap sample. This increase in hardness is attributed to the thermal history of the scrap material, which causes loss of plasticizer content, limiting molecular mobility and increasing resistance to surface indentation.

Table 4.23: Hardness of Blends in All Compositions for 175°C.

Composition (175°C)	Hardness					Average
	1	2	3	4	5	
100/0	77.5	78.0	73.0	74.0	72.0	74.9
75/25	75.0	78.0	79.0	76.0	77.0	77.0
50/50	78.0	80.0	76.0	75.0	79.0	77.6
25/75	80.0	76.0	80.0	81.0	71.0	77.6
0/100	76.0	74.0	75.0	83.0	86.0	78.8

When the processing temperature was raised to 180°C, the hardness values showed a similar upward trend but with a much more significant increase in magnitude. The virgin PVC (100/0) started at 76.9, and the hardness increased sharply through the blends, 78.4 for the 75/25, 80.6 for the 50/50, 83.0 for the 25/75, and 84.2 for the 0/100 pure scrap, as shown in **Table 4.24**. This sharp rise in hardness is mainly due to the enhanced fusion and packing density achieved at the higher temperature. As observed in the SEM images, 180°C promotes a more homogeneous melt flow, enabling the polymer chains to interdiffuse effectively and create a dense, monolithic structure. This dense matrix, combined with the loss of residual volatiles and further plasticiser degradation, results in a significantly more rigid and harder final product (Barnett, 2022).

Table 4.24: Hardness of Blends in All Compositions for 180°C.

Composition (180°C)	**Hardness**					**Average**
	1	**2**	**3**	**4**	**5**	
100/0	78.0	77.5	76.0	75.0	78.0	76.9
75/25	78.0	75.0	77.0	80.0	82.0	78.4
50/50	76.0	79.0	81.0	81.0	86.0	80.6
25/75	80.0	85.0	87.0	77.0	86.0	83.0
0/100	87.0	80.0	82.0	88.0	84.0	84.2

Comparing the two processing temperatures, 180°C consistently results in higher hardness values across all compositions, as shown in **Figure 4.23**. Even the virgin resin exhibited a 2.0-unit increase in hardness at 180°C, confirming that higher temperatures improve the overall density of the polymer network. The gap between pure virgin PVC and pure scrap PVC expanded notably, from 3.9 units at 175°C to 7.3 units at 180°C. These trends align with the results observed in Elastic Modulus and SEM analysis, where superior fusion at 180°C more compact polymer arrangement. While 175°C results in a slightly softer material due to incomplete fusion and micro-voids, 180°C provides maximum surface rigidity at the cost of making the material more brittle and less capable of stretching.

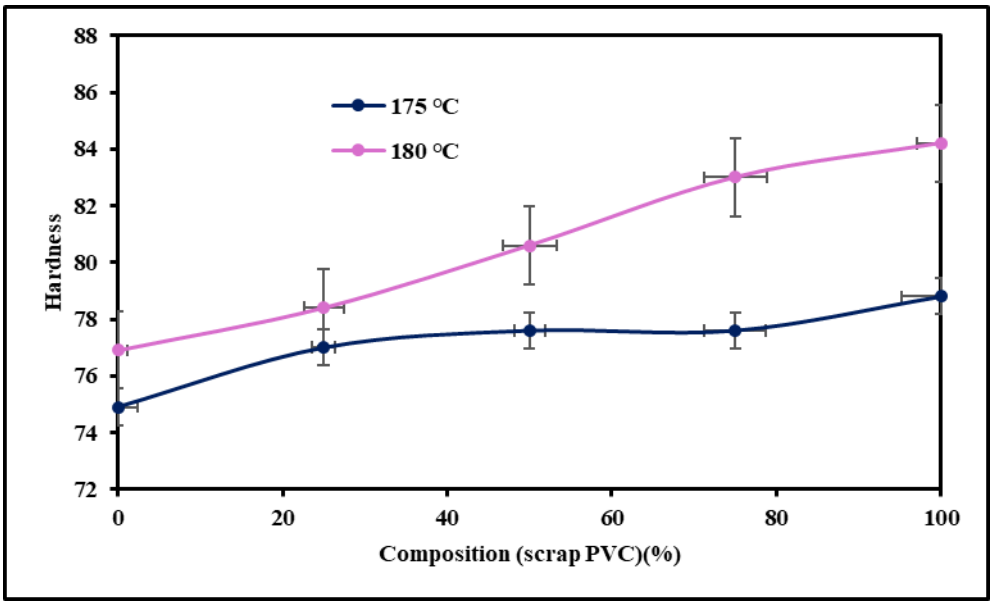

Figure 4.23: Hardness of PVC Blends at Different Processing Temperatures.

4.2.9 Migration Test

Table 4.25: Migration Results of Blends in All Compositions for 175°C.

Composition (175°C)	Weight Loss (%)			Average (%)
	1	2	3	
100/0	0.33	2.13	3.31	1.93
72/25	1.17	0.74	1.26	1.06
50/50	0.00	0.36	2.79	1.05
25/75	0.00	0.66	0.40	0.35
0/100	0.00	0.00	0.52	0.17

Referring to **Table 4.25**, at 175°C, the migration test results show a clear downward trend in weight loss as the scrap content increases. The virgin PVC (100/0) exhibited the highest migration rate at 1.925%, while the 75/25 blend showed a decrease to 1.058%, followed by 1.050% for the 50/50 blend, 0.355% for the 25/75 blend, and a minimum of 0.173% for the 0/100 pure scrap PVC. This trend can be attributed to the fact that virgin PVC contains a higher concentration of mobile

plasticisers and additives designed for initial processing. In contrast, scrap PVC, having already undergone a previous thermal life cycle, likely has a portion of its plasticisers already leached out or degraded. As the scrap content increases, the percentage of weight loss during the migration test decreases.

Table 4.26: Migration Results of Blends in All Compositions for 180°C.

Composition	**Weight Loss (%)**			**Average**
(180°C)	**1**	**2**	**3**	**(%)**
100/0	1.01	1.30	0.00	0.77
72/25	0.78	0.78	0.58	0.71
50/50	0.00	0.56	1.08	0.55
25/75	0.00	0.27	0.33	0.20
0/100	0.16	0.00	0.15	0.11

At 180°C, the migration results follow a similar trend, with higher scrap content leading to reduced weight loss. Referring to **Table 4.26**, the PVC (100/0) showed a migration rate of 0.770%, significantly lower than at 175°C, and the 75/25 blend had a migration rate of 0.712%. The 50/50 blend recorded 0.549%, while the 25/75 blend showed 0.201%, and the 0/100 pure scrap PVC had the lowest at 0.105%. The reduction in migration is consistent with the previous explanation, where the addition of scrap will result in a lesser plasticizer content. However, the notably lower values at 180°C is also proven from its mechanical properties as it has a higher hardness compared to 175°C, proving a lesser plasticizer content.

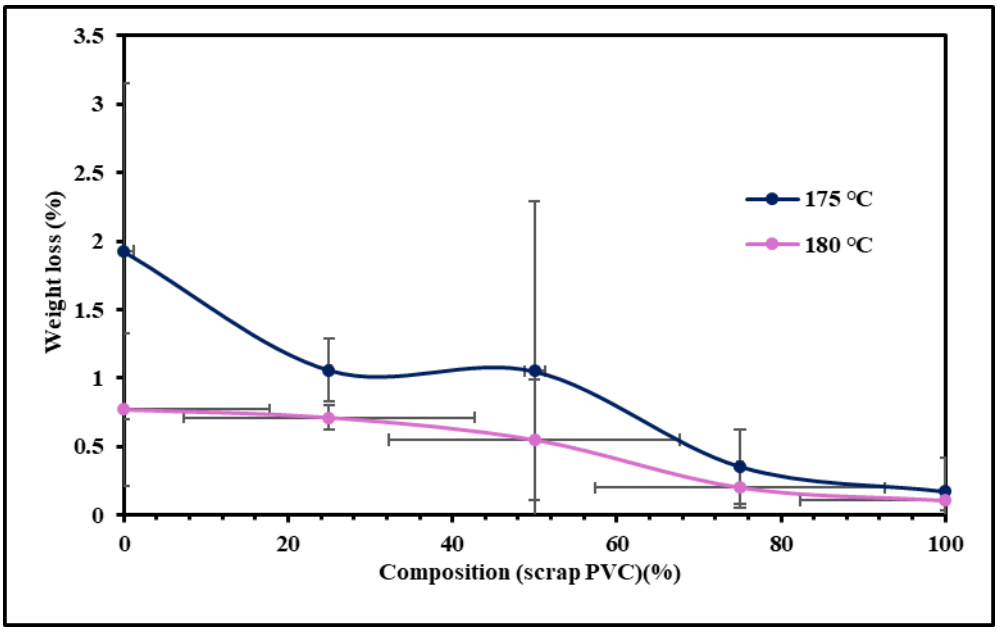

Figure 4.24: Migration Results of PVC Blends at Different Processing Temperatures.

When comparing the two temperatures, the difference in migration rates is shown in **Figure 4.24**. At 180°C, the migration rates are substantially lower than at 175°C for every composition. For the virgin PVC, the weight loss dropped from 1.925% at 175°C to 0.770% at 180°C. This phenomenon is directly linked to the enhanced fusion and integration of the polymer chains at 180°C, as observed in the SEM and E-modulus analyzes. At the higher temperature, the PVC matrix achieves a more monolithic, dense structure with fewer micro-voids, creating a more tortuous path for the low molecular weight plasticizer molecules and effectively trapping them within the polymer matrix (Ramesh et al., 2011). Furthermore, the higher processing heat may cause some initial volatilisation of the plasticisers during compounding, reducing the number of mobile components available to migrate during the test.

In conclusion, the migration analysis confirms that the addition of scrap PVC reduces plasticiser migration, and higher processing temperatures result in a more compact matrix that holds additives more effectively, leading to lower migration rates. This trend highlights the impact of both scrap content and processing conditions on the material's ability to retain plasticizers and other additives.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, this study successfully achieved all three research objectives by systematically evaluating the processing behaviour, material properties, and application suitability of PVC/sPVC blends for bathroom mat applications. The determination of the optimum processing temperature using an internal mixer revealed that the range of 175 °C to 180 °C provides the most favourable processing conditions. At these temperatures, reduced torque values indicated improved melt flow, lower energy consumption, and enhanced fusion between virgin PVC and scrap PVC. In contrast, lower temperatures (165 °C and 170 °C) resulted in insufficient gelation, higher resistance during processing, and inferior mechanical performance, rendering them unsuitable for efficient recycling.

Further investigation into the effect of different PVC/sPVC blend ratios at the optimized temperatures demonstrated that blend composition plays a critical role in balancing processability and material performance. Among all compositions, the 50/50 blend consistently exhibited the most efficient processing characteristics, as evidenced by the lowest loading and stabilisation torque values. This behaviour is attributed to the synergistic interaction between high-molecular-weight virgin PVC and lower-molecular-weight scrap PVC, which enhances chain mobility and reduces internal friction. In terms of physico-mechanical properties, all blends met the minimum tensile strength and elongation requirements, confirming that the incorporation of scrap PVC does not compromise structural integrity. However,

increases in scrap content led to higher stiffness and reduced ductility due to plasticizer loss and chain scission effects. Thermal analysis further confirmed that processing at 175 °C and 180 °C ensures adequate thermal stability, while FTIR results verified that no chemical degradation occurred, indicating that the recycling process is predominantly physical in nature.

From an application perspective, the 50/50 PVC/sPVC blend processed at 180 °C emerged as the most suitable formulation for bathroom mat applications. This condition provided an optimal balance of hardness, strength, rigidity, and durability, while also demonstrating superior water resistance, higher density, and improved chemical stability. The enhanced fusion and reduced porosity at 180 °C contributed to a more compact material structure, minimising water absorption and solvent penetration. Although a slight reduction in elongation was observed at higher temperatures, this trade-off is acceptable given the significant improvements in strength and structural integrity required for the intended application.

Overall, this project demonstrates that recycled scrap PVC can be effectively reintegrated into virgin PVC matrices without compromising performance, provided that appropriate processing conditions and blend ratios are selected. The findings highlight the technical feasibility and sustainability potential of PVC recycling, particularly in value-added applications such as bathroom mats. By identifying the optimal processing window and composition, this study contributes to the advancement of environmentally responsible polymer processing while maintaining compliance with industry performance standards.

5.2 Recommendation

For future work and further improvement of this study, several key areas can be explored to enhance both the material performance and the overall applicability of PVC/sPVC blends. Firstly, although the present study identified 175 °C and 180 °C as the optimal processing temperatures, a more refined investigation within this temperature window (e.g., 176–179 °C) could be conducted to determine a more

precise optimum point. Additionally, the effect of processing parameters such as rotor speed, mixing time, and shear rate in the internal mixer should be examined, as these factors can significantly influence fusion behaviour, thermal degradation, and final material properties.

Secondly, the incorporation of additives offers strong potential for improving the performance of high sPVC-content blends. Future studies may investigate the use of thermal stabilisers, impact modifiers, and compatibilizers to enhance interfacial bonding, reduce degradation, and improve ductility, especially at higher processing temperatures such as 180 °C. The addition of fillers or reinforcing agents, such as calcium carbonate or natural fibres, could also be explored to tailor stiffness, cost efficiency, and wear resistance for specific applications like bathroom mats.

Furthermore, while this study focused on short-term physico-mechanical, thermal, and chemical properties, long-term performance evaluation is highly recommended. Future research should include ageing studies such as UV exposure, thermal ageing, and cyclic loading to assess durability over time. This is particularly important for bathroom mat applications, where materials are continuously exposed to moisture, temperature fluctuations, and mechanical stress.

In addition, advanced morphological and structural analyzes could be further expanded. Techniques such as Differential Scanning Calorimetry (DSC) and X-ray Diffraction (XRD) may provide deeper insight into crystallinity, phase behaviour, and molecular interactions within the blends. This would complement the existing FTIR and FESEM analyzes and provide a more comprehensive understanding of structure–property relationships.

Lastly, scaling up the process from laboratory to industrial level should be considered. Future work may involve pilot-scale extrusion or injection moulding to evaluate the consistency, process stability, and economic feasibility of producing PVC/sPVC blends on a commercial scale. A life cycle assessment (LCA) could also be conducted to quantify the environmental benefits of recycling scrap PVC, thereby strengthening the sustainability argument of this material system.

Overall, these recommendations aim to refine the processing conditions, enhance material performance, and broaden the applicability of PVC/sPVC blends, ultimately supporting the development of more efficient and sustainable polymer recycling technologies.

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