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The use of recycled polypropylene as a potential cheapening agent for manufacturing external/internal automotive components

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List of Abbreviations

ABS – acrylonitrile-butadiene-styrene

aPP – Atactic polypropylene

DMA – Dynamic Mechanical Analysis

DSC – Differential scanning calorimetry

ENB - Ethylidiene-Norbenene

EPDM – Ethylene-propylene-diene-monomer

GPC – Gel Permeation Chromatography

GWP – Global warming potential

HDPE - High density polyethylene

I - Incineration

iPP – Isotactic polypropylene

L - Landfill

LDPE – Low density polyethylene

MFI – Melt flow index

Mn – Number average molecular weight

Mw – Weight average molecular weight

MWD – Molecular weight distribution

MWh – Mega-Watts/hour

ND – Not detected

PC- Polycarbonate

PE – Polyethylene

PET – Polyethylene-terephthalate

PP – Polypropylene

PS – polystyrene

PVC – poly-vinyl-chloride

R - Recycling

rPP – Recycled polypropylene

rPP-1 – Domestic recycled plastic

rPP-2 – Bin lids recycled plastic

rPP-3 – Mixed crates recycled plastic

rPP-4 – Automotive recycled plastic

sPP- Syndiotactic polypropylene

SDT – Simultaneous DSC-TGA

T-20 – 20% by weight Talc

TEU – Total energy use

TGA – Thermogravimetric analysis

TPE – Thermoplastic elastomer

T_d – Degradation temperature

T_g – Glass transition temperature

T_m – Melt temperature

ΔH_m - melting enthalpy

X_c - Crystallinity

vPP – Virgin polypropylene

VW - Volkswagen

Wt % - Weight percentage

List of Units

ºC – Degrees Celsius

ºC/min - Degrees Celsius per minute

g – Grams

J/g – Joules per gram

kJ/m^2 – Kilo joules per meter squared

mm - Millimetre

MPa -Mega Pascal’s

N – Newton’s

N/min – Newton’s per minute

R/Kg – Rand per Kilogram

Abstract

The growing industrialization brings about the demand for the use of vehicles where the manufacturing of plastic components is both costly and environmentally unfriendly. To put things into perspective, virgin polypropylene (vPP), the mostly used thermoplastic in automotive components, costs about R28/Kg before processing into an automotive component and is produced from petrochemical feedstock such as crude oil with harmful gases as by-products. This means the price of this polymer is high, dependent on the volatile price of oil and its carbon footprint ranks very high; hence many companies are gearing towards using recycled materials. As for PP, recycled PP (rPP) is cheaper (averaging R8.40 /Kg) depending on the source as well as the grade of the plastic. Previous studies showed that recycled PP can be used in manufacturing of industrial composites when blended with virgin PP up to a certain percentage to avoid the reduction in fundamental properties of the material. The use of recycled PP plastic in manufacturing can also aid in reduction of waste plastic scrap available globally, and therefore contribute towards its circular economy.

The investigation is based on using recycled polypropylene (rPP) plastic materials to manufacture internal and external automotive components (specifically a door panel and radiator grill), without compromising the properties, and to screen the type of recycled plastic which is best suited for the manufacturing of these components. Raw rPP was upon receipt tested for MFI, crystallinity and composition before blending with vPP. The rPP/vPP blend samples were prepared using typical processing equipment and tested for various properties such as impact strength, flexural strength and heat deflection temperature using an Izod Charpy Impact tester and DMA. The results were compared with the formulations of a commercial door panel and radiator grill. The data indicated that an increase in the amount of recycled materials in the blends decreases the impact resistance and increases flexural strength. Sample rPP-1 50/50 (i.e. 50 rPP:50 vPP blend) has shown fairly good results when compared to other samples in terms of impact and flexural strength. The wide temperature working range for the radiator grill was observed in the rPP-3 80/20 and rPP-1 50/50 blends. The blends of rPP-1 specific to rPP-1 50/50 and blends of rPP-3 specific to rPP-3 80/20 proved that recycled plastics can be used for manufacturing of the door panel and a radiator grill and their use can reduce the automotive manufacturing costs.

Key words: polypropylene, recycled plastics, door panel and radiator grill, impact strength, flexural properties, heat deflection temperature, MFI and crystallinity.

Chapter 1: Outline

This chapter gives a brief outline on the aim and the objectives of the study. It also highlights the motivation for the study carried out.

1.1 Aims

The project's aim is to use recycled plastic material as a potential cheapening agent for the manufacturing of internal and external automotive components (door panel and radiator grill) without compromising the mechanical properties. It is also to screen the type of recyled plastic suitable for manufacturing these automotive components.

1.2 Objectives

- Source out and characterize recycled polypropylene materials as well as a door panel and radiator grill for their rheological,thermal degradation and dynamic thermo-mechanical properties components.
- Use a single step process to homogenous recycled PP within the matrix of the virgin PP using Injection Moulding.
- Evaluate the blends for static and dynamic mechanical performance with respect to the respective automotive components.
- To screen and distinguish between various types rPP sources as potential cheapening agents.

1.3 Significance of the study

This study seeks to use plastic waste (polypropylene) material to positively economically impact the manufacture of automotive components, opening an off-ramping solution to the uptake and reduction of plastic waste for economic and environmental development. The promotion to the use of recycled polypropylene and plastics in general will assist the growth of localization by material cost reduction while assisting to provide social, and economic benefits but may also preserve natural resources and potentially create and/or preserve jobs.

1.4 Scope of the study

The purpose of the study is to use recycled plastic material as a potential cheapening agent for manufacturing internal and external automotive components, namely a door panel and a radiatior grill, without compromising fundamental mechanical properties. The blends will be prepared based on the automotive manufacturing formulation as embedded on the automotive part as well as the 80:20 (CR:V) winning formulation reported in a previous study by Masele *et al* on the development of polypropylene – waste tyre crumbs based TPE's with the aid of Vistamaxx^{TM} as an ethylene propylene monomer (EPM/EPR) compatibilizer. The effect of incorporating recycled plastic on the properties of PP will be investigated and PP-T20-5%EPDM will be used to set a benchmark to test against the recycled polypropylene. This specific formulation was chosen based on the formulation of the door panel; where T20 means 20% by weight of talc is present in the formulation.

The thermal, physical, and mechanical properties of the raw materials as well as the formulated blends will be studied. Thermal properties such as the MFI grade, thermal stability, percent of crystallization, glass transition behaviour as well as the melting behaviour of the blends will be evaluated using the Melt Flow Index tester (MFI), Simultaneous dynamic thermogram (SDT) and Dynamic Mechanical Analysis (DMA). Mechanical properties such as the flexural properties and impact strength will also be studied using the Dynamic Mechanical Analysis (DMA) and Impact Izod Charpy tester respectively.

Chapter 2: Introduction

This chapter provides a summary of the different types of plastics as well as their applications where the focus is mainly on polypropylene which is the most used plastic in the automotive sector. It also highlights the use of recycled polypropylene in the market and how its application affects the properties of the end-use product as well as its cost implications on the sector. The literature provided gives an insight on the promotion of this recycled plastic to reduce the manufacturing costs of internal and external automotive components as well as the properties to be looked out for which need to be investigated prior to their use.

2.1 POLYMERS

Polymers are all around us existing as in the natural form and synthetic form. These polymeric materials are defined by their monomers which are the repeating building blocks of each polymer [1]. Examples of natural polymers can be microscopic and macroscopic, where DNA, protein, carbohydrates, and lipids are a few good examples of microscopic natural polymers. On the other hand, cellulose, skin, wool, latex, and silk are some of the good examples of macroscopic natural polymers [1]. Furthermore, synthetic polymers are polymeric materials that are manufactured by means of chemical reaction, where the examples of these polymers include but are not limited to bakelite, fibrous glass, nylon, silicon rubber, and plastics [1]. Plastics are materials which are capable of being shaped and moulded, and most of them are derived from petrochemical feedstock which is originally from oil, coal, and natural gas where the majority of monomers used to make plastics such as propylene and ethylene are derived from fossil hydrocarbons [2].

Plastic materials have become an indispensable part of daily life due to having several desirable characteristics and properties such as low density, low-cost, high durability, easy to process, long shelf-life, fabrication capabilities, reusability, and recyclability [3-5]. Plastics are used in many applications which include medical delivery systems, water desalination, communication materials, and in the manufacturing of vehicle components such as bumpers, grills, door panels and an underbody cover [6].

According to Awoyera *et al*, the most common plastics which are widely used in domestic and industrial applications due to their intrinsic characteristics are polypropylene (PP), low density polyethylene (LDPE), high density polyethylene (HDPE), polyethylene terephthalate (PET or PETE), polyvinyl chloride (PVC), and polystyrene (PS) with their global production, properties, recyclability, and applications summarised in Table 2.1; the largest producers of plastics in South Africa are SAFRIPOL, DOW PLASTICS, TRINSEO, PETCO and INTERGULF [3, 4].

Table 2.1: Various plastic applications and production rates [7].

Type of plastic	Percentage of plastic used in applications (%)	Applications
PP	26.8	Internal and external automotive components, containers, crates, carpets, fabrics, plumbing pipe, irrigation hoses, plastic pails, bin lids, pharmacy prescription bottles, ropes and cords, straws.
LDPE/LLDPE	20.3	Films, sheets, flexibles such as flexible tubing, plastic bags, geo-membranes.
PVC	18.3	Cabling, insulation jackets, synthetic leather, clear jars, shower curtains, cling film, containers for window cleaners and edible oils.
HDPE	17.9	Internal and external automotive components, pipes and hoses, carpets, crates, cooler box containers, pharmacy prescription bottles, containers, 3D printing filaments, plastic chairs and tables, bins.
PET	8.6	Fabrics and carpets, beverage bottles, take away packaging, jars for cool drink and peanut butter, fleecy jackets.
PS and others	8.1	Sheets and screens, forms, CD cases, disposable cups, toys, egg cartons.

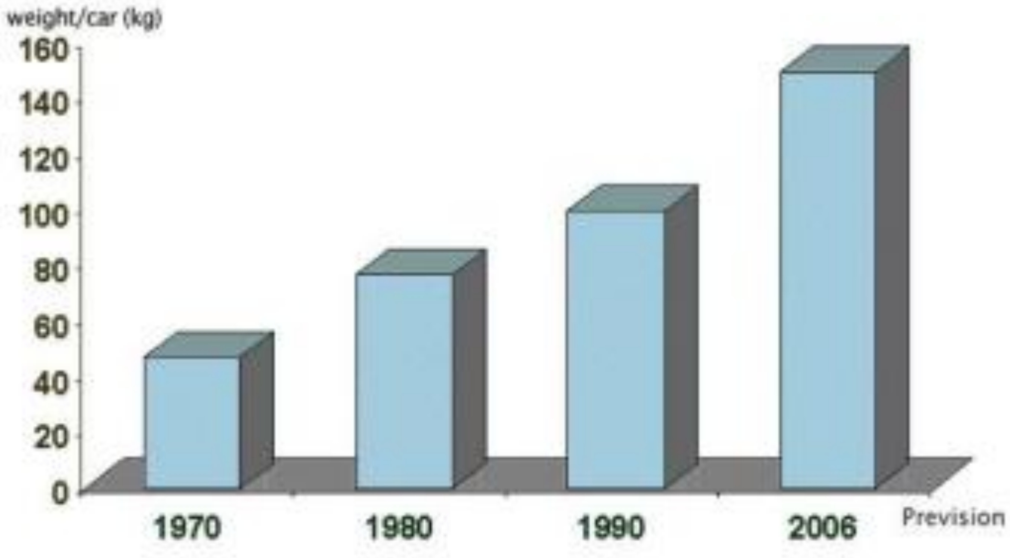

Figure 2.1: Increase distribution of plastic by weight in vehicles between 1970-2006 [8].

Ferdous *et al* reported that the production of plastics globally has increased from 180 million tons to 360 million tons between 2000 and 2020 with Asia being the largest producer of plastics with a percentage of 51% followed by Europe (16%), Africa (7%) and Latin America (4%) [3].

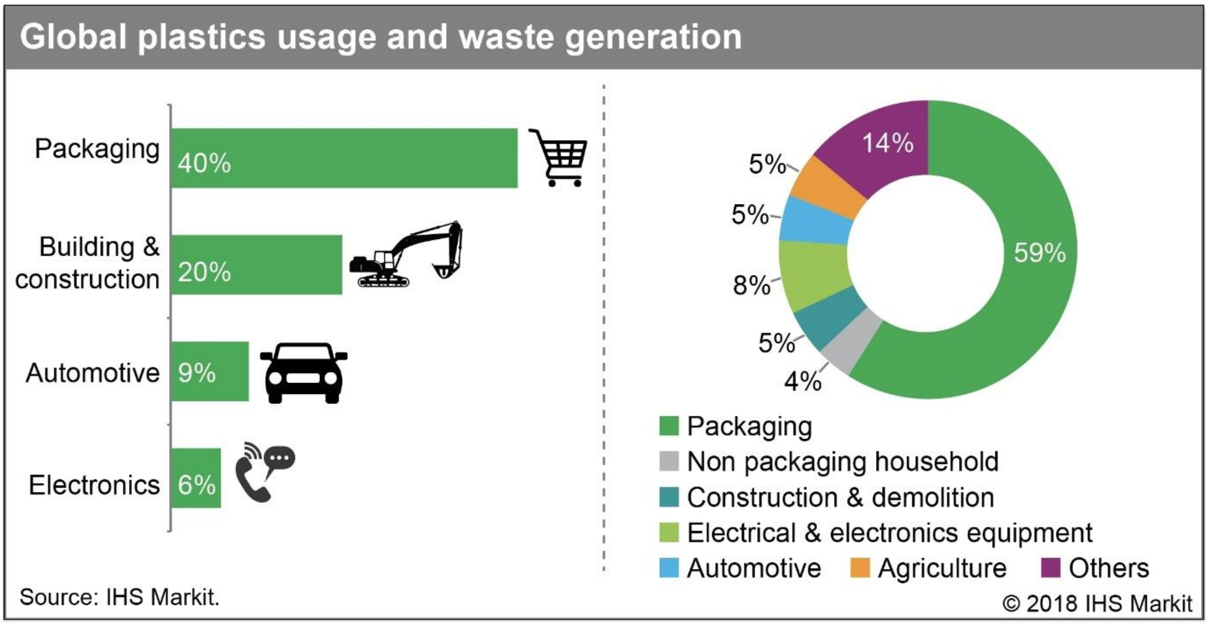

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Figure 2.2: Global plastics usage and waste generated [9].

The on-going growth in the production and disposal of these non-biodegradable plastics raises environmental concerns as there is contamination of soil, water and air which may threaten the lives of both humans and livestock. Also, there is a big debate of whether plastics should be recycled, incinerated, or disposed in landfill sites where the results from the lowest to the highest best practice of managing plastics are summarised in Table 2.2, with the low negative impact practise being recycling followed by landfilling then incineration [3, 10].

Table 2.2: Best practice of plastic management [3]

Year of study	**Material/application**	**GWP (tonnes)**	**TEU (kJ/kg)**
2019	PET and PE	R < L < I	-
2018	Plastic films	R < L < I	-
2013	PET	R < L < I	R < I< L
2009	Non-recyclable plastic	I < L	-
2005	PE, PP, PS, PET and PVC	I< L < R	I < R < L
2003	PE and PET liquid containers	R < L < I	R < I < L
2001	Plastic packaging	R < L	R < I < L
2001	HDPE, PVC, PET	R < L < I	R < L

Ferdous *et al* further reported that recycling 1 ton of plastic saves about 16.4 barrels of oil, 5,8 MWh of energy and approximately 22.9 m^3 of the landfill space, but several aspects such as the quality of the recycled plastic product and economic value must be taken into consideration [3].

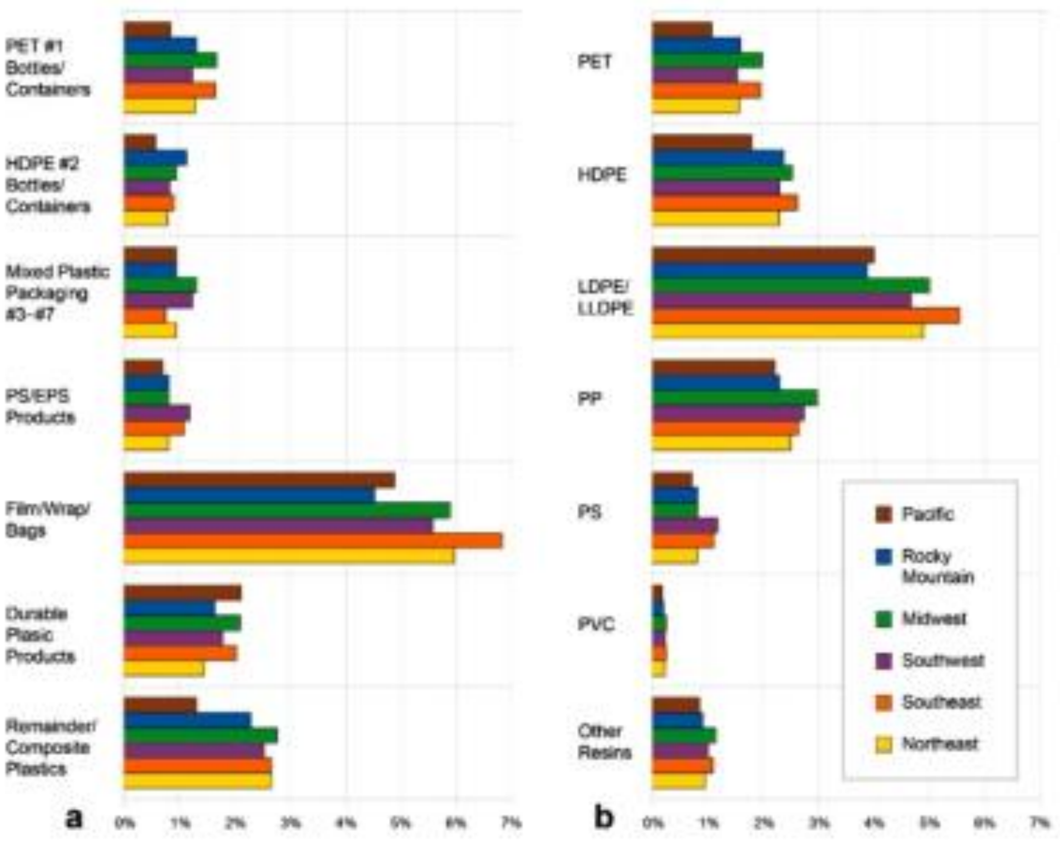


Figure 2.3: Illustration of average plastic waste by materials and resin type [7].

3.1 PLASTICS

Plastics can be divided into two types of materials known as thermoplastics and thermosets. Thermosets are materials which tend to form and set shape upon heating, and this process is not reversible [11]. These materials can either be rigid or flexible depending on the degree of cross-linking between the polymer chain as shown in Figure 2.4. Also, thermosetting plastics have superior properties when compared to thermoplastics such as high thermal stability, rigidity, strength, excellent electrical and thermal insulating properties [10]. The highlighted properties are stemming from thermosets being highly cross-linked polymers which have a 3D-network of atoms that are covalently bonded affording them to be used mainly in structural applications where high strength and stiffness is required to resist a heavy load [12]. Furthermore, the high degree of crosslinking in these plastics make them not to be recyclable, remoulded, or reformed when heated [12].

The common examples of thermosets include polyurethanes, vulcanised rubbers, epoxy resins, phenolic resins and amino resins with these types of resins being widely used to modify textiles such as cotton and rayon where they enhance properties such as crease resistance, water repellence and control in shrinkage [13]. Thermosets are used in many applications such as in 3D printing, encapsulation, electrical insulation, making of sealants, adhesives, and castings [14].

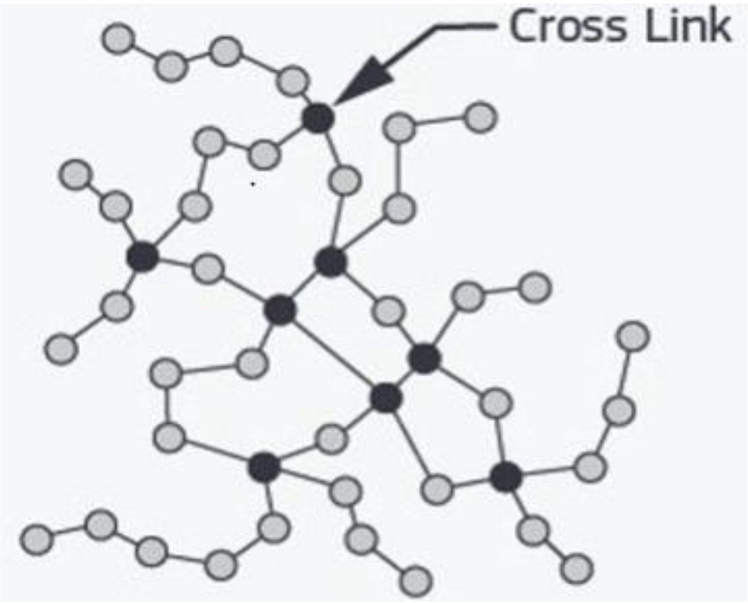


Figure 2.4: Molecular alignment of thermosetting plastics [14].

On the other hand, thermoplastics are two-dimensional polymer molecules which can be melted and reshaped through the application of heat and pressure [15]. These materials fall within two classes of molecular arrangement namely amorphous and semi-crystalline where the amorphous thermoplastics are brittle below the glass transition temperature with restricted mobility of the molecular chain. Above the glass transition temperature, the polymeric materials become less rigid and more flexible due to increased mobility of the molecular chain where the plastic becomes soft and elastic [16]. Due to the random alignment of the molecules with not set patterns, the polymer transitions are restricted to glass transition temperature only [14]. However, crystalline thermoplastics have a much more defined molecular alignment as shown in Figure 2.5. These types of materials exhibit melting which is associated with the collapse of the crystalline molecular structure.

Semi-crystalline thermoplastics have a combination of both the crystalline and amorphous regions in their molecular structure. This combination of the regions is essential for the formation of materials which must possess good strength and have some degree of flexibility or softness which is contributed by the amorphous regions [1, 17]. Additionally, these plastics are brittle below the glass transition (T_g) with a limited molecular motion of the polymeric chains and above the glass transition (T_g) they are less rigid and the polymer chains are randomly arranged where the polymer material is soft and elastic [14, 16, 17]. Furthermore, the semi-crystalline thermoplastics have a clear glass transition with the main thermal transition being a melting point [1].

Figure 2.5: Molecular alignment of thermoplastics [18].

According to the Michelin Group Company, the most critical property of thermoplastics is their ability to be reused, repurposed, and recycled. This is achievable since thermoplastics soften when heated enabling them to be remoulded into a new shape. This process is known to be reversible since there is no chemical bonding taking place which further enables manufactures to be able to recycle the material without it degrading [14].

Another key property of thermoplastics is in their chemical and shrink-resistance which allows them to be slow to corrode, degrade and lose performance when in-contact with chemicals, gases, and fluids. This makes thermoplastics ideal to be used as seals and valves more especially in the “can’t-fail” applications such as in energy production and transmission, water filtrations and pharmaceutical production sectors [14].

Additionally, thermoplastics have an excellent strength-to-weight ratio which makes them to be useful in industries where weight is critically considered such as in the automotive and aerospace industries where these plastic materials are preferred over some metal parts. Also, these engineered thermoplastics are used due to their durability, high resistance to abrasion and temperature [14].

The use of thermoplastics in the automotive industry is very essential since the thermal characteristics of these plastics are important in the design and selection of the automotive components. The light-weightiness of these plastics translates to great fuel economy and low carbon dioxide emission (15 kg CO_2/kg of plastic) [14, 19]. Furthermore, the easy production of these polymer material saves costs as they can be moulded in precise dimensions and geometries without the use of excess material, and in shorter production cycles which significantly saves energy [12].

Lastly, the applications of these plastics in industry are stress and temperature dependent as these have an intense effect on the molecular arrangement of the polymer thus also affecting the properties of the thermoplastic [14]. Examples of common thermoplastics used in industrial applications include but not limited to linear density polyethylene (LDPE) , high density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), acrylonitrile-butadiene-styrene (ABS), polyamide (PA), poly(vinyl) chloride (PVC) and copolymers as show in Table 2.3 [12].

Table 2.3: Commonly used thermoplastics in Industrial Applications [1].

Thermoplastic	**T_m (ºC)**	**T_g (ºC)**	**Crystallinity**
Polyamide (PA 66)	260	50	Crystalline
Polycarbonate (PC)	-	150	Amorphous
Polyethylene terephthalate (PET)	70	265	Semi-crystalline
Polyvinylchloride (PVC)	-	50-80	Amorphous
Polypropylene (PP)	165	-10	Semi-crystalline
Acrylonitrile-butadiene-styrene (ABS)	-	110	Amorphous
Polystyrene (PS)	-	100	Amorphous
High density polyethylene	135	-125	Semi-crystalline
Low density polyethylene	115	-125	Semi-crystalline

There are two types of polyethylene plastics that are popular, and these are LDPE and HDPE. LDPE is used to make plastic grocery bags, plastic bottles, and other packaging products. This is possible due to properties it possesses such as being flexible, having good elongation, impact strength and transparency while HDPE which has high melting point, rigidity, strength, low water absorption, excellent electrical properties and good residence to radiation and corrosion is used in the manufacturing of 3D filaments, pipes, toys, and plastic furniture [8].

PVC is an amorphous thermoplastic which offers good mechanical strength, chemical stability and high electrical performance enabling it to replace a variety of building materials such as metals, wood, rubber, and ceramics while its vinyl content leads to a good tensile strength. PVC is used in many applications such as in the manufacturing of automobile instruments panels, sheathing of electrical cables, pipes and chemical tanks [8, 14].

Polystyrene is commonly used in the production of styrofoam cups, buttons and car fittings due to it being easy to manufacture even though it has poor resistance to radiation [8]. ABS is a durable thermoplastic, and it is resistant to some chemicals. It is rigid with a rubber-like characteristic that gives this plastic good impact resistance and affords it to be used in the making of vehicle dashboards and covers. Polyamide on the other hand is known as nylon 6 / nylon 6.6, both nylons are resistant to abrasion and have good chemical resistance. They are hydrophilic as a result they expand in wet/humid condition; this causes a challenge in applications where dimensionally stability is required. Additionally, PA is used to make gears, bearing and weather-proof coatings [8].

Polypropylene is the most abundant thermoplastic, especially in the automotive sector, and therefore of interest to this study.

3.2 POLYPROPYLENE

Polypropylene (PP) is one of the most produced thermoplastics and it is made from the propylene monomer via the process called polymerization due to its variety and versatility of being used in many applications. For instance, in the food sector it represents 32% in products such as packaging, lids, Tupperware's, and bottles while in the consumer goods sector it represents 17% of the market [1, 20]. According to Barbosa *et al*, polypropylene represents 9% of the materials used in the automotive industry where it is used to manufacture dashboards, door panels, bumpers and grills, making it the most dominant plastic used in automotive components [20, 21].

PP exists in many forms which are isotactic, atactic (amorphous) and syndiotactic where the difference lies in the arrangement of the methyl pendant group which is attached to every second carbon in the chain; thus giving rise to different properties and enabling it to be used in many applications [1]. When the methyl groups are on the same side of the polymer chain, the product is called an isotactic PP, and when these pendant methyl groups are attached to the backbone of the polymer chain in an alternating manner a syndiotactic PP is obtained. A PP structure with the methyl pendant groups attached randomly to the backbone of the polymer chain are referred to as an atactic PP [1].

According to Seymour *et al*, isotactic and syndiotactic polypropylenes have similar T_g's but are different in terms of stiffness and toughness with the isotactic PP being stiff and having a relatively high T_g when compared to the atactic and syndiotactic polypropylene [1, 23]. Nielsen *et al* reported that the isotactic polypropylene is highly crystalline and this degree of crystallinity in this plastic is dependent on the thermal history, tacticity, and deformation with iPP having a degree of crystallinity ranging between 40% and 60% [24, 25].

PP which has a "perfect" isotactic arrangement has a melting point of 171 ^{o}C whereas the commercial isotactic PP has a melting point ranging between 160 ^{o}C to 166 ^{o}C and this depends on the tacticity and crystallinity [1]. According to literature, the syndiotactic PP is 30% crystalline with a melting point of 130 ^{o}C while the atactic PP is amorphous [26]. A wide range of techniques such as DSC, X-Ray diffraction, X-ray scattering and Raman spectroscopy may be used to provide a quantitative measure for the degree of crystallinity [24, 27].

The isotactic polypropylene is the most used type due to its high crystallinity which makes it to possess properties that are desirable for many applications such as high tensile stress, stiffness, and hardness while also leading to a decrease in the impact strength as well as in processability of the polymer. The physical properties as well as the processing characteristics of this type of PP are dependent on the molecular weight, molecular weight distribution, MFI, crystallinity, type, and the amount of the copolymerizing monomer [21].

The average molecular weight which is expressed as Mn and Mw with the molecular weight distribution (MWD) of a plastic are important factors which affect the physical and mechanical properties of the final product polymer where gel permeation chromatography (GPC) is the most used technique to determine them [28].

2.3.1 FLOW BEHAVIOUR AND PHYSICAL PROPERTIES OF PP

The flow behaviour properties of polypropylene are influenced by crystallinity, molecular weight, MFI, melting point, and viscosity of the polymer. The tacticity of PP dictates the viscosity of the polymer. Because polypropylene exists in many forms, its flow behaviour differs, and this is greatly linked to its crystallinity which is highly dependent on tacticity [29]. For example, the atactic PP easily flows due to the random arrangement of the methyl pendant groups on the backbone of carbon chain which allows it to have more molecular motion as compared to the isotactic and syndiotactic polypropylene. Also, this form of PP does not exhibit crystalline regions in its structure but rather it is amorphous which makes it to have a low melting point as compared to iPP and sPP thus limiting its use in many applications [14, 30].

Additionally, the isotactic arrangement/configuration in PP prevents PP from crystallizing in a zig-zag planer shape but rather in a helical crystal structure making it to have a high degree of crystallization. This decreases the molecular motion of the polymer chains thus leading to an increase in melting temperature, meaning that there will be an increase in the melt viscosity during processing [30].

Furthermore, the flow behaviour of polypropylene (viscosity) is affected by the melt flow index which is dependent on the molecular weight/chain length of the polymer [31]. According to literature, an increase in the molecular weight of polypropylene translates to a decrease in the melt flow index and leads to an increase in viscosity. This is possible since an increase in molecular weight decreases the mobility of the polymer chain because of increased chain interactions such as Van de Waals forces and entanglements of polymeric chain which makes lamellar crystals to be formed as the chain length is increased [14]. Additionally, the interactions existing between the polymeric chains make individual polymer chains to be strongly fixed in their respective positions and to resist any deformations, and matrix breakup.

The physical properties of PP such as hardness, tensile and impact strength are strongly linked to the molecular weight, molecular weight distribution, MFI, crystallinity, type, and the amount of the copolymerizing monomer [21]. According to Maddah *et al*, polypropylene has high softening or glass-transition point, high resistance to flexing stress, low water-absorption, good electrical resistance, dimensional stability, and high impact strength which is affected by the degree of crystallinity in the material which is dependent on tacticity [32].

A low degree of crystallinity in PP leads to a decrease in tensile strength and hardness while causing an increase in the impact resistance; this is due to the decrease in the rigid sites of the PP matrix as there is a decrease in chain interactions thus more mobility in the molecular structure [33]. On contrary, an increase in the crystallinity of PP leads to an increase in tensile strength and hardness, while causing a depression in properties such as tensile elongation and impact resistance due to an increase in the available rigid site of the matrix [19, 20].

Additionally, a decrease in the molecular weight and a wide molecular weight distribution of a polymer improves physical properties of PP while also leading to a depression in tensile strength, elongation, impact strength and stress cracking resistance. This can be related to a decrease in the polymer chain crystallinity (low crystallinity) [33].

2.3.2 MECHANICAL FAILURE AND MODIFICATION OF PP

A homo-polymer propylene (HPP) is widely used in industries and is a two-phase system which contains both crystalline and amorphous regions where these regions have both isotactic PP and atactic PP. Maddah *et al*, reported that the isotactic PP in the amorphous regions is crystallisable. However, it crystallizes slowly over a long period of time [32]. Additionally, this propylene has only one propylene units along its chain which is mostly made of isotactic propylene units to give a crystalline structure. Because of the high degree of crystallinity in this PP, it has high stiffness, high melting point and high softening or glass-transition point, and a high impact strength [32].

However, low impact strength is observed in polypropylene during low temperature applications such as when it used to manufacture an underbody cover and radiator grill of a vehicle, which is affected by low temperatures in snow condition. In instances such as these, the polypropylene is used closer to its glass transition temperature and when a force is applied to these polymeric chains which are less mobile during the low temperature application of this plastic, the material becomes brittle and sensitive to fracture as a way to relieve stress [14].

There are ways which have been introduced to lower the T_g of PP which include the addition of filler materials such as glass fibre, and the copolymerization of polypropylene with other thermoplastics such as ABS and polyethylene [34]. According to the studies by Maddah *et al*; the type and amount of the copolymerizing monomer affects the physical properties of polypropylene particularly the impact strength where random copolymers such as ethylene/propylene copolymers produced by copolymerizing the propylene monomer and small amounts of ethylene monomer [32].

During copolymerization, the ethylene monomer disrupts the orientated regular structure of polypropylene and leads to the reduction of the crystalline uniform regions in the polymer. This is possible since the relationship between the ethylene monomer is inversely proportional to the crystalline thickness, meaning that an increase in the ethylene content causes a decrease in crystalline thickness which results in a low melting point [32]. This decreased melting point in the copolymers enhances the flexibility of the matrix thus giving better/ improved impact properties of PP [32].

Maddah *et al* highlighted that for low temperature applications of polypropylene which are below −20°C, it is ideal to copolymerize it with polyethylene since the ethylene content which acts as a reinforcement that can improve impact strength. However, the stiffness of the material becomes retained resulting in excellent stiffness/impact balance [32].

3.3 RECYCLED rPP

Recycling is the process of using waste materials to make new products and it involves five steps, which are; collection, sorting, cleaning, reprocessing by melting and producing rPP products [14, 35]. According to Leblanc *et al,* the first three steps are the same as recycling most other commodities while the last two are critical in the reprocessing of recycled polypropylene [14].

Polypropylene is an adaptable plastic material with a printed ‘resin code’ of 5 which is extremely useful during recycling as it is indicative of the type of plastic the material is made of. Furthermore, this ensures separation and efficient recycling of different types of plastics [14]. Recycled PP can be used to make many different types of products which include fibres for clothing and industrial materials, kitchenware, food containers, and gardening apparatus such as compost bins, plant pots and garden edging [14].

The recycling of PP reduces the amount of waste disposed in landfills which significantly contributes to the conversion of waste products as well as in saving energy [36]. However, Rebeiz *et al* highlighted that the recycling of polypropylene can have technological and economic constraints which can limit its use due to the possible contamination of PP with other materials such as dirt, non-ferrous and ferrous metals whose removal is a lengthy and a complex process when using magnetic and eddy current separators [37]. The metal contamination present in PP can then damage the equipment used for reprocessing where usually the collected PP products are fed into an extruder, melted at 240 °C and cut into granules which will enable PP to be used in the production of new products [38, 39].

Najaf *et al*, on the other hand depicted that recycled PP obtained from various sources have been exposed to different storage and reprocessing conditions and because of that it contains many grades, colours, and contaminants. Also, recycled PP has different performances which is dependent on its degradation level [27]. Furthermore, the grades of rPP have different molecular structures and properties therefore each plastic component in a mixed waste will have a different melting behaviour, rheology, and thermal stability which can further complicate processing [40].

Vilaplana *et al* highlighted that polymer materials such as PP suffer from chemical and physical changes during their processing and service life where they undergo oxidative reactions leading to the formation of new functional groups such as the carbonyl groups which enhance the sensitivity of the recycled materials to further undergo both thermal and photo-degradation [41]. Furthermore, the oxidative moieties formed lead to the consumption of some parts of stabilizers; this subsequently causes a decrease in the stability of PP and deterioration in its mechanical properties thus also affecting its performance of the end product made from recycled PP [39, 41].

Vilaplana *et al* further argued that the deteriorations in the rheological and mechanical properties of the recycled PP are due to macromolecular chain scissions which cause a decrease in molecular weight and an increase in the MFI of the recyclates [41, 42]. This was further supported by an investigation on the changes of rheological properties of plastics after repetitive extrusion and injection moulding where the results showed that recycled PP have a decreased melt viscosity which lead to a decrease in the mechanical properties of the plastic such as the tensile and impact strength [42]. This decrease in melt flow viscosity can be attributed to an increase in the melt flow index and a decrease in molecular weight. Additionally, this decrease in melt flow viscosity is usually observed when recycling is carried out at high temperatures and shear stresses, and it is due to the contaminants present which increases the density of the recycled PP [28].

Ferg *et al* reported that the continuous recycling of the hydrocarbons over a few years causes a decrease in the average chain length and molecular weight decreases of the polymer. This influences the properties of the final product such as injection moulding flow, impact, and stiffness properties [31]. While on the other hand, J. Aurrekoetxea *et al* reported that the MFI of recycled PP increases after four recycling cycles/steps and this is suggestive of chain scission as a dominant degradation [43]. Also, it has been observed that recycled PP have a reduced molecular weight which causes entanglements and molecular interaction to decrease with the decreasing chain length. This causes an increase in the mobility of the polymer chains and allows them to fold into a chain thus forming a thick lamella which translates to a high degree of crystallinity [43].As a result, the rPP viscosity decreases.

According to da Costa *et al*, recycled PP degrades at 270 ºC, as well as after 19 extrusion cycles, and this is indicative of the reduction in the viscoelastic nature of PP. Also, the increase in the number of short chains in rPP and reduction in the molecular weight causes the polymer material to behave more like a liquid-like material that has low viscosity [43]. Additionally, at high temperatures and after multiple processing (extrusion) cycles, the rheological properties of PP change where not only viscosity decreases but also the elasticity of the polymer becomes lost [43].

Yoa *et al* highlighted that the mechanical properties of recycled polypropylene material are believed to be inferior to those of virgin polypropylene due to the degradation of PP which leads to short chains and low molecular weight and because of that their application is limited [29]. The studies conducted by Barbosa *et al* reported that the tensile properties of virgin and recycled polypropylene are similar while the impact properties such as absorbed energy of the recycled polymers was observed lower than that of the virgin polypropylene [20]. Furthermore, Barbosa *et al* indicated that the decrease in mechanical properties such as elongation at break and tensile strength with repeated processing cycles can be explained by the lowered molecular weight [20].

Tzoganakis *et al* reported that when analysing for a strain behaviour of rPP's using tensile test, a reduction in ductility can be observed at the lower molecular weights. This is due to the decrease in the of tie molecules and tie molecule entanglements in the inter-lamellae regions which then reduces the ductility. Also, there's systematic loss of impact strength as the number of tie molecules decreases and the loss of ductility of polypropylene [29].

2.4.1 IMPROVING THE PROPERTIES OF RECYCLED POLYPROPYLENE

Plastic waste can be classified into two categories which are pre-consumer and post-consumer plastic waste where the agriculture, electronics and the automotive industry are the main sources of the post-consumer waste [44]. The pre-consumer waste of PP which is also known as industrial scrap refers to the plastic waste that is generated during the conversion or manufacturing process of products [30]. The pre-consumer PP waste is usually free of contaminants, contains minimal amount of highly degraded material and is available in high volumes when compared to the post-consumer PP waste as a result, this type of waste is recycled to a great extent directly by the industries where it is reused in industrial processes or sold to processors without reaching the waste management sites [30].

Additionally, different sources, grades or products and the processing method of recycled polypropylene influences the both the rheological and mechanical properties of the end user product. Furthermore, recycled plastics from different sources may vary in terms of the MFI, molecular weight, crystallinity, degradation, inorganic material content, melting point, impact, and tensile strength. As a result, the applicability of PP for a particular product needs to be assessed as the quality requirements are product specific [30].

Spiker *et al* highlighted that best reproducibility is attained when pre-consumer waste is used due to manufacture products the fore-mentioned advantages [30]. Thus, the manufacturers of plastics mix a regrind material from the scrap plastic waste with virgin material to minimize and control the degradation level of the end –product [30]. This process does not affect the overall material properties of the product. However, high proportions of recycled PP in a matrix that contains virgin PP leads to the deteriorations of the end-product material properties such as having poor impact resistance which limits the use of rPP to only general domestic and packaging applications, having minimal use in high performance applications such as automotive industry [30].

Because of the decreased properties in recycled PP, there are several methods which have been suggested to promote the quality of recycled plastics that will enable them to be used in various applications. These approaches include the addition of a filler, blending of PP with various elastomers such as ethylene-propylene random copolymer

(EPR), isoprene-styrene di-block copolymer (ISR-A) and ethylene-propylene-diene monomer (EPDM) which are impact modifiers, blending with virgin materials, compatibilization, process optimization and formulation design [45].

Fernandes *et al*, compared the mechanical properties of virgin high impact polypropylene and the recycled polypropylene with the aim of incorporating the recycled polypropylene in the automotive industry as a potential cheapening material. the study highlighted that two composites were made with one was composed of 30% recycled PP and 70% virgin PP while the other one was made of 50% recycled PP and 50% virgin PP [20, 46].

The mechanical properties were evaluated and the tensile strength of the two compositions were similar to each other. However, the results showed that only 30% of the recycled PP was acceptable in terms of impact resistance for automotive use. Specimens which contained more than 30% of recycled plastic specifically 50% and 100% recycled PP showed a large reduction in impact strength [20, 46]. This is possible since the recycled PP fraction have short polymer chains than the virgin PP material because it has been already affected by degradation during the previous processing cycle [30].

Raj *et al* reported that the tensile and impact resistance of injected moulded blends of virgin and recycled polypropylene in different proportions showed no significant variation in yield strength and elastic modulus. However, the impact resistance decreased as the percentage of recycled PP increased; this is further supported by the reported values of 55,9 kJ/m^2 for 100% virgin PP and 45,3 kJ/m^2 for the mixture of 60% virgin PP and 40% recycled PP [47]. The observed decrease in this property was justified by the uncertainty of the composition of the samples since the raw materials comes from the second stage of recycling. Also, it was suggested that the decrease in impact strength may be due to the reduction of the molecular weight of the propylene which is promoted by recycling [47].

Additionally, it has been reported that the degradation suffered by the polypropylene material leads to a shearing of the main chain which consequently causes a reduction in viscosity and directly affects the mechanical properties [47]. Previous work demonstrated that for certain percentages of recycled PP in a mixture with virgin PP, the mechanical properties suffer few reductions, and the process is economic viable [47].

Even though there are some reductions in mechanical properties of materials when recycled plastics have been used, Gu *et al* reported that there are several cases where these plastics have been used in the automotive industry to manufacture some automotive components to reduce the manufacturing costs involved [48].

The automotive industry in many countries has the biggest economic contribution despite the ever increase fuel prices. However, the use of virgin raw materials leads to an increase in the manufacturing costs which then translate to the increase in the price of the industrial composites such as vehicles in the market. The mostly used plastic in the automotive sector is virgin polypropylene and it costs R28/Kg. This price is not fixed due to the various factors such as increase in production costs as well as the demand of end-products. It is because of this reason that secondary resources must be considered since they are as equally important as the primary resources, and they promote a circular economy where their recycling and reusability to make end-products which are high performance at low cost can lead to reduction of costs and job opportunities in many waste management sites.

Also, these plastics are cheaper than the virgin PP depending on the source as well as the grade of the plastic. Examples of price costs for recycled plastics is shown in Table 2.4. However, there are many factors which must be considered when the recycled plastic is used during the manufacturing of the automotive components such as contamination, temperature for processing, MFI and end-user product properties etc.

Table 2.4: Recycled plastic cost.

Recycled plastic material	Price (R/Kg)
Domestics rPP	8
Bin lids rPP	7.50
Crates rPP	6
Automotive rPP	12

This study seeks to use plastic waste (polypropylene) material to provide practical and economic viable solutions that will close the loop in the automotive industry and alternatively solve the environmental issues around plastics where recycled PP is used to manufacture second generation products. The use of recycled polypropylene in this industry will not only provide long-term environmental, social, and economic benefits but will also preserves natural resources and lead to job creation and/or preservation.

Chapter 3: Methodology

This chapter consists of two sections where section 1 provides information on materials used, formulation development and sample preparation. Section 2 is based on the instrumentation, methods and procedures employed in this study.

Section 1: Materials, formulation development and sample preparation

3.1 Materials

3.1.1 Polymers

The base polymer and matrix of the blends utilized was the Hostacon TRC 352N C12507 from Lyondell Basell, which is an injection moulding co-polymer grade polypropylene masterbatch filled with 20 wt % of talc (PP-T20). The grade boasts a melt flow of 18 g/10 min as per technical data sheet [65]. The impact modifier utilized in the study was a Nordel^{TM} IP 4725. Ethylene-Propylene-Diene-Monomer (EPDM) manufactured by Dow Chemicals. This material contains 5% Ethylidiene-Norbenene (ENB) with an ethylene content of 70% and 25% with a general chemical structure shown in Figure 3.1.

The green domestic, bin lids and mixed crates recycled polypropylene were sourced from Bretco plastics (from here onwards referred to as rPP-1 – rPP-3) while the automotive rPP from scrap of both internal and external automotive components was sourced from Vistarus (from here onward referred to as rPP-4). This grade has 10 w% of inorganic material with a melt flow index of 7.86 g/10 min. The general chemical structure of polypropylene is shown Figure 3.2.

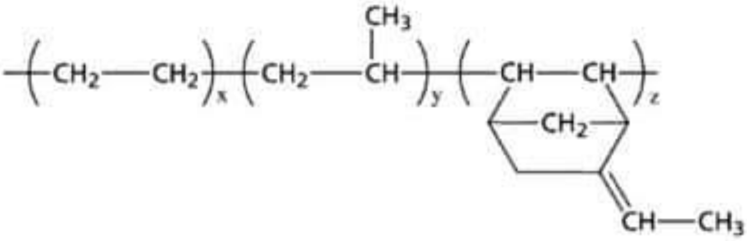


Figure 3.1: The general chemical structure of EPDM, where x-ethylene, y-propylene, and z-diene [49].

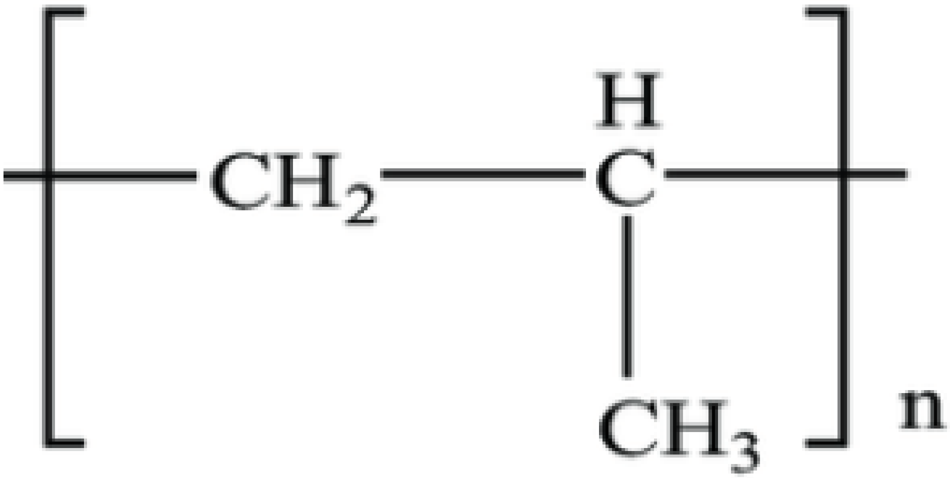


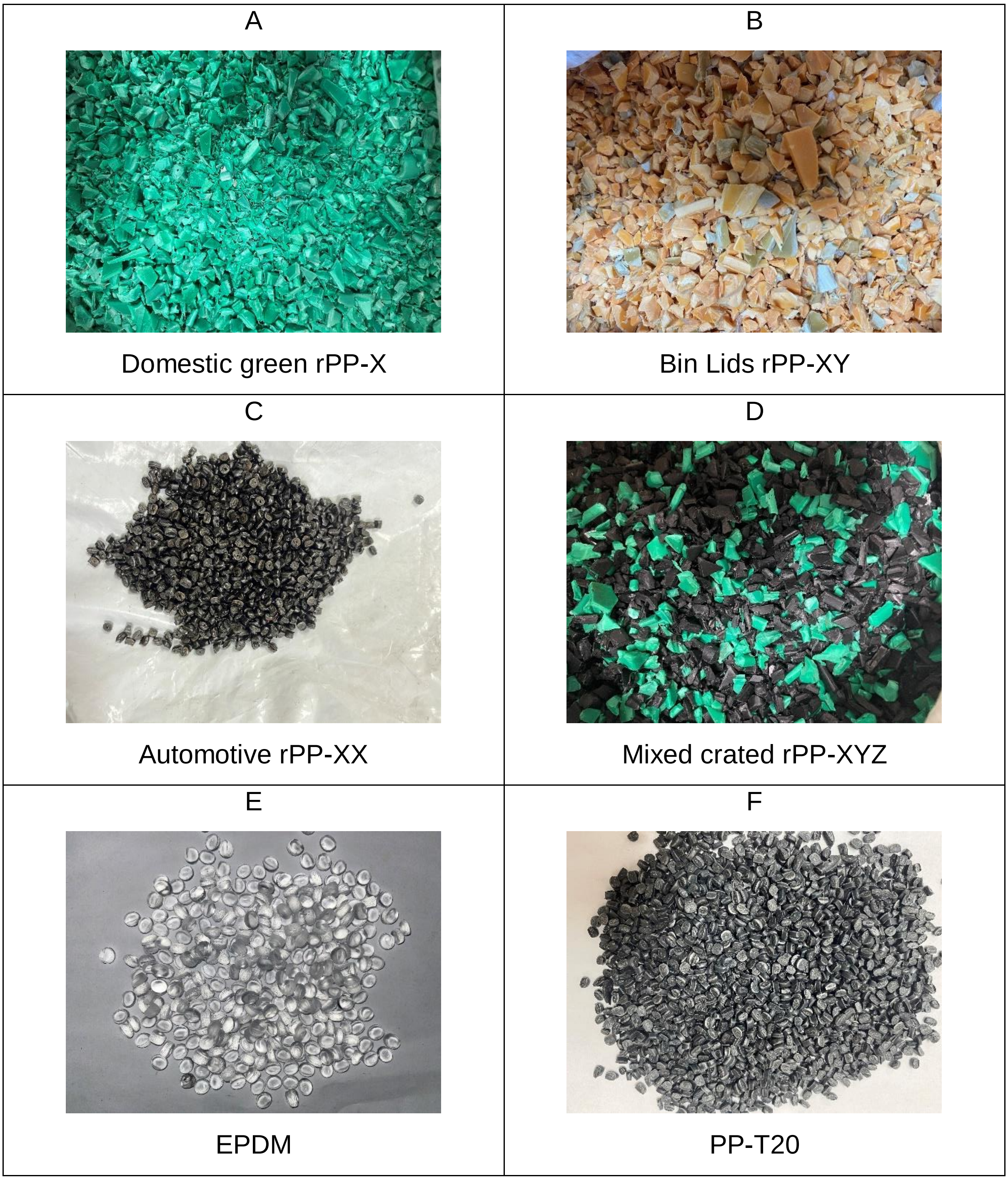
Figure 3.2: The general chemical structure of polypropylene [50].

3.2 Formulations and sample preparation

Images of the different components used in the study are shown in Figure 3.3. The various samples of rPP/PP-T20/EPDM were prepared by mixing different grades of recycled polypropylene with EPDM and virgin PP-T20 in ratios of 10% - 50% rPP by weight vs PP-T20 while keeping the amount of EPDM constant (5 w%) throughout the formulations as shown in Table 3.1.

Table 3.1: Composition of the samples.

PP/rPP/EPDM	PP (g)	rPP (g)	EPDM (g)
PP	300	0	0
rPP	0	300	0
90/10	256.5	28.5	15.0
80/20	228.0	57.0	15.0
70/30	199.5	85.5	15.0
60/40	171.0	114.0	15.0
50/50	142.5	142.5	15.0



A

Domestic green rPP-X

B

Bin Lids rPP-XY

C

Automotive rPP-XX

D

Mixed crated rPP-XYZ

E

EPDM

F

PP-T20

Figure 3.3: Images of pelletized and granulated raw materials used.

3.2.1 Injection moulding

Injection moulding is a process whereby a thermoplastic material which can be in granule or pellet form is passed from a hopper of the injection moulding machine into the barrel where the molten material is used to produce an article. The main objective of an injection moulding machine is to continuously mass produce plastic articles which have a consistent shape, dimension, and quality with the advantage of that multiple articles can be produced in a short period of time [51]. The sample is supplied into the injection moulding unit and a pre-set amount of the molten polymer is sent to the front of the extruder screw. The accumulated melt of the polymer is then injected into the mould cavities where it is cooled. The sample produced is then ejected and the process is repeated for the rest of the samples.

The ARBURG 250 tonner Injection Moulder was used in this study to prepare family moulded PP-T20/rPP/EPDM blends by following ASTM D638; and obtained 14 articles per sample. The articles were used to test various properties of the blends such as impact resistance, flexural properties, and crystallinity. Figure 3.4 shows a photograph of the injection moulding machine while the parameters for operation are in Table 3.2. An article obtained from the injection moulding blends is shown in Figure 3.5.

Figure 3.4: ARBURG 221-55-250 reciprocating screw Injection Moulder.

Table 3.2: Parameters of the Injection moulding machine.

Rear Zone (ºC)	200
Centre Zone (ºC)	220
Front Zone (ºC)	210
Mould Temperature (℃)	RMT
Injection Pressure (bar)	30
Delay time (s)	3
Injection Time	15
Holding Time	10
Holding Pressure (bar)	50
Cooling Time (s)	30
Pause and Ejection time (s)	5

Figure 3.5: Single Shot of the Family moulded article.

3.3 Section 2: Instrumentation, methods, and procedures

3.3.1 Physical testing

Melt Flow Index (MFI)

An extrusion weight of 2.16 kg was used and the barrel temperature was set at 230 °C in accordance with ASTM 1133. The machine was allowed to heat up for 30 minutes to an hour and the preheat time, sample heat time and cut-off mechanism time (15 seconds) were set to allow individual cut-offs as the molten polymer material flows through the orifice of the machine. This is advantageous since it also reduces errors associated with the weight of the cuts.

About 5-6 g of the samples were weighed on the analytical balance and inserted in the barrel of the MFI for sampling. After the 5 minutes have elapsed, the automatic cutter was switched on and sampling was done whereby the sample was allowed to pass through the die, and it was cut off after every 30 seconds. The first sample cut was discarded while the other ones obtained were weighed on the analytical balance to an accuracy of 0.0001 g. The mass of each sample cut was recorded, and the average mass was calculated and inserted to the instrument for the determination of the sample's MFI. After each sampling, the instrument was cleaned. Equation 1 gives an illustration of how the MFI of the sample is calculated.

$$\text{MFI} = \frac{\text{Cut−off weight in grams(g)}}{\text{Time (min)}} \times 10 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{equation 1}$$

Figure 3.6: A picture of the MFI instrument used in this study

3.3.2 Mechanical Testing

Pendulum Impact Tester

Impact strength is defined as a measure of energy that is needed to break a sample [1]. This property is important in polymer materials since the energy absorbed during measurements can be related to the toughness of the material. An increase in the impact strength of a material is indicative of its high toughness [52]. Also, it must be noted that there are many factors which can influence the impact resistance of the plastic such as the polymer chain lengths and the crystallinity where an increase in crystallinity of the polymer materials leads to a decrease in impact strength; this can be related to the sample being brittle due to the increased rigidity in the material thus prone to fracture [52]. Furthermore, the impact strength of the material decreases as the molecular weight decreases [52].

There are 2 main categories of impact tests which are employed in various research facilities; these are the falling-mass tests and pendulum (Izod) tests where the assembly of the falling-mass is usually used for bulk test pieces and the pendulum (Izod) test is used to measure the amount of energy that is needed to break a sample that is notched under the standard conditions specified on ASTM D-256 [1].

In this study, an average of 10 samples were clamped in the base of a pendulum testing apparatus of the Izod impact tester and a pendulum was released from a specific height with a swing energy of 7.5 J at room temperature. The test was performed for all the specimens of the material articles and the force needed to break the sample was then calculated from the height and weight of the pendulum required to break the specimen. The average value was calculated and reported in kJ/m^2.

Figure 3.7: A picture of the Pendulum Impact Tester used in this study

3.3.3 Thermal characterisation

Simultaneous dynamic calorimetry (SDT)

SDT is a thermal analysis technique that simultaneously measures weight loss or gain, rate of weight change and the heat flow of a sample as a function of temperature in a controlled atmosphere. A simultaneous DSC-TGA can be used in different phases of research, quality control, and manufacturing operations [53]. The primary use of a SDT measurement is to determine the composition of a material and its thermal transitions [53]. It can also be used to study the characteristics of a polymer including thermal stability, thermal transitions, chemical composition, and the degradation. The results can be recorded as a TGA-DSC curve or a thermogram.

Figure 3.8: A picture of the TA-Instruments' SDT Q600 used in this study

3.3.3.1 Characterization of the raw materials by an SDT

The thermal characterization of the recyclates along with PP-T20 were investigated by the simultaneous DSC-TGA in attempts of determining the materials composition and to predict their thermal stability using the degradation patterns where samples of mass 7 -10 mg were heated from ambient temperatures to 800℃ under nitrogen (baseline of 0.5) purge gas flowing at 100 ml/min and air with a constant heating rate of 20℃/min.

3.3.3.2 DSC simulation

The percentage crystallinity of raw materials and blends were evaluated by the DSC simulation measurements where the thermogram provides information about melting temperature of the polymer materials. It is of importance to note that as the polymer crystals begin to fall apart, that is they melt; they absorb heat known as the latent heat of melting which is characterised by a dip in the thermogram of the material [54]. This area under the melting peak can then be used to determine the crystallinity of the polymer. A higher value of the heat of fusion suggests a higher degree of crystallinity and vice versa. The melting and crystallization values were obtained by using the relationship of the melting enthalpy; this is the area under the endothermic peak and melting enthalpy of 100% crystalline PP (209 J/g) [52].

During analysis, the 7- 10 mg of samples weighed were sealed using aluminium *Tzero*^{TM} pans and lids. They were further subjected to two heating segments with a cooling segment in between under nitrogen purge (nitrogen baseline 5.0) and with the use of LN2P cooling. The experimental procedure was done under the flowing conditions:

- Nitrogen flow rate at 100 ml/min
- Heat at 20℃/min to 200℃
- Cool at 5.0℃/min to 90℃

The percentage of the crystalline structure was calculated from equation 2:

$$\mathrm{Xc}(\%) = \frac{\Delta \mathrm{Hm}}{\Delta \mathrm{Ho}} \times 100 \text{ ....equation 2}$$

where Xc is the crystalline region percentage of the polymer, ΔH_m is the enthalpy of fusion at the temperature of fusion of the tested material, and ΔH_o is the enthalpy of fusion at the temperature of fusion of theoretical 100% crystalline PP/PE material. For polypropylene, this value is 209 J/g while for polyethylene it is 294 J/g.

Dynamic Mechanical Analysis (DMA)

DMA is a technique that is used to characterize the properties of a material as a function of temperature, time, stress and a combination of the highlighted parameters [55]. The instrument works by the application of a sinusoidal deformation to the sample that has known geometries. The sample is then subject to a controlled stress/strain where in an event of a known stress, the sample will begin to deform for a certain amount [55]. The force motor in the DMA is used to generate the sinusoidal wave which is then transmitted to the sample specimen. It must be noted that the DMA measures the stiffness and the damping of the material, and these are both reported as modulus and tan delta where the modulus is reported ether as storage modulus (E' or G') which is responsible for measuring the elasticity behaviour of the sample or as loss modulus. The damping is used to measure the energy dissipation of the sample under a cyclic load [55].

Figure 3.9: A picture of the TA-Instruments' DMA Q800 used in this study

3.3.3.3 FLEXURAL STRENGTH

Figure 3.10: Illustration of flexural strength testing [63].

The flexural strength testing was carried out to determine the viscoelastic behaviour of polymers of interest. Sample dimensions were 20 mm × 5.23 mm × 2.20 mm, and the test was performed using the 3-point bending mode with a ramp force of 3N/min to 17.5 N.

The experimental procedure was done under the flowing conditions:

- Sample dimensions: 20 mm × 5.23 mm × 2.20 mm
- Ramp force: 3 N/min to 17.5 N

3.3.3.4 HEAT DEFLECTION TEMPERATURE UNDER LOAD (HDTUL)

Heat distortion temperature test/ Heat Deflection Temperature under load (HDTUL) tests help in the identification of temperature at which the article deforms under the given load. This was carried out by using cut rectangular strips from injection-moulded article and clamping the sample between rectangular torsion fixtures of the 3-point bend clamp. The test was carried out at a temperature range of 20 to 120 ºC, with a force 1.50 N at the heating rate of 5 ºC/min.

3.3.3.5 TEMPERATURE SCAN

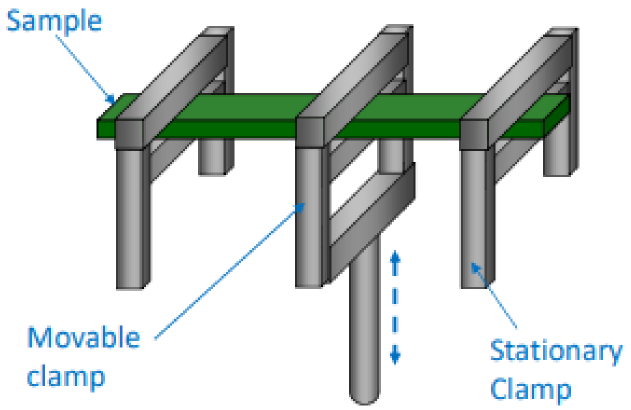


Figure 3.11: Illustration of temperature scan testing [64].

Temperature scan is a test used to study the glass transition temperature of the polymer materials where T_g is characterized from tan delta. The samples measurements were performed at a heating rate of 5 ºC/min in the temperature range –50 °C to 70 °C at a nitrogen flow rate of 100 ml/min with a stress of 15 MPa using a dual-cantilever clamp.

Chapter 4: Results & Discussion

This chapter consists of two sections where section 1 focuses on the characterisation of the raw materials and section 2 is based on mechanical evaluation and testing of blends for automotive use.

Section 1: Raw Materials

4.1.1 Thermal Characteristics

Prior to the processing of the raw materials (PP-T20, rPP1-rPP4), the thermal characteristic properties such as melting point, glass transition (T_g), and degradation temperatures (T_d) were determined using an SDT and a DMA to understand the temperature in which the raw materials can be injection moulded to prevent challenges such as degradation of materials during processing. Figures 4.1 to 4.3 shows the obtained thermal characteristics of raw materials.

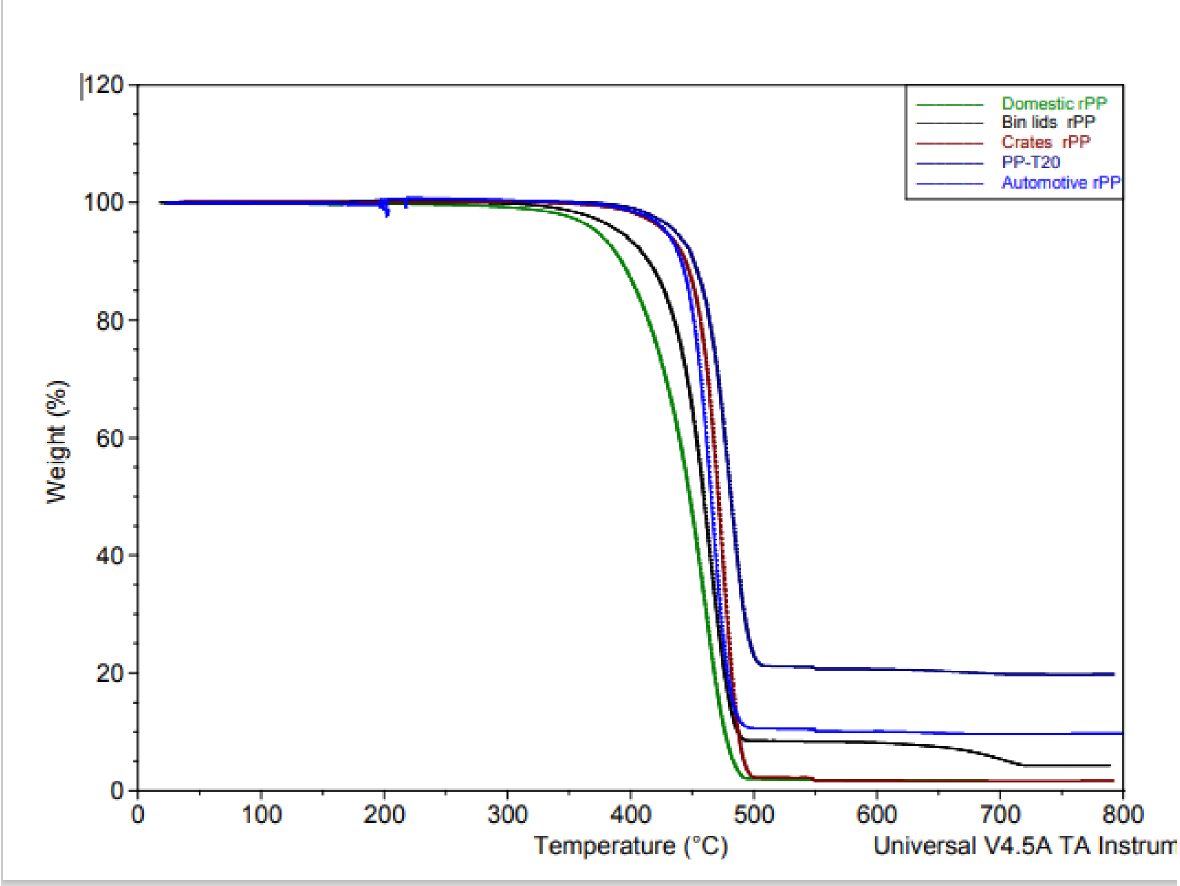


Figure 4.1: TGA overlay thermograms of recycled PP materials with PP-T20.

Table 3.3: Composition degradation characteristics of the recycled plastic material.

Raw plastic materials	T_d (°C)	Polymer content (%)	Ash content (%)
PP-T20	394	80	20
rPP-1	322	98	2
rPP-2	334	91	9
rPP-3	359	98	2
rPP-4	371	90	10

Figure 4.1 indicates that all the recycled plastic materials begin to decompose at temperatures which are beyond 300 ºC. Also, it can be observed that rPP-4 has the highest degradation temperature of 371 °C among the recycled materials while rPP-1 was found to have the lowest degradation temperature of 322 °C which may have been due to high temperatures and shear forces application during reprocessing which probably led to the loss of stabilisers as well as shorter chains in the structure of the rPP; consequently, making it to degrade faster than the other rPP's. The high degradation temperature observed for rPP-4 is possible since the recyclate is a VW pre-consumer waste material recovered from the scrap after the manufacturing of the automotive components. This plastic is free of contaminants and contains minimal degradation of material as compared to rPP-1¸ rPP-2 and rPP-3 which are post-consumer waste recovered from the waste management sites and have undergone multiple extrusion /reprocessing.

The data provided highlight that PP-T20 has a high degradation temperature than the rPP's and this is due to it not having scission in its chain as a result the properties and behaviour of this plastic would differ to those of the recycled plastics. Furthermore, the high degradation temperature observed for these raw materials indicate that they would be stable and not degrade when being processed in the injection moulding machine.

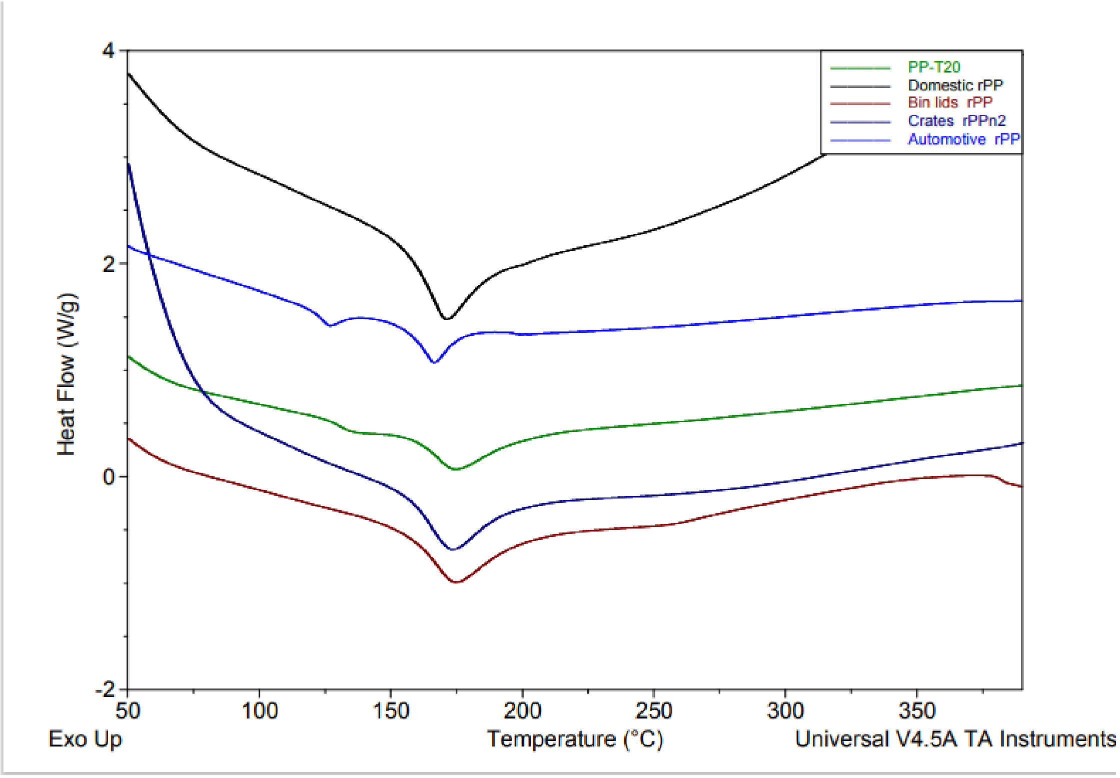


Figure 4.2: Melt thermogram of recycled PP materials and PP-T20

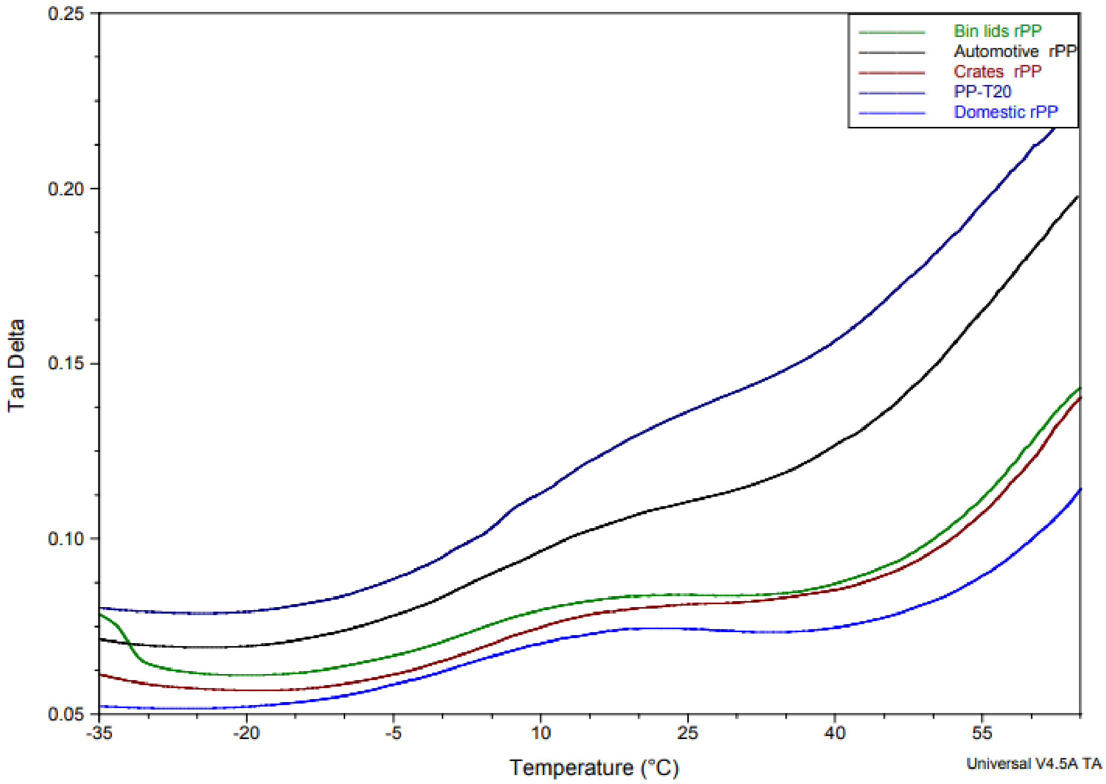


Figure 4.3: Tan delta thermogram of recycled PP materials and PP-T20

Table 4.2: Summary of thermal properties and crystallinity of raw materials.

Material	T_g (°C)	T_m (°C)	PP ΔH_m (J/g)	PE ΔH_m (J/g)	$\%X_c$ PP (%)	$\%X_c$ PE (%)
PP-T20	19	127 & 169	20	0.6	10	0.2
rPP-1	16	171	56	ND	27	ND
rPP-2	16	170	6	ND	3	ND
rPP-3	16	173	41	ND	20	ND
rPP-4	16	126 & 166	25	2	12	0.68

Figure 4.2 reveals the heating curves of the recycled plastic materials used in the study along with PP-T20 where the similar DSC thermogram were observed for rPP-1 to rPP-3 with the melting points being 171 ºC, 170 ºC, and 173 ºC respectively. This melting point is slightly different to the melting point of PP-T20 and a homo-polypropylene melting point of 166 ºC and this might be due to the presence of inorganic material fillers and contaminants in the plastics. rPP-4 showed to contain traces of high density polyethylene at a melting temperature of 126 ºC; this is possible since this recycled plastic material is a waste material recovered from industrial automotive products which are made from a co-polymer grade PP made up of PP blended with HDPE which melts at 130 ºC to improve the material properties [56].The melting temperature of PE in this rPP is different from the melting temperature of virgin PE and this can be related to the degradation of the material. PP-T20 on the other side is a co-polymer PP grade hence it has two characteristic melting temperatures at 127 ºC & 169 ºC belonging PE and PP respectively.

The glass transition of the recycled plastics does not present significant changes due to the process of recycling as they are closer to the glass transition of PP-T20. The T_g data shows that the recycled plastic material has fairly ordered molecules due to the short polymer chains in its structure induced by the mechanical recycling process which leads to the scissions of the large molecular chain of the plastic material. However, PP-T20 had a broader peak when compared to the recycled plastics.

Crystallinity is one of the important properties of recycled plastics as it influences the performance and properties of the end-use product. This property depends on the molecular structure of the material as well as the crystallization conditions. Also, the crystallinity data can provide insight on the fracture behaviour of PP which is related to the impact resistance as well as the flexural properties of the end-product [57].

The data obtained highlights that rPP-1 has a higher degree of crystallinity which is 27% among the recycled plastics material with rPP-2 having a low degree of crystallinity which is 3%. The high degree of crystallinity in rPP-1 may be due to less molecular chain breakage in the recyclate during reprocessing. However, the low degree of crystallinity in rPP-2 can be attributed to chain scissions which might have happened during reprocessing resulting to less extension of the polymer chain and more branched structures with low molecular weight. As a result, this rPP has an increased mobility of the chain or rather expected to behave as an amorphous plastic where there is a decrease in the fold of the molecular chain which then decreases the crystallinity [58].

Also, the low degree of crystallinity in rPP-2 makes this recycled plastic not ideal to be used for the manufacturing of the door panel which must be tough and a radiator grill which is designed to withstand high temperature air. The use of this rPP in the manufacturing of these automotive components will lead to the reduction of properties as well as performance since most of its structure is amorphous rather than crystalline. For example, if it is used to make a radiator grill, it will most likely soften when exposed to hot temperature air of the engine from the radiator while the less crystallinity will reduce the amount of energy that needs to be absorbed by the door panel in response to a crushing force of the door during a side collision in a vehicle.

4.1.2 RHEOLOGICAL AND MELT FLOW INDEX MEASUREMENTS

Multiple processing of polypropylene leads to the degradation of the material as well as a decrease in the molecular weight of the material which consequently affects both the physical and mechanical properties of a polymer. Melt flow index is a useful method that can be used to determine the degradation history of a polymer, rheological behaviours (flow behaviour) and an idea of how the molecular weight of the polymer material changed. It is used to measure the ability of the polymeric material to flow under pressure. The results obtained for MFI test are presented in Table 4.3.

Table 4.3: Melt flow index of the raw materials.

Materials	**MFI (g/10min)**
PP-T20	21.64
rPP-1	19.94
rPP-2	ND
rPP-3	16.16
rPP-4	7.86

Table 4.3 summaries the melt flow index of the virgin PP-T20 along with recycled plastic materials. PP-T20 has a higher MFI value when compared to the recycled plastics of 21.64 g/10 min. It can be observed that the rPP-1 has a higher MFI value of 19.94 g/10 min among the recycled raw materials while rPP-3 had a value of 16.16 g/10 min and rPP-4 was found to have low MFI value of 7.86 g/10 min. The MFI of bin lids was not determined due to it having big granules that could not fit to the barrel of the MFI instrument; as a result, it was not used in the study as these granules would also complicate processing as the movement of the screw in the injection moulding machine would be restricted and the blends would not be mixed thoroughly with the matrix of PP-T20-EPDM.

The high MFI values of the recycled plastics specifically rPP-1 and rPP-3 show an effect of reprocessing where these polymers may have been exposed to thermal, mechanical and shear stress which led to a decrease in the molecular weight, increase in molecular weight distribution, induced chain scission and sidechain branching [42,60]. Huang *et al* reported that there is an increase of MFI from 14 g/10 min to 20 g/10 min of raw PP when it is subjected to 5 recycling cycle where there is increased fluidity in the plastic when compared to virgin plastic materials due to degradation as well as scission of polymer chains and broadened molecular weight distribution [56, 59]. Additionally, the high MFI observed in these recycled plastics is possible as these polymers are from different sources and may have been contaminated to some degree [42].

It can be deduced that the two recycled plastics which are rPP-1 and rPP-3 flow easy when compared to rPP-4 making them suitable materials to be used in the processes of converting plastics to end-products. Also, rPP-1 has a high MFI which implies that it has shorter chains in its molecular structure as compared to the other recycled plastics and therefore, it has a lower molecular weight, and it easily flows during processing (during injection moulding).

The data also shows that the rPP-4 has a low MFI, and this is due to that this recycled plastic is a combination of many scraps material that is originally from different components of a vehicle whose formulation are different; meaning that the rPP may be made from various plastic materials. This also gives an indication that this rPP is still loaded with antioxidants and stabilizers which prevent radical formation in the polymer and chain breaking thus enabling its products to have a long service life. As a result, when it is processed into any product, the antioxidants will slow down the thermo-mechanical degradation where they get depleted first due to overheating and shear before there is any degradation of the polymeric plastic [61]. Furthermore, the blends made from the rPP-4 are expected to be more difficult to be processed as compared to the blends made from rPP-1 and rPP-3 due to the plastic having long chains in its structure and high molecular weight.

4.2 Mechanical Evaluation and Testing

To understand the quality of materials, an investigation to utilization in the field is environment is critical. As a result, mechanical and physical characteristics assist in giving that indication where it can be predicted how long will the product or material last, determining the performance threshold and sensitivity becomes mandatory. In this study, the blends performance was determined using various static, dynamic mechanical and thermo-mechanical evaluation to try and understand how would the blends perform with respect to the benchmark formulation used for the respective automotive components. These properties include: Impact resistance, Flexural strength, Heat Deflection and Dimensional stability using temperature scan.

4.2.1 Impact strength

Table 4.4: Impact strength of the rPP-PP-T20-EPDM blends

Materials	**kJ/m^2**				
	10%	**20%**	**30%**	**40%**	**50%**
rPP-1	102.75	103.75	99.00	97.50	108.75
rPP-3	88.75	84.75	102.75	101.50	66.75
rPP-4	99.00	95.25	95.75	110.00	99.25
PP-T20-EPDM	122.50				

10 –50% are rPP additions on the PP-T20-EPDM composition

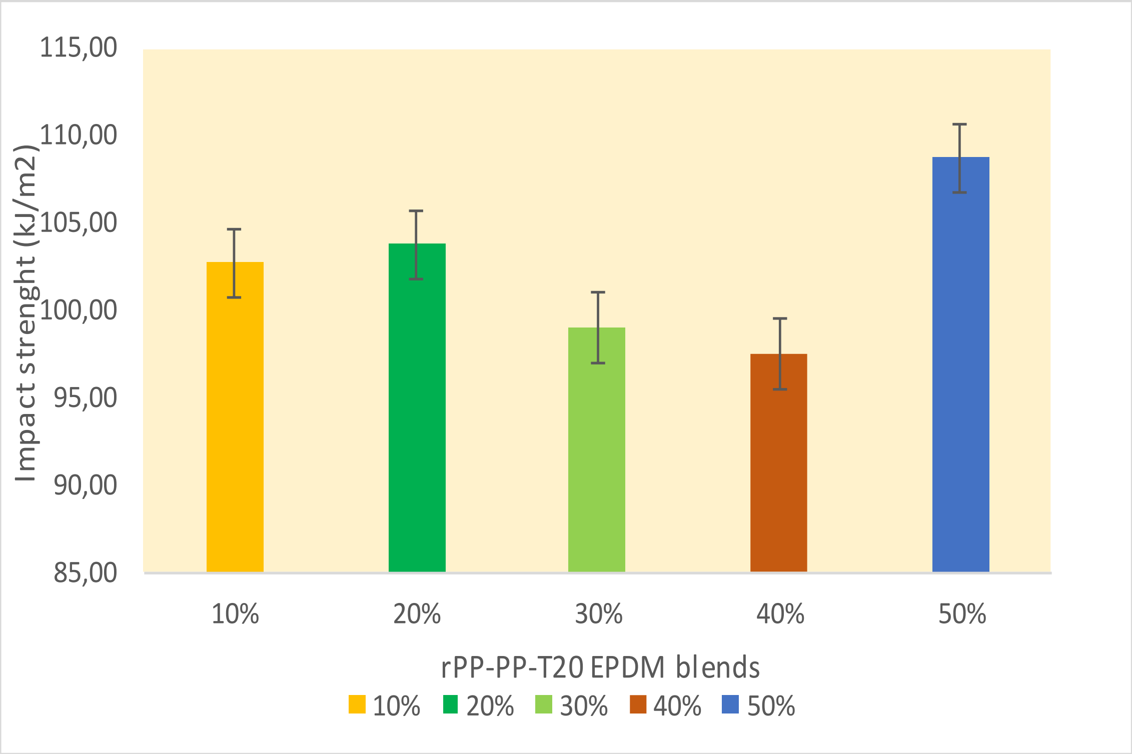


Figure 4.4: Impact strength of the domestic rPP-PPT20-EPDM blends

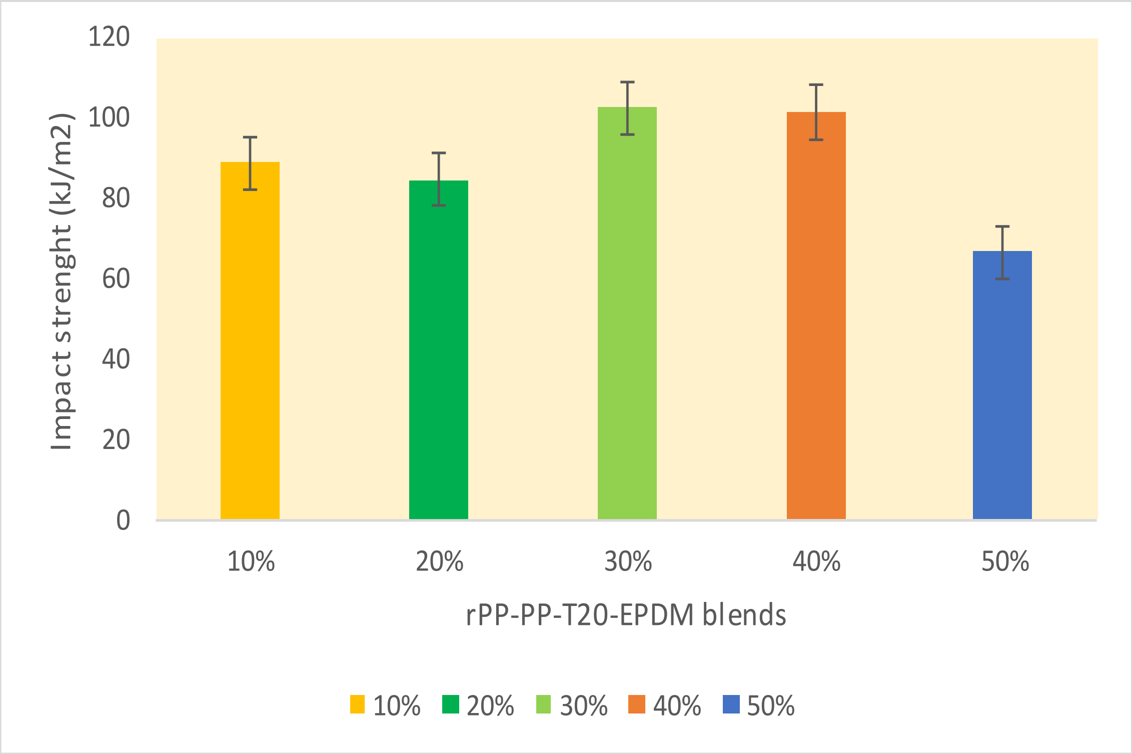


Figure 4.5: Impact strength of the crates rPP-PPT20-EPDM blends

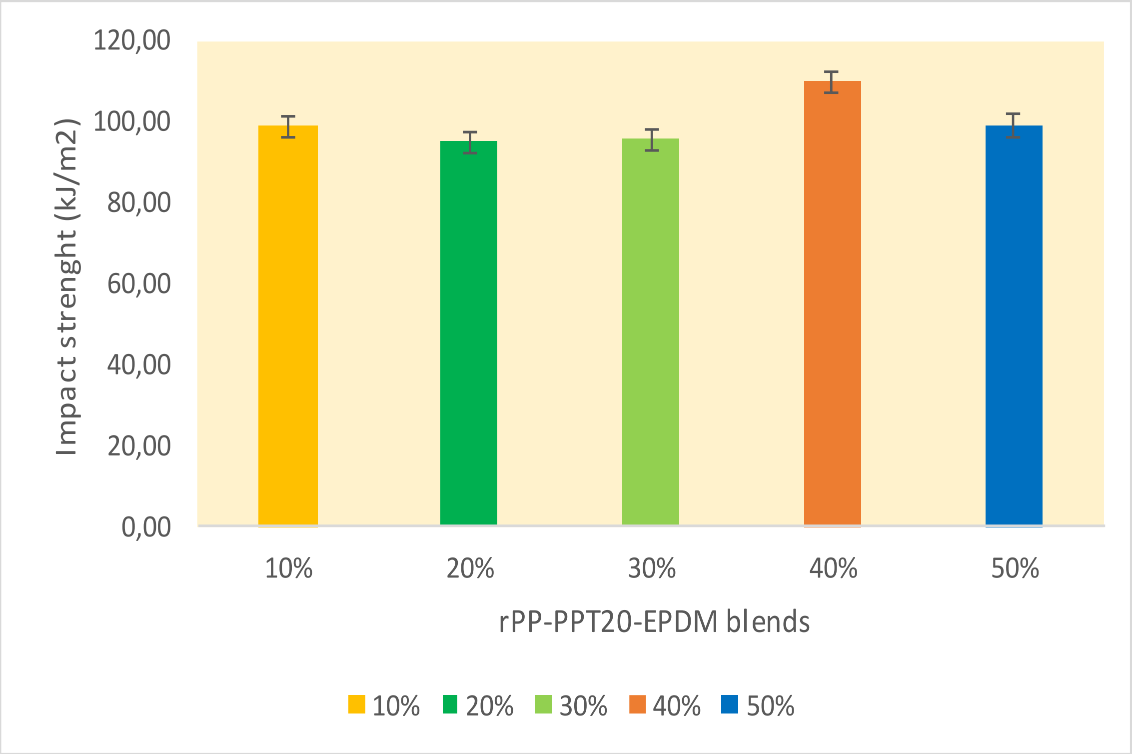


Figure 4.6: Impact strength of the automotive rPP-PPT20-EPDM blends

Table 4.5: Percentage reduction of impact strength.

Recycled plastic	10%	20%	30%	40%	50%
rPP-1	-16	-15	-19	-20	-11
rPP-3	-28	-31	-16	-17	-46
rPP-4	-19	-22	-22	-10	-19

Table 4.4 highlights the influence of different recycled on the impact resistance of PP-T20 and EPDM compound. The performance of these recycled plastic materials is very close to each other where all the articles of the blends exhibited a complete break. From the data, it is worthy to mention that the addition of recycled plastic reduced the impact strength of the material where the impact strength values were in the range of

99 -108.75 kJ/m^2, 66.75 -102.75 kJ/m^2, and 95.25 -110 kJ/m^2 for rPP-1, rPP-3, and rPP-4 recyclates respectively.

The data showed a significant reduction in the impact strength when the virgin polypropylene was partially replaced with rPP-3 with significant difference observed at 50% of this recycled plastic in Table 4.5. This is possible since rPP-3 is a mixture of crates which have varying degradation and thermal history. The reduced impact strength in rPP-4 on the other side might be due to the high inorganic filler content as highlighted in Table 3.3 which is made of $CaCO_3$ and talc, where the presence of the filler materials significantly influence both the rheological and mechanical properties of PP. Gu *et al* reported that the presence of talc can make PP to be trans-crystallized on the cleavage of the talc's surface leading to PP crystals being aligned perpendicular to the surface of the talc; this structure leads to the reduction in the impact energy absorption of the material as a result there would be decreased impact properties of the material [48].

However, rPP-1 showed less reduction of the impact strength in comparison with the other recycled plastics; this is possible since rPP-1 is recovered from domestic materials and has more crystallinity as well as less inorganic material in its structure.

Due to no significant difference observed in reduction of this property when virgin PP is partially replaced with 30% and 40% of recycled plastic, the blends at 50% and 20% were studied further since they are extremes and have significant influence on the impact strength. The addition of these amounts of recycled plastic material during manufacturing can drastically reduce the costs involved when manufacturing the automotive components as opposed to an addition of only 10% of the recycled plastic material.

Table 4.6: Summary of impact strength data for 20% and 50% extremes.

Recycled plastic	**Impact strength (kJ/m2)**		**Reduction in impact strength (%)**		**Xc (%)**		**MFI (g/10 min)**
	20%	**50%**	**20%**	**50%**	**20%**	**50%**	
rPP-1	103.75	108.75	-15	-11	15	15	19.94
rPP-3	84.75	66.75	-31	-46	13	15	16.16
rPP-4	95.25	99.25	-22	-19	14	10	7.86
PP-T20-EPDM	122.50				10		21.64

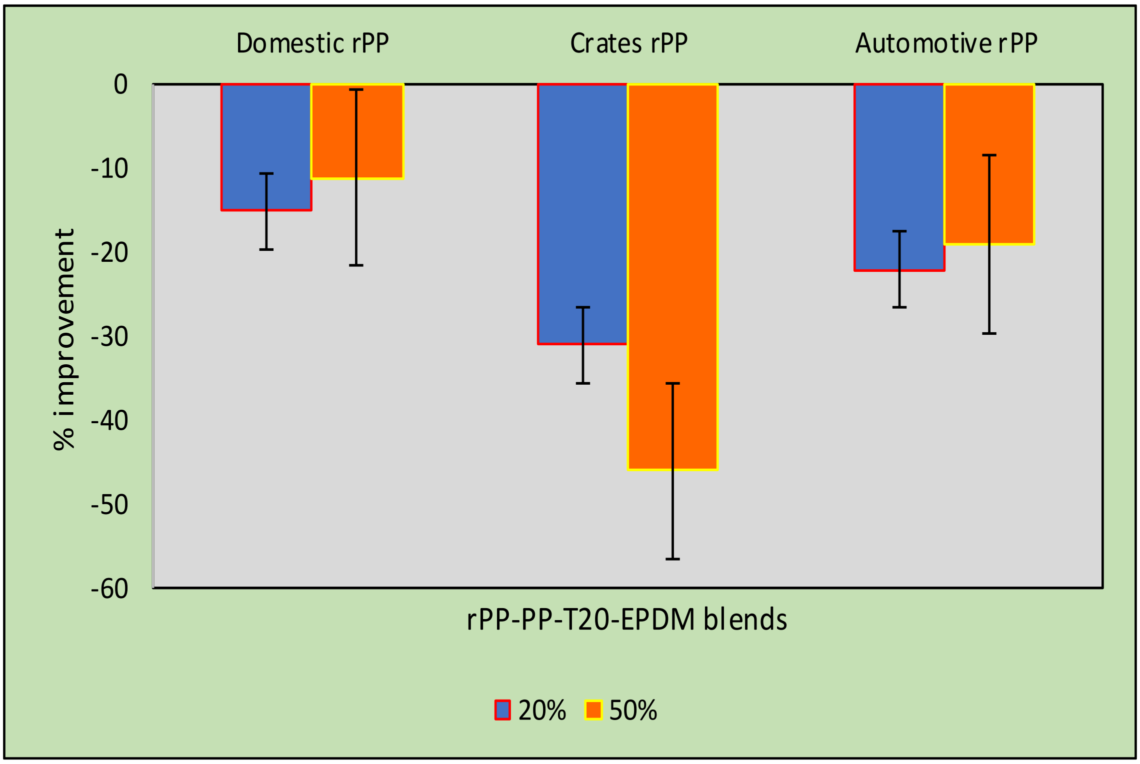


Figure 4.7: 20% and 50% rPP performance with respect to the PP-T20.

The high impact strength observed in PP-T20 -EPDM is due to the material not being degraded, and the effect of EPDM which is an impact strength modifier. A decrease in the impact strength is observed when rPP-3 recycled plastic material is added to the matrix of PP-T20-EPDM especially at 50% and this might be due to the matrix having more of the recycled plastic material which is highly degraded due to the high temperature and shear rates used during reprocessing. Because the matrix has more of the recycled plastic material, the influence of EPDM which is an impact modifier in the matrix becomes reduced. Furthermore, the photo-degradation of these materials at the waste management sites as well as contamination might have affected the crystallization of the material which then might have led to a decrease in the impact resistance. rPP-1 shows to be a promising recyclate among the three rPP's, since the use of this plastic had less influence on the impact strength of PP-T20-EPDM irrespective of the amount used.

It must be noted that the decrease in impact strength of the recycled material blends cannot be fully explained by crystallinity since the crystallinities of these blends are similar to each other but rather a correlation can be drawn between the impact strength and the MFI of the recyclates. It is assumed that the higher the MFI of the recycled material, the lesser the reduction in the impact resistance of the material. This is possible since there is more chain breakage/ higher molecular weight distribution at high MFI which allows some degree of mobility/ elasticity in the molecular chain where the material would then be less brittle thus less prone to fracture when compared to rPP-4 which has a lower MFI and possibly long molecular chains in its molecular structure. The long molecular chains in this rPP enhanced the toughness thus the brittleness of the material, making it to be more prone to fracture.

However, these findings do not give a broader understanding on the behaviour of blends since MFI alone cannot be used to explain the structure of the recycled plastic materials. As a result, molecular weight and molecular weight distribution studies must be conducted to assist with the explanation. Unfortunately, these tests were not done as part of this study due to time constraints.

4.2.2 Flexural properties

Flexural strength is significantly defined by the ability of the material to deform, where stress or force is applied resulting in the material increasing in strain which can be interpreted as deformation. Table 4.7 below give a summary to the deformations of various blends under stress which are compared to the benchmark material (PP-T20). An increase in strain under stress is interpreted as a decrease in the flexural strength, therefore improvement in the property is observed by a decrease in the strain under stress.

Table 4.7: Flexural strength of the rPP blends

Materials	Strain (%)				
	10%	**20%**	**30%**	**40%**	**50%**
rPP-1	1.41	1.29	1.20	1.17	1.12
rPP-3	1.20	1.26	1.35	1.26	1.23
rPP-4	1.50	1.36	1.42	1.41	1.55
PP-T20-EPDM	1.72				

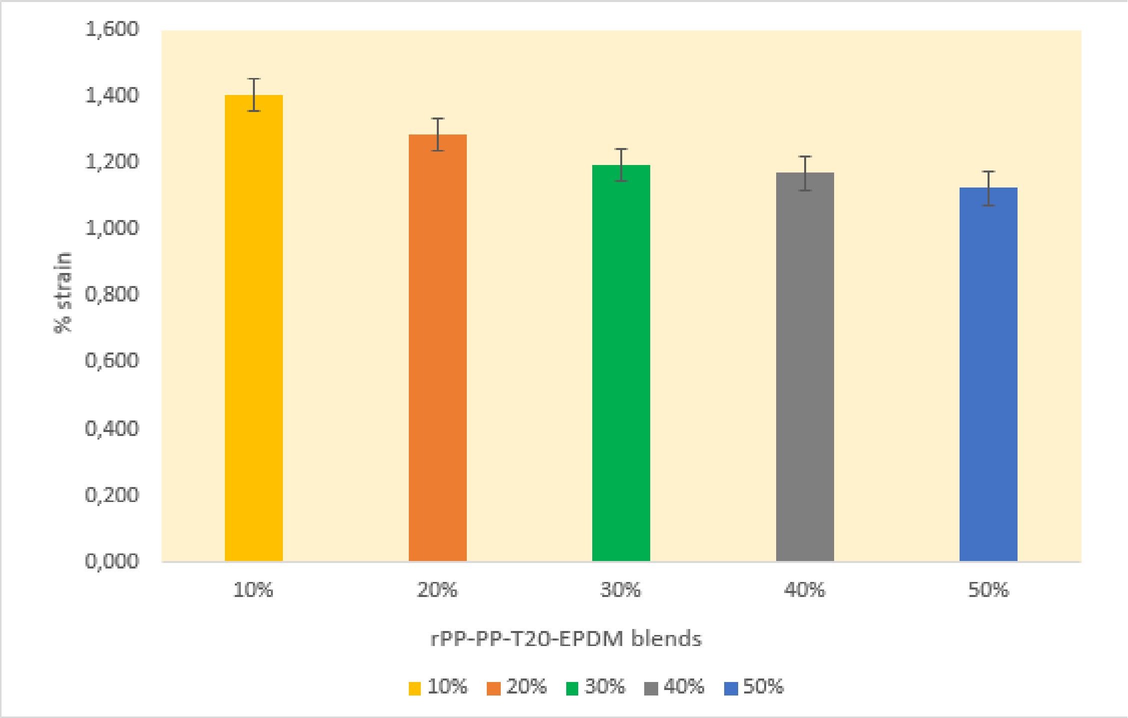


Figure 4.8: Flexural strength of the domestic rPP-PPT20-EPDM blends

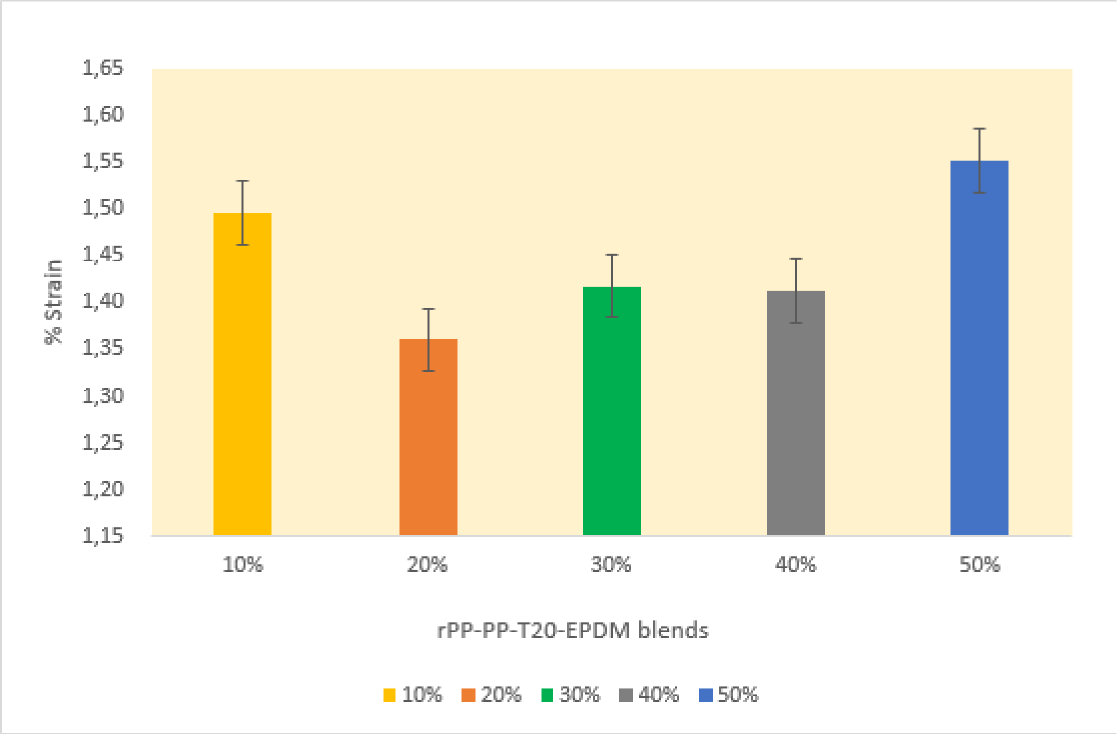


Figure 4.9: Flexural strength of the automotive rPP-PPT20-EPDM blends

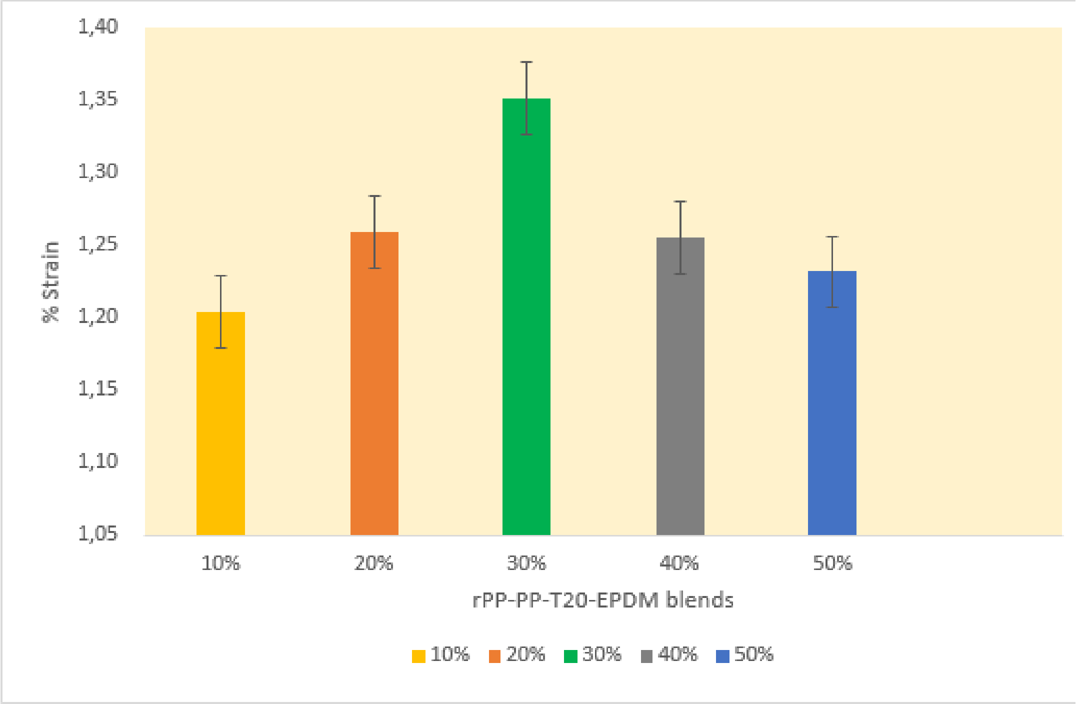


Figure 4.10: Flexural strength of the crates rPP-PPT20-EPDM blends

Table 4.8: Summary percentage flexural strength improvement of the rPP blends.

Recycled plastic	10%	20%	30%	40%	50%
rPP-1	18	25	31	32	35
rPP-3	30	27	21	27	28
rPP-4	13	21	18	18	10

Table 4.7 highlights the influence of different recycled on the flexural strength of PP-T20-EPDM compound. The strain at break of the material decreases with an increase in the addition of rPP-1 while there is no significant change in the strain of the material with the increase in addition of rPP-3 and rPP-4 to the PP-T20-EPDM matrix.

The summary on Table 4.8 shows the percentage flexural strength improvement of the PP-T20-EPDM with the addition of the recycled plastic. The 10% increments in the addition of rPP-1 to PP-T20 showed a linear positive influence of the flexural strength where the data shows that a threshold (plateau) gets reached at 30% of this plastic whereby any further addition to the matrix has no significant influence to this property. The trend observed in this plastic in comparison with the other recycled plastics, highlights that the blends made with rPP-1 have a high modulus which means that they are not easily deformed as a result more energy would be needed to cause permanent deformation in this plastic. Also, the low strain observed in the blends of this plastic shows that there is some elongation in the material before it breaks.

rPP-4 on the other side had less improvement on the flexural strength, this might be due to this plastic being less degraded thus having longer chains in its structure which increased both the modulus and the yield point which is defined as a point in which the material loses or has reached its elastic behaviour and starts to behave like a plastic where it becomes more brittle thus prone to deforming completed when enough stress is applied.

Because no discernible difference was observed in improvement of this property when PP is partially replaced with 30% and 40% of recycled plastic, while changes in the materials flexural strength were observed at 20% and 50% addition of the rPP's. The 20% and 50% recycle plastic blends were studied further.

Table 4.9: Summary of flexural strength data for 20% and 50% extremes.

Recycled plastic	**Improved flexural strength (%)**		**Xc (%)**		**MFI (g/ 10 min)**
	20%	50%	20%	50%	-
rPP-1	25	35	15	15	19.94
rPP-3	27	28	13	15	16.16
rPP-4	21	10	14	10	7.86

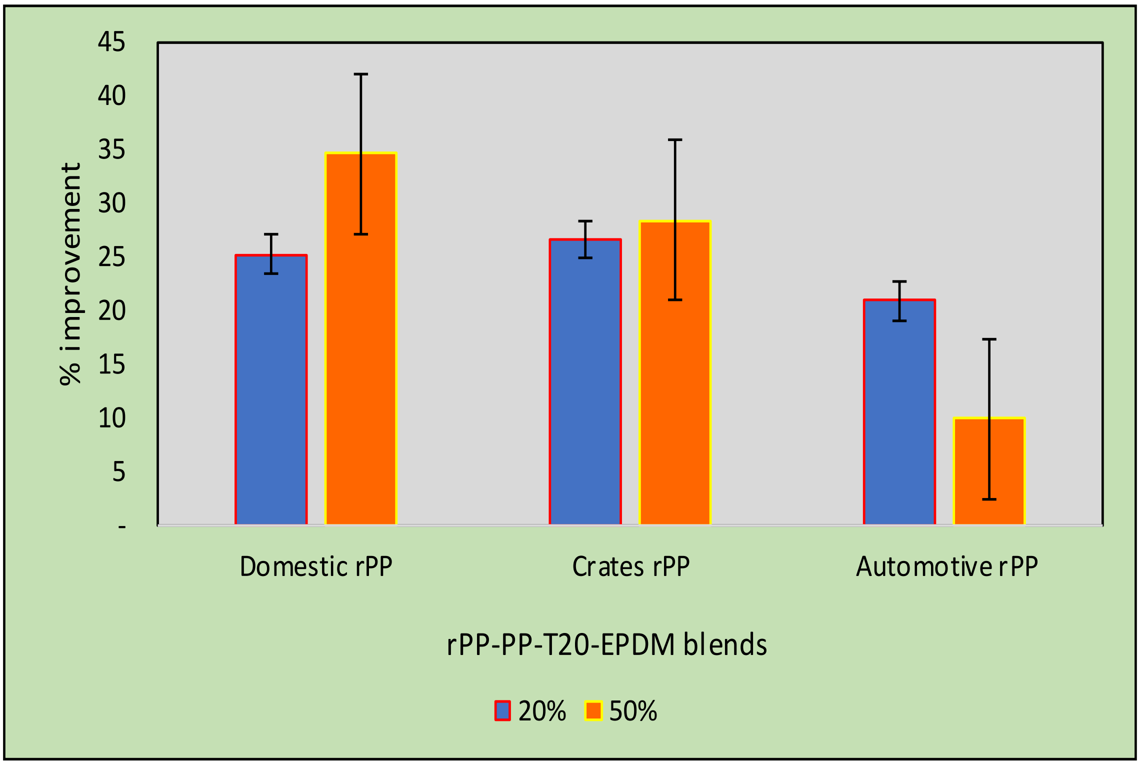


Figure 4.11: 20% and 50% rPP Improvement in flexural strength.

From the data in Table 4.8, there is not much significant difference in the blends of 20% and 50% recycled plastic. However, an increase in improvement of the flexural strength (there is less strain in the material) is observed when 50% rPP is added to the PP-T20-EPDM matrix especially for rPP-1 and rPP-3. This can be correlated to the impact of the high crystallinity of the raw rPP-1 and rPP-3. As a result, the crystallinity influenced the toughness of the material. Also, the high MFI in these plastic increases the molecular chain breakage leading to mobility in the matrix of the blends thus these recycled plastic materials blends have low yield stress thus they elongate before breaking as oppose to the recycled plastic rPP-4 which has longer chains in its structure and brittle.

4.2.3 Dynamic Thermo-mechanical behaviour

The heat deflection temperature is a representation of the materials resistance to distort / lose stiffness at a physical load in increased temperature. As a result, HDTUL gives an indication of the performance of the material in high temperature applications while the temperature ramp highlights the lowest temperature in which the material can be used. Poor Heat-Deflection is observed by the dimensional change on-setting at a lower temperature, therefore improvement in Heat-Deflection is determined by an increase on the on-setting Temperature of dimensional change.

Table 4.10: Temperature ramp and HDTUL

Materials	Onset Tg (˚C)	Tg (˚C)	Tan delta	HDTUL (˚C)	Working temperature range (˚C)
PP-T20	-5	19	0.12	84	79
rPP-1	-9	16	0.07	73	64
rPP-3	-8	16	0.08	84	76
rPP-4	-6	16	0.11	80	74
rPP-1 80/20	-5	22	0.12	92	87
rPP-3 80/20	-7	20	0.10	97	90
rPP-4 80/20	-7	19	0.12	83	76
rPP-1 50/50	-7	20	0.10	93	86
rPP-3 50/50	-8	19	0.10	95	87
rPP-4 50/50	-8	21	0.10	82	74

The heat deflection temperature of the copolymer PP-T20 was found to be 79 ˚C as shown in Table 4.10 while the heat deflection temperature of the recyclates was found to be 64 ˚C, 76 ˚C and 74 ˚C for rPP-1, rPP-3 and rPP-4 respectively.

The heat deflection temperature of rPP-3 and rPP-4 was found to be higher than the heat deflection temperature of rPP-1, these differences in the deflection temperature can be attributed to a variety of influencing factors such as the extrusion or reprocessing conditions, the morphology of the recyclate as well as to the presence of fillers such as talc or $CaCO_3$. However, this trend was not observed in the recycled materials but the high deflection temperature observed for rPP-4 can be attributed to the high content of the inorganic material/filler content while the low deflection temperature of rPP-1 can be attributed to the high processing conditions which led to the degradation of its materials and high MFI value.

From the data obtained, the observed heat deflection temperatures are ideal since they are high meaning that these plastics will lose their structural property such as dimensional stability in high temperature applications at the given high temperatures.

The thermomechanical behaviour of PP-T20 with its blends of different recycled plastics were evaluated and the data is shown in Table 4.10. Even though the HDTUL of the blends are very close to each other, the DMA scans revealed that the blends of PP-T20-EPDM with rPP-3 presented a higher HDT with the highest temperature observed in the rPP-3 80/20 blend being 97 ˚C. This increase in the HDT of the rPP-3 blends may be associated with an increase in the crystallinity of the raw rPP material, meaning that this blend requires more energy /load to change shape/ lose its structural property. In addition, the high temperature observed in the blends of this rPP translate to better thermal stability for high temperature applications such as when used in the manufacturing of the radiator grill which is exposed to hot air from the engine through the radiator of a vehicle.

The blends of rPP-1 and rPP-4 also showed an increase in the heat deflection temperature, this might be due to the contribution of the PP-T20 which has a HDT 84˚C ultimately raising the deflection temperature of the respective blends.

The addition of recycled plastic materials (blends of the recyclates) seemed to increase the onset glass transition temperature of PP-T20 making the recycled blends to be suitable for low temperature applications. The tan delta values decreased with the addition of the recycled plastic; this is an indication of an increase in the crystallinity of the blends. This trend suggests that these blends will not soften when used in high temperature applications (upon exposure to hot temperature air from the radiator).

rPP-1 blends namely rPP-1 80/20 and rPP-1 50/50 had low T_g temperatures of -7 ˚C and -5 ˚C with high heat deflection temperatures observed at 92 ˚C and 93 ˚C respectively. This is suggestive that the plastic has a high temperature working range suitable for both high and low temperature applications.

Chapter 5: Conclusion

The study successfully demonstrated that not all recycled PP can be utilized as cheapening agents for automotive components. Therefore, the source of rPP and historical characteristics are very critical since these affect the mechanical properties of the blends. The degradation of the plastic material affects the molecular weight thus the end-user properties of the plastic blends formulated. Also, the influence of this degraded material may have a negative and positive influence on the properties of interest. For an example, it was observed that recycled plastics which show a high effect of reprocessing such as the domestic rPP had more notable difference in the mechanical properties investigated than the other recycled plastic materials.

The study emphasized on the influence of various recycled plastic on polypropylene in the manufacturing of internal and external automotive components. The MFI showed to be feasible to determining the physical property changes of the recycled materials and helped in the prediction of the flow behaviour of the materials as well as highlight important aspects such as controlling the amount of time the plastic is recycled to be used in secondary applications. rPP-1 had a high MFI of 19.94 g/10 min with rPP-4 having a low MFI of 7.86 g/10 min. rPP-2 (bin lids rPP) was not determined as the materials could not fit into the barrel of the MFI as a result, they would complicate processing of the blends and were not used further in the study.

DSC analysis was used to determine the various types of plastics contained in recycled plastics where rPP-1, rPP-2 and rPP-3, deconvolution of the isotherms showed that these recyclates are made from polypropylene with the melting point in from the range 170 – 173 ˚C. Whereas rPP-4 showed two characteristics melting peaks at 126 ˚C and 166 ˚C which can be attributed to PE and PP respectively. The high degradation temperature of the recycled plastic materials at about 300 ˚C is in agreement with the degradation of polypropylene, confirming that the recycled plastic materials are made from the polypropylene plastic.

This study also showed that the impact strength the PP-T20-EPDM decreases significantly with increasing amounts of recycled material irrespective of the grade but less decrease in this property was observed when rPP-1 was used. There was no correlation between this property and the crystallinity of the blends, however, the MFI showed that recycled material with low MFI (high molecular weight) exhibit a decreased impact strength and the opposite is true.

The flexural strength of the blends showed a positive improvement with addition of the recycled plastics, and this can be correlated to the MFI data. The higher the MFI of the recycled material, the lesser the strain observed on the blends. This was deemed possible since high MFI translates to chain scissions thus less crystallinity of the molecular chain and low molecular weight. Less strain of the material was observed when 50% of rPP-1 was added to PP-T20-EPDM. Overall, there was less impact reduction and high flexural properties observed when rPP-1 especially at rPP-1 50/50 blend.

The HDTUL of the blends are very close to each other, the DMA scan revealed that the blends of PP-T20-EPDM with rPP-1 and rPP-3 presented a higher HDT with the blends having a HDT observed at rPP-3 80/20 for rPP-3 and rPP-1 50/50 for rPP-1. The blends of rPP-4 presented decreased deflection temperature when compared to the other rPP materials irrespective of the composition and this might be due to the low crystallinity exhibited by the raw material rPP-4. The increase in the HDT of the rPP-1 and rPP-3 blends may be associated with an increase in the crystallinity of the raw rPP materials as well as the easy flow of this rPP due to high MFI of 19.94 g/10min and 16.16 g/10min meaning that these blends require more energy /load to lose its structural property. In addition, the high temperature observed in the blends of these rPP's translate to better thermal stability for high temperature applications such as when used in the manufacturing of the radiator grill which is exposed to hot air of the engine through the radiator of a vehicle.

The addition of recycled plastic materials (blends of the recyclates) increased the onset glass transition temperature of PP-T20 making the recycled blends to be suitable for low temperature applications. The tan delta values decreased with the addition of the recycled plastic; this is an indication of an increase in the crystallinity of the blends. This trend suggests that these blends will not soften when used in high temperature applications (upon exposure to the hot temperature of the radiator). rPP-1 blends namely rPP-1 80/20 and rPP-1 50/50 had low T_g temperatures of -7 ˚C and -5 ˚C with high heat deflection temperatures observed at 92 ˚C and 93 ˚C respectively.

This is suggestive that the plastic has a high temperature working range suitable for both high and low temperature applications.

From the data observed, it is proposed that rPP-1 and rPP-3 blends may be used for the manufacturing of the automotive components (door panel and radiator grill) since there is less reduction of the mechanical properties (impact strength), improved flexural strength and had a wide working temperature range as opposed to the rPP-4 blends.

Nevertheless, materials have limitations in terms of the mechanical properties to some degree and no material can exhibit all the desired properties. As much as rPP-1 and rPP-3 blends show that they can be used for the manufacturing of automotive components with the rPP-3 blends being cost effective, it doesn’t rule out that the other recycled plastic materials can be used for other applications such as structural applications etc.

RECOMMENDATIONS

- GPC to study the molecular weight and molecular weight distribution of the recycled plastics.
- FTIR to study the carbonyl groups in the recycled materials as the presence of these group at 1750 cm^{-1} suggests thermo-oxidative degradation of the materials when can lead to reduced mechanical and thermal properties.
- Use PXRD to verify the crystalline behaviour of the blends as well as to study the crystallites of the recycled plastics.
- Electron Microscopy Analysis (SEM/TEM/AFM) to study the morphology of the blends where segregation of the rPP can potentially explain the low mechanical properties observed.
- Use XRF to study the elemental composition of the inorganic materials in the recycled plastics.
- Granulating the rPP's to ensure smaller pieces which fit into the screws and to endure homogeneity of the plastic matrix.
- Masterbatching and using a twin screw to ensure the homogeneity of the blends and dispersion of material.

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